Physical dispersion of radioactive mine waste at the rehabilitated Radium Hill uranium mine site, South Australia

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The Radium Hill uranium deposit, in semiarid eastern South Australia, was discovered in 1906 and mined for radium between 1906 and 1931 and for uranium between 1954 and 1961 (production of 969 300 t of davidite ore averaging 0.12% U_3O_8). Rehabilitation was limited to removal of mine facilities, sealing of underground workings and capping of selected waste repositories. In 2002, gamma-ray data and samples of tailings, uncrushed and crushed waste rock, stream sediment, topsoil and vegetation were collected to assist in examining the current environmental status of the mine site. The data indicate that capping of tailings storage facilities did not ensure the long-term containment of the low-level radioactive wastes due to the erosion of sides of the impoundments. Moreover, wind erosion of waste fines (phyllosilicates, ore minerals) from various, physically unstable waste repositories has caused increasing radiochemical (from a background dose of 35–70 nSv/h to max. 0.94 μSv/h) and geochemical (Ce, Cr, La, Lu, Rb, Sc, Th, U, V, Y, Yb) impacts on local soils. Plants (saltbush, pepper tree) growing on waste dumps display evidence of biological uptake of lithophile elements, with values being up to 1–2 orders of magnitude above values for plants of the same species at background sites. However, radiation doses associated with the mine and processing site average 0.67 μSv/h; hence, visitors to the Radium Hill site will not be exposed to excessive radiation levels. Although rehabilitation procedures have been partly successful in reducing dispersion of U and related elements into the surrounding environment, it is apparent that 20 years after rehabilitation, there is significant physical and limited chemical mobility, including transfer into plants. Additional capping and landform design of the crushed waste and tailings repositories are required in order to minimise erosion and impacts on surrounding soils and sediments.

KEY WORDS: contaminants, erosion, Radium Hill, South Australia, tailings, uranium.

INTRODUCTION

Mining, mineral processing and metallurgical extraction of uranium ores result in the production of tailings, waste rocks, and heap-leach residues. Potential environmental impacts of uranium mine wastes prior to, during and after mining include: excessive radioactivity levels and radon emissions; inappropriate use of tailings and waste rocks; failure of tailings storage facilities; soil, sediment, and ground and surface water contamination; and acid mine drainage (Lottermoser 2003). Hence, uranium mine sites and in particular their waste repositories require appropriate remediation measures. Recent research on rehabilitated uranium mine sites located in wet climates has revealed the varied success of the applied rehabilitation efforts (Menzies & Mulligan 2000; Peacey *et al.* 2002; Ritchie & Bennett 2003). In wet and seasonally wet climates, acid mine drainage development and the leaching of waste repositories are dominant pathways of contaminants into surrounding environments. In fact, a number of studies on Australia's

uranium mine sites located in wet climates (e.g. Rum Jungle) have highlighted the importance of leaching processes and chemical mobility of contaminants (Richards *et al.* 1996; Taylor *et al.* 2003). In comparison, there is little knowledge of the status and environmental impacts of rehabilitated uranium mines in dry climates. To date, the few studies conducted on rehabilitated uranium mine sites in semiarid and arid climates have largely focused on uranium mill tailings repositories and related ground and surface water investigations (Abdelouas *et al.* 1998; Lottermoser & Ashley 2005).

In this paper, we investigate the transfer of radioactive material from waste rock dumps and tailings storage facilities into soils, sediments and plants at the rehabilitated Radium Hill uranium mine that is located in semiarid South Australia. The study was undertaken to determine: (i) the radiometric, mineralogical and geochemical characteristics of uraniferous waste rock dumps and tailings repositories; (ii) the geochemical properties of soils and sediments impacted by the waste

repositories; and (iii) the performance of the rehabilitation measures applied to the waste repositories. Hence, this case study contributes to improved rehabilitation of waste repositories of uranium mine sites in semiarid climates.

RADIUM HILL AREA

Physiography, climate and vegetation

The abandoned uranium mine and town site of Radium Hill is located 440 km north-northeast of Adelaide, South Australia (32°21′S, 140°38′E) (Figures 1, 2). The site is located in gently undulating topography with altitudes

reaching 270 m and an average elevation of 220 m above sea level. Radium Hill has a semiarid climate. Average annual winds are predominantly blowing from the south, north and west (Broken Hill weather station, 100 km to the northwest: Bureau of Meteorology 2005). The average annual rainfall is 200 mm. Average temperatures range from 3°C in winter to 33°C in summer (Forbes 1991). Consequently, vegetation is relatively sparse, with saltbush and bluebush species, native grasses and small trees (mulga, black oak, false sandalwood). Larger trees such as river red gums occur along some of the major ephemeral streams. The main land use in the district is low-density grazing.

Soils in the area are commonly skeletal loams on the hills, but thicken into red duplex and calcareous soils on
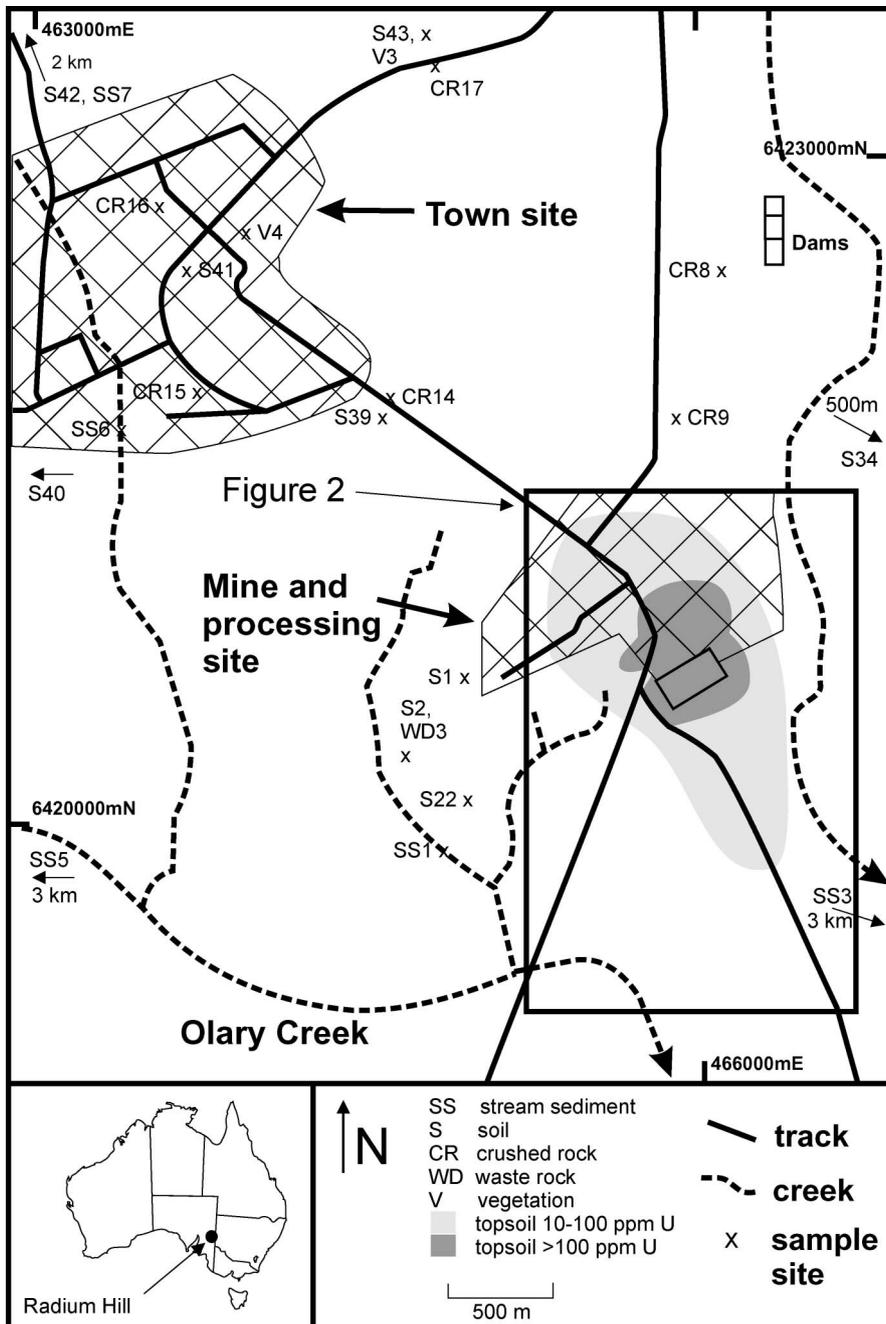
Figure 1 Plan of the Radium Hill town site and mine and processing area. Locations of various sample media are indicated. The uranium distribution in topsoils of the mine and processing site is also indicated. Highly contaminated soils (>100 ppm U) are associated with the main tailings storage facility.
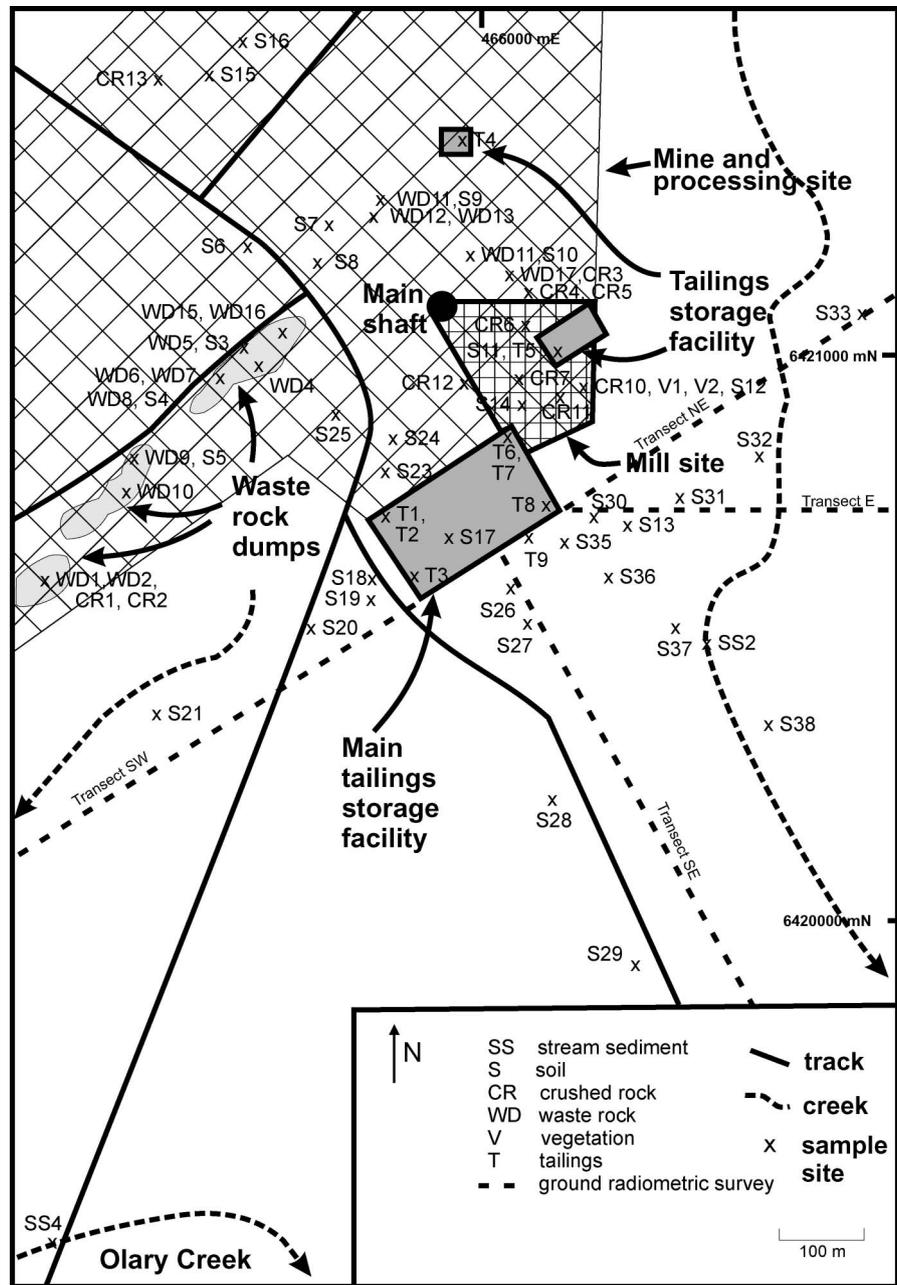
Figure 2 Detailed plan of the Radium Hill mine and processing site showing the location of the main tailings storage facility and waste rock dumps. Locations of ground radiometric survey transects and various sample media are also indicated.

plains. Calcrete development is common in all non-alluvial soils. Rock outcrop is moderate in the hill regions, but sparse to absent elsewhere. Finer soil material may be partly wind-deposited and, in the vicinity of the mine site, can include a minor to significant proportion of windborne and waterborne mine tailings and other detritus.

Drainage from the Radium Hill mine and town area is via two approximately south-flowing ephemeral creeks (and their tributaries) into the major water-course of the district, Olary Creek (Figure 1). The streams are locally entrenched up to 3 m into Holocene and Late Tertiary windblown silt and sand, and fluvial sands and gravels. It is only after heavy rain events that there is surface water flow, although it is evident that these events are the major cause of erosion and sediment transport in the region.

Geology

Uranium mineralisation at Radium Hill is hosted in high-grade metamorphic rocks of the Willyama Supergroup in the Olary Domain. These are of Palaeoproterozoic age (*ca* 1700 Ma) and include metasedimentary quartzo-feldspathic gneiss, composite gneiss, quartz–feldspar–biotite schist and amphibolite. It is likely that these rocks are part of the Wiperaminga Subgroup of Conor (2000) and correlate with the lower part of the Willyama Supergroup sequence in the Broken Hill region, 50–100 km to the northeast.

The host-rocks for mineralisation have been folded into a dome-like structure. Several subparallel vein-like orebodies (lodes) occupy northeast-striking shear zones cutting drag folds on the overturned western limb of the dome (Blissett 1975). The lode systems were traced

continuously for 1400 m along strike and typically dipped to the southeast at 30–70° (Parkin & Glasson 1954). The lodes occupied shear structures containing abundant biotite and quartz, with patchy to nodular aggregates of oxide minerals. The latter form complex intergrowths and include ilmenite, rutile, magnetite, hematite and davidite. Parkin and Glasson (1954) noted that lode development was commonly wider and of better grade where lodes intersected amphibolite. In such zones, strong biotite (-oxide mineral) alteration is commonly evident. Lode zones were also associated with lode-parallel and cross-cutting pegmatite and aplite masses, and were cut by later amphibolites. Surface oxidation effects are relatively minor as the oxide material forming the ore was refractory; minor carnotite occurs as a replacement of davidite, and oxide minerals are mainly physically dispersed into the regolith materials.

History of mining

Uranium was discovered at the site of Radium Hill in 1906, and the new UTiFe mineral davidite was reported from the location by Mawson (1906) and Whittle (1959). Mining occurred intermittently for radium between 1906 and 1931, and owing to the need to locate uranium for the then incipient atomic age, an exploration program commenced in 1944, leading to the development of an underground mine, with uranium production starting in 1954 (Parkin & Glasson 1954). Mining occurred to a depth of 290 m and along a maximum strike length of 915 m in a series of vein-like lode systems averaging 1 m in width but up to 7.5 m wide (Blissett 1975). Although mineralisation was intersected in drillholes to a depth of 450 m, reserves of easily accessible ore at depth were negligible. Mining continued until 1961, with production of 969 300 t of davidite ore, averaging 0.12% U_3O_8. This was beneficiated on site to a concentrate that was subsequently railed for treatment at Port Pirie to produce 852 t U_3O_8, plus by-product rare earths and scandium oxide (Parkin 1965; Blissett 1975; McKay & Miezitis 2001).

Leading up to the start of mining in 1954, a substantial town and industrial site was constructed, with the town eventually having a population of about 1000. The town was located about 3 km west-northwest of the mine/industrial site (Figure 1).

Rehabilitation

Following closure of the mine, most buildings were transported away or demolished, leaving only foundations. However, a few of the larger concrete structures remain (Figure 3a). Waste rock and mill tailings dumps were simply left uncovered (Figure 3b). Owing to the semiarid climate and propensity for windy conditions (particularly from the northwest to southwest quadrants), the finer mill tailings material was subject to wind deflation, leading to spreading of wind-deposited tailings about the main tailings storage facility. As a result of this condition, capping of mill tailings material with a soil layer was instigated in the early 1980s.

SITE DESCRIPTION

Mine/industrial area

The Radium Hill mine site and associated processing area and workshops, etc., cover an area of ~1 km². The site encompasses numerous relics and foundations of buildings and other structures, although the only substantial remains are those of the main orepass and crusher, plus two large concrete ore bins, adjacent to the former main shaft and mill site (Figure 3a). Several roads serviced the area, as well as a rail siding near the mill. Numerous waste dumps of uncrushed rock occur adjacent to former shafts over a strike length of ~800 m along the trace of the line of lode. These are up to 5 m thick and cover individual areas of up to 10 000 m² (Figure 2). Adjacent to the mill site are several dumps of finely crushed rock (commonly <2 cm grainsize), some individually containing up to ~40 000 t, as well as smaller dumps of more coarsely crushed waste rock (Figure 3b).

There are at least three dumps (dams) in which fine mill tailings have been stored (Figure 2) that have subsequently been largely covered by soil and weathered rock excavated from trenches alongside each dump (Figure 3c). A couple of other sites have also been soil-covered, but what lay underneath was not ascertained. A small tailings dam about 250 m north of the main shaft may relate to an earlier phase of mining (sample T4, Figure 2). The other identified tailings dams are to the south and southeast of the main shaft, with a smaller dam adjacent to the mill site (sample T5, Figure 2) and the larger main tailings storage facility a few hundred metres to the south (Figure 2).

The larger tailings storage facility, hereafter called the main tailings storage facility, has dimensions of approximately 250 × 150 m, is at least 5–6 m thick and has slopes of 20–25° (Figures 2, 3c). It is one of the main foci of this study due to its size and the fact that it was subject to considerable wind and water erosion prior to being capped. The capping material on the main tailings storage facility is ~1 m thick and composed of relatively consolidated soil, with minor weathered rock and calcrete. The surface is now partly vegetated by saltbush and acacia species, although the steep sides are relatively bare and have been subject to local water erosion, thus exposing bedded fine tailings in places (Figure 3c). At one corner of the small tailings dam near the mill site, erosion of the cover has again exposed bedded tailings (Figure 3d).

Wind and water dispersion of tailings and crushed rock dumps has occurred and remains active at uncovered sites. Prior to covering, wind deflation was evidently significant about the main tailings storage facility, and fine tailings material has been dispersed in all directions (Figure 4). Windblown tailings material, up to tens of centimetres thick, is particularly common up to 80 m away on the northeast and southeast sides of the main tailings storage facility. Small amounts of windblown tailings remain evident for at least 500 m distant on the southeast side of the main tailings storage facility. The dispersion to the northeast and southeast reflects the direction of the prevailing strong winds to
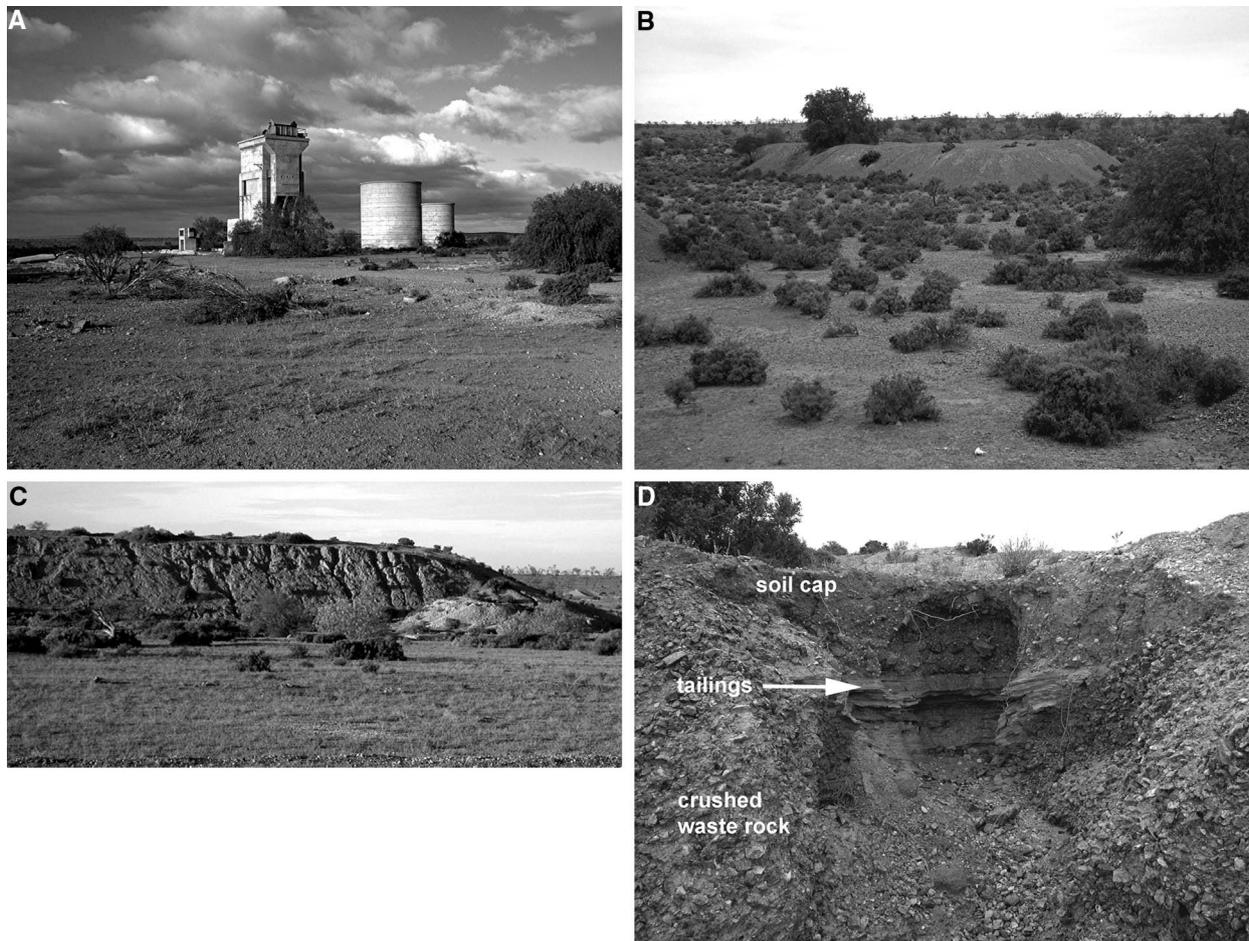
Figure 3 (a) Remnant crusher and ore bins adjacent to the former main shaft and mill site (near main shaft, Figure 2). Residual strongly mineralised material is scattered about the structures. (b) Dump containing finely crushed waste rock material (427 ppm U, 0.48 μSv/h) (near CR10, Figure 2). There has been significant physical dispersion of this material by water and wind. Plants growing on this material (saltbush, foreground; pepper tree, background) demonstrate uptake of U and related trace elements, relative to a background site. (c) Rill erosion of the soil-capped main tailings storage facility, northwest corner (height of facility approximately 6 m) (near T1, T2, Figure 2). The soil capping is being removed, resulting in the exposure of tailings in rills. (d) Erosion and incision of a covered mill tailings dam (near S11, T5, Figure 2). The tailings (3.5 μSv/h, 5500 cps, 1600 ppm U) were originally (1950s–1960s) placed in a depression of crushed waste rock and then capped with soil containing calcrete and rock fragments. The soil cover reduces the radiation levels to 0.1 μSv/h, as measured at the cover's surface.

the north, south and east (Bureau of Meteorology 2005), although east of the main tailings storage facility, the dispersion plume has probably been largely removed by subsequent flooding of a wide stream channel. Uncovered dumps of finely crushed rock remain susceptible to wind and water erosion and it is evident that major rainfall events have caused movement of even coarsely crushed waste rock for hundreds of metres (Figure 3b).

Town, roads and railway

Throughout the mine/industrial site, finely to coarsely crushed rock from the mine has been used for ground cover at worksites, roads (including as a component of asphalt) and concrete structures. The asphalt road linking the town to the mine used finely crushed material and many other roads leading away from the town and mine used coarsely crushed material for

surfacing. Coarsely crushed waste rock was used as railway ballast along the length of the 18 km spur line from Radium Hill to the main Broken Hill–Port Pirie railway and was also used on the latter route prior to the standard-gauge railway being opened in 1969.

MATERIALS AND METHODS

Ground radiometric survey

A ground radiometric survey of the waste rock dumps, tailings repositories and adjacent soils was conducted in the form of a series of transects and loops using a portable Exploranium GR-320 spectrometer with a 512 channel spectrometer and a 350 cm^3 sodium iodide detector. Radiometric data were continuously recorded for 60 s during the survey and acquired at a speed of

Figure 4 Aerial photograph of the Radium Hill mine and processing site (courtesy of Mapland, Environmental Information, Department for Environment and Heritage South Australia). Uncovered material has a grey colour with a blue tint, whereas soil coverings are pale orange-brown. The windborne dispersion plume of fine tailings about the main tailings storage facility (large rectangular structure) is evident for several hundred metres distance (except to the southwest), giving a pale grey-blue colouration to the soil.

~1 m/s. Measurements are confined to the upper 0.3 m of the soil/rock and were taken at a detector elevation of ~1 m above dry ground. This survey design ensured that the gamma-ray data represent large soil/rock units of several metres in lateral dimension. Units of radiation exposure (μR/h, nSv/h) and radionuclide abundance (wt% K, ppm U, ppm Th) were recorded. In addition, a Scintrex BGS-1SL scintillometer was used to count the local gamma-ray activity by means of traverses and loops and at each sample site in counts per second (cps).

Sampling and sample preparation

Fieldwork was conducted in June 2002, with collection of several different sample media [waste rock dumps; crushed rock (including road gravel and railway ballast); tailings; soils; stream sediments; vegetation].

All non-vegetation samples were representative composites, and each constituted several kilograms. Soil samples were topsoil materials, from depths of 0–10 cm. They were taken from the town and mine area and surrounding district. Outlying soil samples were taken at distances up to 8 km from the mine area in order to obtain representative background element values. Stream sediment samples (active material) were collected from: (i) uncontaminated Olary Creek upstream and west of the Radium Hill site (local background); and (ii) local streams draining the site.

All samples were air-dried. Stream sediment and soil samples were dry-sieved to <180 μm. Consistent with common geochemical stream-sediment surveys (Van Loon & Barefoot 1989), the <180 μm size fraction was selected as the fraction most likely to reflect element dispersion and mine site pollution. Rock samples were passed through a steel-jaw crusher, thoroughly mixed and a 100 g aliquot pulverised in a tungsten carbide steel ring mill.

Two vegetation species were collected, including saltbush (*Atriplex* spp.) and pepper tree (*Schinus* spp.). Four samples of vegetation were obtained: one of each species from near-background sites near the town site and one of each species from a fine crush rock dump south of the mill site (Figure 3b). Samples of live twigs and leaves of pepper tree and saltbush were obtained from plants growing on one of the large dumps of finely crushed material south of the mill site. The substrate material was several metres thick and had a typical total count scintillometer reading of 2100 cps. Samples of the same species were collected from sites on background soils (total count scintillometer of ~125 cps) near the town. The vegetation samples were thoroughly washed and disaggregated, then ashed in an electric furnace at 600°C for 4–6 h.

Analytical methods

Processed solid samples were analysed by instrumental neutron activation analysis (INAA) (Becquerel Laboratories, Sydney) for a range of major elements and trace elements (Ag, As, Au, Br, Ca, Ce, Cs, Co, Fe, Eu, Hf, Ir, K, La, Lu, Na, Rb, Sc, Se, Sm, Ta, Te, Th, U, W, Yb). Sample aliquots were also submitted to Australian Laboratory Services, Brisbane, where sample powders underwent fusion (lithium metaborate) and were analysed by inductively coupled plasma mass spectrometry (ICPMS) for Ba, Cu, Mo, Nb, Pb, Sn, Ti, V, Y, Zn and Zr. Paste pH measurements were performed on several powdered tailings and topsoils, following the procedure of Morin and Hutt (1997).

Polished thin-sections of waste rock samples were prepared and subsequently investigated for their mineralogy and petrography by optical microscopy. The mineralogy of selected waste rock, crushed rock, tailings, soil and stream sediment samples was identified using X-ray diffraction (Cu Kα: Siemens D5000 X-ray diffractometer) and computational software (SIRO-QUANT, EVA) at the Advanced Analytical Centre (AAC), James Cook University Townsville. Microprobe analyses were performed on brannerite, monazite and uraninite present in waste rock samples using a Jeol

JXA-8200 Superprobe also at AAC. The microprobe analyses are regarded as semi-quantitative because sample materials returned insufficient total element values compared with published mineral compositions obtained by microprobe analyses.

RESULTS

Imagery

The Radium Hill site is prominent on aerial photographs (Figure 4). Apart from obvious cultural remnants (e.g. roads, railway, building foundations, large concrete structures), the waste rock dumps, crushed rock dumps and tailings storage facilities are conspicuous. Uncovered waste rock and tailings materials have a grey colour with a blue tint, whereas soil coverings are pale orange-brown. The windborne dispersion plume of fine tailings about the main tailings storage facility is evident for several hundred metres distance (except to the southwest), causing a pale grey-blue coloration of the soil.

Radiometric imagery of the region reflects bedrock geology and regolith, but the U channel also clearly demonstrates the effects of environmental dispersion (Figure 5). Diffuse U channel highs to the north, northeast and east-northeast of the mine and town sites are most likely due to outcropping bedrock. The mine area has an intense U channel high, with the sharp anomaly that is subcircular and about 1.5 km in diameter. Away from the mine site, there is a diffuse weak U anomaly extending to the east and south for at least 0.7 km, and this is interpreted to be in part due to the dispersion of windborne tailings. A slightly less intense U anomaly (with three high lobes) occurs over the town site. The gravelled road extending about 1.8 km east-northeast of the town and the asphalt road between the town and the mine form prominent U anomalies. The former town site and main roads stand out due to the use of mine-derived crushed rock for construction.

On the Th channel, the immediate mine site also forms a prominent anomaly <1 km in diameter (Figure 6). The town site is hardly discernible on this image, but bedrock and subcrop areas to the north, east-northeast and immediately south of the mine form prominent diffuse anomalies. On the K channel, again the bedrock and subcrop regions form prominent diffuse highs, and the sandy (feldspathic) alluvium in Olary Creek draining southeast from the Radium Hill area forms a distinctive K channel anomaly. The mine area forms a sharp K channel anomaly about 1 km in diameter, probably due to K-bearing rocks being exposed by mining and incorporated into dumps, tailings and other forms of ground cover. A weak K channel anomaly is evident over the town.

Waste rock dumps

The waste rock dumps consist of broken rock material from the underground mine workings and are a thorough representation of the various rock types
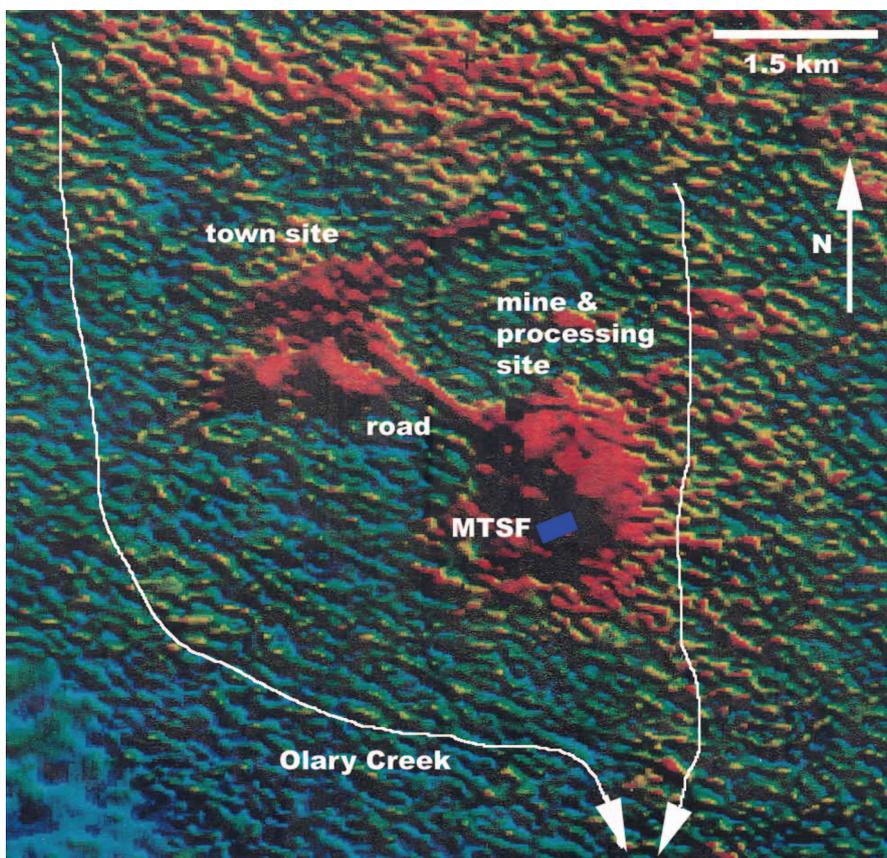
Figure 5 Radiometric image (uranium channel) of the Radium Hill site (courtesy of Primary Industries and Resources South Australia). The former town site and main roads stand out due to the use of mine-derived crushed rock for construction, and the mine area has a marked, complex U anomaly ~1.5 km in diameter and a diffuse dispersion to the E and S for a further 1–2 km. The main tailings storage facility (MTSF) and local creeks are also shown.
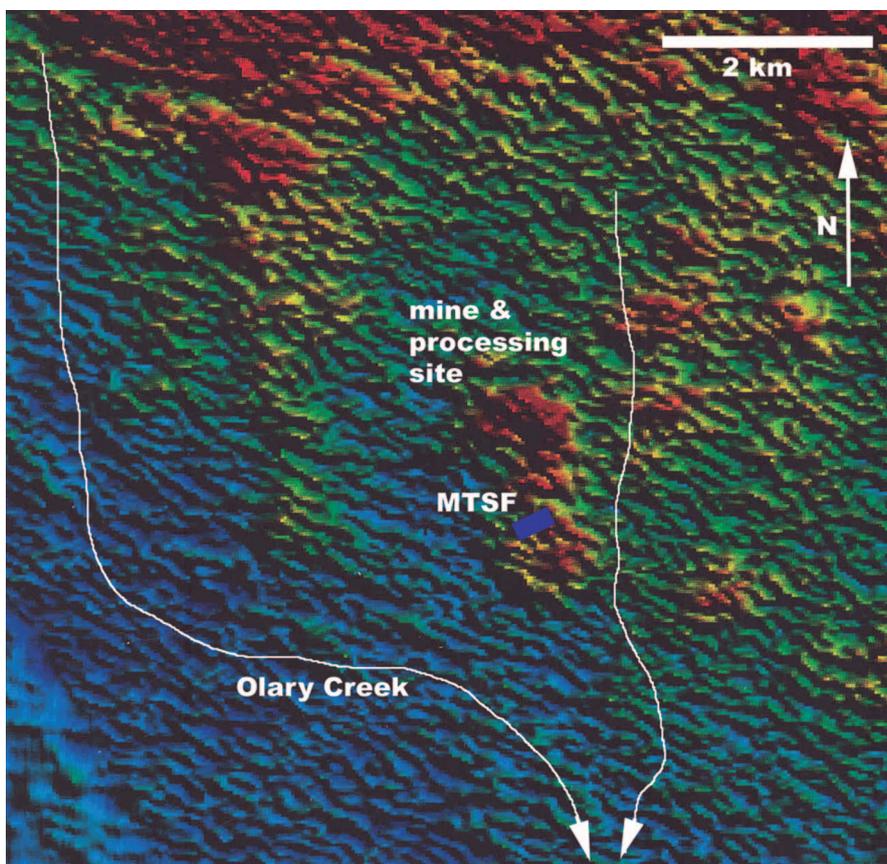
Figure 6 Radiometric image (thorium channel) of the Radium Hill site (courtesy of Primary Industries and Resources South Australia). The mine area has a prominent Th anomaly ~1 km in diameter. Bedrock and subcrop areas to the N, ENE and S of the mine site form diffuse anomalies. The main tailings storage facility (MTSF) and local creeks are also shown.

encountered during mining. Particle size in the waste rock dumps varies from several tens of centimetres down to sandy material, and these dumps have remained relatively stable. Rock types include feldspar–quartz (–biotite) gneiss, locally grading into more micaceous and schistose types and biotite-rich altered types; amphibolite and its biotite-altered equivalents; pegmatite and various types of lode and shear-zone rock material.

Lode material is commonly rich in coarse bluish quartz and black to bronze biotite, along with variable amounts of pink K-feldspar, albite, hornblende, rutile, ilmenite, hematite, chlorite, sericite, monazite, xenotime, allanite, apatite and traces of sulfides (pyrite, chalcopyrite, molybdenite). The uranium ore minerals brannerite and uraninite occur as minute grains (0.01–0.1 mm across) intergrown with oxide, REE mineral and sulfide phases, as evidenced by SEM studies. Evident ore-grade material (0.1–0.2 wt% U) is characterised by aggregates of Fe–Ti oxide minerals and high radiation levels (max. 5000 cps; 0.3–4.2 μSv/h). Waste rock samples display major (>1 wt%) median concentrations of Fe, K and Na, minor (>1000 ppm) Ca and Ti, sub-minor (>100 ppm) Ba, Ce, Cr, La, Rb, U and V, and traces (<100 ppm) of As, Br, Co, Cs, Cu, Eu, Hf, Lu, Mo, Nb, Pb, Sb, Sc, Sm, Sn, Ta, Th, Y, Yb, Zn and Zr (Table 1). A correlation matrix of log-transformed geochemical data indicates high degrees of correlation ($r > +0.9$) between ore elements Ce, Cr, Sc, La, Lu, Nb, Ta, Th, Ti, U, V, Y and Yb in the waste rocks, reflecting the occurrence of an ilmenite–rutile–brannerite–uraninite–davidite–monazite–xenotime–apatite–allanite association. Electron microprobe analyses revealed Th-rich brannerite (up to 6.15 wt% ThO$_2$) and traces of uraninite as the dominant uranium ore minerals. Davidite was not detected in the collected samples.

Crushed rock dumps and dispersed crushed rock

Crushed rock material from the mine is found in several dumps in the mine and mill areas, and has been widely dispersed around the mine and town sites. Coarse crush material typically has a particle size of 2–10 cm and appears to have been screened. This material has been widely used as ground covering, gravel road surfacing and railway ballast, and for concrete. It typically has a total count scintillometer reading of 300–800 cps and radiation levels of 0.2–0.6 μSv/h. Fine crush material includes screenings (~0.5–2 cm size), widely used for asphalt roads and concrete, and non-screened material that includes a high proportion of fines (sand- to silt-sized material). Dumps of the latter material have been subject to significant water and wind erosion (Figure 3b). Fine crush material is typically more radioactive than coarse crush and has total count scintillometer readings of 1000–2500 cps and radiation levels of 0.7–1.7 μSv/h. The composition of the crushed rock is likely to be an integration of all waste rock material, with abundant quartz, feldspars, biotite, plus local chlorite, sericite, amphibole and oxide minerals, including residual uranium minerals.

Crushed waste rock samples display relative elemental abundances largely identical to the waste rock samples (Table 1). They have major (>1 wt%) median concentrations of Fe, K and Na, minor (>1000 ppm) Ca and Ti, sub-minor (>100 ppm) Ba, Ce, Cr, La, Rb, U, V, Y and Zr, and traces (<100 ppm) of As, Br, Co, Cs, Cu, Eu, Hf, Lu, Mo, Nb, Pb, Sb, Sc, Sm, Sn, Ta, Th, Yb and Zn (Table 1). Also, the analysis of log-transformed data indicates a high correlation between ore elements Ce, Cr, Sc, La, Lu, Nb, Ta, Th, Ti, U, V, Y and Yb ($r > +0.8$) and Pb, Zn, As and Sb ($r > +0.9$), reflecting the occurrence of an ore mineral association and sulfide aggregates.

Tailings

The majority of mill tailings (probably >500 000 t) are contained in the main tailings storage facility, with small volumes in two other identified dams. Exposed mill tailings in dams are commonly laminated (a consequence of wet sedimentation) and have a sandy to silty grainsize and texture. They are typically <1 mm in grainsize and rich in quartz, feldspars and micas. Oxide minerals are also present, and residual uranium minerals evidently occur, as all tailings material is moderately to strongly radioactive, with typical total count scintillometer readings of 1400–5500 cps and high radiation levels (max. 3.5 μSv/h). Prior to capping, the tailings storage facilities were evidently prone to wind and water erosion, and gullying is still occurring on the sides of the dams (Figure 3c, d). Wind deflation of tailings before capping may have led to some preferential enrichment of mica in windblown material, as mica flakes would tend to be lifted and made airborne more readily than quartz and feldspars. Consequently, deposits of windblown tailings and topsoils about the main tailings storage facility are enriched in phyllosilicates (biotite, chlorite) as evidenced by XRD studies.

The tailings comprise variable amounts of primary gangue minerals (quartz, biotite, sericite, albite, chlorite, hornblende, K-feldspar). Paste pH measurements of the tailings indicate that the waste is non-acid producing with an average pH value of 9. The materials display major (>1 wt%) median concentrations of Fe, K and Na, minor (>1000 ppm) Ca and Ti, sub-minor (>100 ppm) Ba, Ce, Cr, La, Rb, U and V, and traces (<100 ppm) of As, Br, Co, Cs, Cu, Eu, Hf, Lu, Mo, Nb, Pb, Sb, Sc, Sm, Sn, Ta, Th, Y, Yb, Zn and Zr (Table 1). Tailings have distinctly higher median Cr, Cu, Rb, Sc and V concentrations than the waste rock dump and crushed waste rock materials (Table 1), reflecting a greater abundance of ore mineral aggregates and mica in the tailings. A correlation matrix of the log-transformed geochemical data indicates the highest degrees of correlation ($r > +0.9$) for all sample types between Fe, Ti, U, Th, Sc, Nb, Co, Pb, Y and REE (La, Ce, Sm, Eu, Yb, Lu) in the tailings. This correlation probably reflects the residual coexistence of Fe–Ti oxide (ilmenite–rutile), uranium mineral (brannerite, uraninite, davidite) and REE mineral (monazite, xenotime, apatite, allanite) assemblages in the analysed tailings.

Table 1 Geochemistry of waste rocks, crushed rocks, tailings, soils, sediments and ashed vegetation.

Sample type	As	Ba	Br	Ca	Ce	Co	Cr	Cs	Cu	Eu	Hf	Fe	K	La	Lu	Mo
Waste rocks (WD) (n = 17)																
Minimum	<1	206	<1	<3000	133	12.4	154	3.43	28	1.49	4.39	42 900	15 000	70.6	0.54	<2
Maximum	3	557	3.61	13 400	1230	48.9	811	7.25	695	4.2	9.75	81 800	68 900	1360	21.2	21
Mean	1.3	367	1.6	3700	440	23.0	326	4.56	102	2.25	6.59	56 860	36 150	381	5.53	4.9
Median	1.5	393	1.5	<3000	353	21.3	249	4.2	52	2.18	6.84	57 900	35 800	264	3.89	<2
Crushed rocks (CR) (n = 17)																
Minimum	<1	244	1.3	<5000	160	14.2	192	2.82	20	1.2	2.85	29 100	20 400	103	1.33	2
Maximum	20.1	753	3.6	67 200	671	28.2	454	7.66	300	2.37	7.37	62 700	55 100	583	8.78	10
Mean	2.5	345	1.7	9030	428	18.4	315	4.77	72	1.91	4.59	41 540	27 440	354	4.82	4.4
Median	<3	323	<3	<5000	447	17.5	327	4.3	38	2.03	4.51	42 100	<30 000	351	5.02	4
Tailings (T) (n = 9)																
Minimum	<1	229	<1	<5000	203	13.5	252	6.31	19	0.87	2.22	36 900	15 000	180	1.94	<2
Maximum	<6	664	<6	<5000	1180	42.2	458	8.34	463	4.75	3.46	64 000	57 700	1280	24.4	7
Mean	1.6	414	1.6	<5000	465	19.9	366	7.48	122	1.83	2.82	45 290	35 680	440	6.04	<2
Median	1.5	330	1.5	<5000	359	16.7	386	7.49	89	1.46	2.75	41 600	34 100	321	3.04	<2
Soils (S) background (n = 14)																
Minimum	2.04	220	1.1	3900	86.5	9.11	54.5	2.48	24	1.23	8.9	35 300	12 200	44	0.47	<2
Maximum	5.34	461	8.18	53 000	243	13.8	109	5.74	268	2.94	14.1	62 100	21 900	127	1.06	<2
Mean	4.2	298	3.6	12 890	124	11.9	70.5	3.75	77	1.72	11.2	44 730	15 420	64	0.68	<2
Median	4.5	287	3.2	6600	107	12.2	64.8	3.48	42	1.62	11	42 150	14 350	54	0.61	<2
Soils (S) regional contaminated (n = 16)																
Minimum	<1	217	<1	<3000	94	11.8	79.2	2.21	27	1.26	6.05	38 400	13 000	54.5	0.59	<2
Maximum	5.41	500	9.36	64 200	246	26.6	281	6.31	400	1.84	11.3	58 000	30 900	184	1.94	4
Mean	3.6	331	3.4	15 610	156	14.4	138	4.21	93	1.55	8.41	46 320	20 130	98	1.16	2
Median	3.4	307	3.1	4950	152	13.3	110	4.39	49	1.53	8.11	45 650	20 000	92	1.13	<2
Soils (S) highly contaminated (n = 13)																
Minimum	<1	229	<1	<3000	226	14.6	116	3.35	10	1.09	2.6	37 400	12 700	163	1.65	<2
Maximum	4.85	496	7.44	16 200	435	20.3	365	7.17	242	2.2	14.3	54 600	37 800	359	3.19	2
Mean	1.6	331	2.1	4808	306	16.5	274	5.44	58	1.53	5.9	45 080	18 820	243	2.55	<2
Median	1.5	319	1.5	<3000	297	15.8	271	5.66	45	1.61	5	43 900	15 000	218	2.69	<2
Stream sediments (SS) (n = 7)																
Minimum	1.91	150	<1	5200	70.7	9.04	91.3	<1	24	1.07	4.58	27 400	5000	36.4	0.4	<2
Maximum	7.42	330	4.47	24 800	333	40.1	416	4.78	794	4.14	8.89	234 000	13 900	177	1.83	2
Mean	4.5	271	2.4	13 490	119	16.3	185	2.85	200	1.69	6.18	66 610	10 140	62	0.64	<2
Median	3.7	321	2.4	13 700	74	12.3	146	3.12	65	1.19	6.05	39 600	10 400	38	0.44	<2
Vegetation from crushed waste rock dump																
V2 saltbush	3.68	122	162	24 000	125	<2	69.8	2.86	92	<0.5	0.7	8100	69 600	106	1.33	7
V1 pepper tree	5.44	69.6	232	168 000	18.4	5.28	<5	<1	241	<0.5	<0.5	2900	146 000	17.5	0.11	23
Background vegetation																
V3 saltbush	6.68	179	147	65 800	33.3	<2	33.7	<2	112	<0.5	2.24	11 500	79 900	15.8	0.12	<2
V4 pepper tree	2.59	403	269	234 000	2.94	3.68	8.4	1.1	106	<0.5	<0.5	1200	93 700	1.19	<0.1	<2

Sample type	Na	Nb	Pb	Rb	Sb	Sc	Sm	Sn	Ta	Th	Ti	U	V	Y	Yb	Zn	Zr
Waste rocks (WD) (n = 17)																	
Minimum	9960	13	8	118	0.1	15.4	6.75	2	<1	22.5	3400	8.84	80	23.3	3.55	28	121
Maximum	24 800	122	85	233	0.62	115	15.8	15	12.8	147	41 900	1970	1190	559	119	279	281
Mean	19 120	37	28	185	0.27	43	11.2	5	3.7	55.3	13 700	396	358	145	32	64	185
Median	19 300	25	19	185	0.25	28	10.7	4	2.5	46.1	9400	206	204	89	23	46	187
Crushed rocks (CR) (n = 17)																	
Minimum	14 200	11	7	112	<0.2	16.7	6.28	1	<1	18.2	3000	43.1	155	54.5	8.09	24	107
Maximum	29 300	37	1510	231	8.26	61.2	12.8	6	3.63	56	13 800	518	582	254	48.6	2520	239
Mean	19 690	24	107	176	0.69	37	9.6	4.1	2.23	38	8250	250	359	151	28	192	152
Median	18 400	26	19	178	<0.5	37.1	9.9	4	2.5	39	8000	232	349	152	30.5	46	144
Tailings (T) (n = 9)																	
Minimum	8640	11	9	210	<0.2	40.5	4.16	3	<1	23.7	4100	149	312	65.5	12.2	40	78.7
Maximum	17 400	30	53	275	0.5	105	17.5	11	2.49	113	13 500	1600	1050	842	137	126	176
Mean	14 930	16	17	243	0.26	54	8.3	6.8	1.33	41	6270	370	472	200	35	55	111
Median	16 500	13	10	254	0.25	47	6.7	7	1.31	29	4700	219	379	98.9	18.2	44	93
Soils (S) background (n = 14)																	
Minimum	7410	10	12	61	0.27	9.79	7.27	0.5	<1	15.3	4000	2.22	74	26.7	3.2	46	243
Maximum	12 400	17	23	120	0.58	14.9	17.9	5	2.19	36	6500	9.51	130	52.1	7.27	87	437
Mean	9330	13.2	15.3	88	0.43	12.3	9.94	1.64	1.40	20.9	5121	4.92	91	35.9	4.57	64	340
Median	9550	13	14.5	86	0.44	12.2	8.9	1.00	1.35	18.7	5100	3.30	88	34.6	4.07	64	346
Soils (S) regional contaminated (n = 16)																	
Minimum	7050	9	11	93.6	<0.2	14.3	6.88	1	<1	16.8	3600	10.3	98	31.6	3.84	46	155
Maximum	16 800	29	26	181	0.62	31.8	9.7	6	2.61	34	11 400	98.3	347	102	11.8	137	381
Mean	11 040	15.6	17.4	120	0.33	20.4	8.31	2.86	1.27	21.3	5980	40.6	189	55.4	7.39	65	260
Median	10 300	14.5	16	108	0.38	18.7	8.15	2.5	1.32	20.7	5350	34.9	175	48.2	7.25	57	246
Soils (S) highly contaminated (n = 13)																	
Minimum	11 200	9	10	95.9	<0.2	22.2	5.46	2	<1	22.6	4100	101	131	42.9	10	42	93.5
Maximum	20 900	20	38	247	1.07	45.6	12.4	5	1.77	34.8	7500	225	296	117	19.8	128	467
Mean	16 260	13.5	17.5	184	0.30	35.4	7.95	3.1	1.32	27.8	5400	154	235	74.7	15.6	66	185
Median	16 800	14	15	197	0.25	38.2	7.9	3	1.34	27.4	5300	155	262	72.3	15.9	59	156
Stream sediments (SS) (n = 7)																	
Minimum	5020	9	7	29.7	<0.2	4.96	6.19	2	<1	11.6	2700	<2	60	20.3	2.7	28	141
Maximum	29 000	24	17	118	0.44	18.1	25.3	7	2.48	53.9	8400	4.17	281	82.1	12.3	81	240
Mean	16 690	12.7	12.6	79	0.29	10.5	9.74	3.6	1.04	19.7	4430	2.05	110	32.8	4.38	56	197
Median	15 700	11	13	79	0.36	10.8	6.87	3	1.06	13.5	3800	<2	85	25.1	3.01	60	209
Vegetation from crushed waste rock dump																	
V2 saltbush	123 000	5	19	120	1.71	15.3	3.09	1	2.50	11.4	1700	61.0	120	49.6	8.6	521	54.4
V1 pepper tree	24 400	<1	9	45.0	7.41	1.37	0.64	<1	1.00	1.19	200	17.2	12	7.8	0.81	600	13.1
Background vegetation																	
V3 saltbush	110 000	5	15	30.0	8.08	6.14	2.94	4	2.50	6.03	1600	<2	35	10.6	0.91	83	16.9
V4 pepper tree	25 600	<1	2.5	10.0	2.19	0.46	0.30	3	1.00	0.76	100	<2	−5	0.9	<0.5	238	11.8

All values given in ppm. All samples possess <5 ppm Ag, <5 ppb Au, <20 ppb Ir, <5 ppm Se, <10 ppm Te, <2 ppm W.

Soils

Background soil in the Radium Hill area is dominated by orange-brown (goethite–hematite-pigmented) silt–sand material, with abundant quartz, feldspar and clay minerals (largely kaolinite). In places, nodular calcrete is present at shallow depth in the soil profile. Such material has high paste pH values (mean pH 8.2), low total count scintillometer readings of 90–150 cps and low radiation levels (35–70 nSv/h). Contamination of soil by mine-derived material includes admixing of crushed rock due to deliberate addition and dispersion by surface water flow. It also includes admixing and covering by windborne and waterborne mill tailings, resulting in soils adjacent to the main tailings storage facility having >90 vol% of tailings material. Visibly contaminated soils display total count scintillometer readings of 180–1500 cps and elevated radiation levels (max. 0.94 μSv/h).

Residual soil over the subcrop zone of the line of lode in the mine area commonly contains detrital aggregates of oxide minerals up to 2–3 cm across, although uranium minerals are rare. Cappings of tailings storage facilities has involved the use of adjacent excavated soil, calcrete and weathered rock. It is possible that the sites of the excavations already had significant surficial contamination, but overall, the top surfaces of the capped tailings storage facilities have low to moderate total count scintillometer readings (150–500 cps) and low radiation levels (62–222 nSv/h).

The ground radiometric survey revealed highly variable environmental (nSv/h) and assay data (wt% K, ppm U, ppm Th) of the soils southwest, southeast, east and northeast of the main tailings storage facility. Radiation levels range from 0.035 to 0.94 μSv/h. Elevated gamma-ray readings in the topsoils correspond to areas close to the main tailings storage facility (Figure 7a). Radiation levels gradually decrease with distance from the main tailings storage facility. Background radiation levels (35–70 nSv/h) and U contents (0.4–2 ppm U) are attained ∼400 m (southwest), 900 m (southeast), 700 m (east), and >900 m (northeast) from the main tailings storage facility (Figure 7a, b).

Soils in the study area have been divided into three populations based on U content: background soils;

(a)

(b)
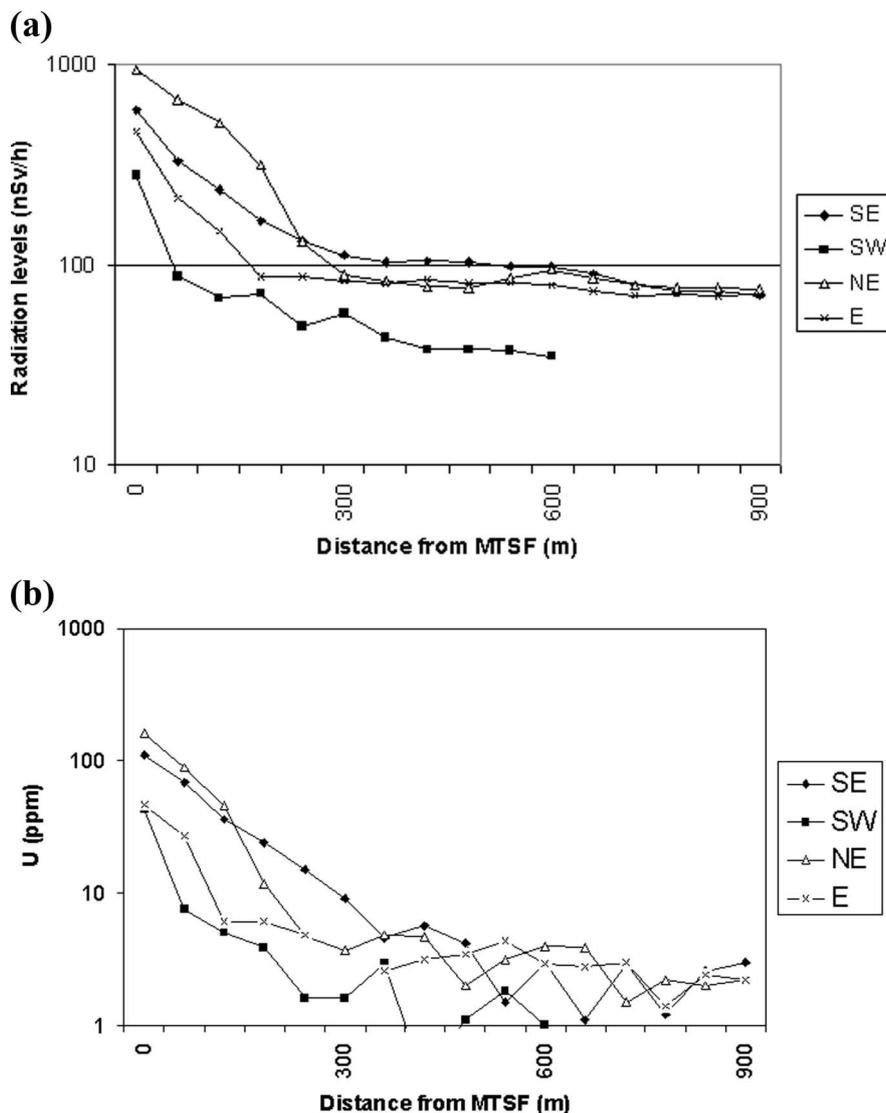
Figure 7 (a) Radiation level (nSv/h) and (b) U content (ppm) around the main tailings storage facility and adjacent soils. The data of the four ground radiometric survey transects (SE, SW, NE, E) are plotted so that the distance from the main tailings storage facility (MTSF) increases from left to right (60 m intervals). Locations of the survey transects are shown in Figure 2.

regional contaminated soils; highly contaminated soils (Table 1). The highly contaminated population around the main tailings storage facility has U >100 ppm and covers about 1 km^2 (Figure 1). A regionally contaminated population is identified with U in the range 10–100 ppm. This contaminated area is conservatively estimated at 2 km^2, mainly to the northwest and southeast of the main tailings storage facility (Figure 1). The elongated northwest–southeast dispersion pattern does not entirely conform to the airborne radiometrics (Figure 5) and probably reflects the low-density soil sampling conducted during this study. Soils with U <10 ppm have been defined as the background population. These samples were taken at distances of ~0.5–8 km from the mine and processing site.

Background soils contain low concentrations of U with the median U value of 3.3 ppm, being consistent with established U concentrations in soils worldwide (Smith & Huyck 1999). There is a strong correlation between Fe, Th, Cr and REE (>+0.9), indicating that these elements are largely held within Fe-oxyhydroxides. Such correlation may reflect the weathering of monazite and possibly oxide minerals, and subsequent incorporation of liberated REE into secondary Fe-rich phases in the soil profile.

Regional contaminated soils show marked increases in the median concentrations of U (10×) as well as La, Lu, V, Ce, Cr, Sc, Y and Yb (1.5–2×) compared with background soils (Table 1). Moderate correlation coefficients (>+0.8) are present for Na, REE, Cr and U, suggesting the presence of uranium (brannerite, uraninite, davidite) and REE (monazite, xenotime, apatite, allanite) minerals in the soils.

Highly contaminated soils at the mine and processing site and around the main tailings storage facility show extreme U values (median = 155 ppm) as well as elevated median contents of Th (1.5×), Rb and Y (2×), Ce, Sc, V and Yb (3×), and Cr, La and Lu (4×) compared with background soils (Table 1). There is a strong correlation between Cs, Rb and Sc (>+0.9) and, to a lesser degree, between U, La and Ce (>+0.6), indicating that these soils contain admixtures of phyllosilicates as well as fine-grained ore mineral particles. Thus, the observed trace-element enrichment of topsoils appears to be largely due to the physical dispersion of tailings components from the waste repositories into the surrounding soils.

Stream sediments

In larger watercourses in the Radium Hill area, stream sediments are dominated by medium- to coarse-grained quartz–feldspar-lithic sand, grading to gravel. Smaller watercourses contain more silty stream sediments, due to a higher proportion of clays over detrital quartz and feldspar particles. Sandy beds locally contain concentrations of dark heavy minerals, evidently including ilmenite and magnetite, but no detrital uranium mineral concentrations were detected. All stream sediment sites sampled had near-background total count scintillometer readings of 80–125 cps.

Stream sediment samples display major (>1 wt%) median concentrations of Fe, Ca, K and Na, minor (>1000 ppm) Ti, sub-minor (>100 ppm) Ba, Cr, and Zr, and traces (<100 ppm) of As, Br, Ce, Co, Cs, Cu, Eu, Hf, La, Lu, Mo, Nb, Pb, Rb, Sb, Sc, Sm, Sn, Ta, Th, U, V, Y, Yb and Zn (Table 1). Similarly to the background soils, there is a strong correlation between Fe, Ti, Th, Co, V, Y, Cr, Nb and REE (>+0.9), indicating that these lithophile elements are largely held within Fe-oxyhydroxides and detrital oxide minerals. In addition, there is a strong correlation between K, Ba, Rb, Cs, Pb, Sc and Zr (>+0.9). Such correlations are thought to reflect the presence of alkali and alkali-earth elements in feldspars and zircon inclusions in micas.

Vegetation

Vegetation samples (V3, V4, Table 1) taken from background soil contain low lithophile (Cr, Rb, REE, Sc, Th, Ti, U, V, Y, Zr) element contents. At a crushed rock dump near the mill site where vegetation samples were taken, lithophile element values in substrates are higher, and the ashed plant samples clearly reflect the higher values (V1, V2, Table 1). A comparison between the same species growing on background versus contaminated sites shows that ashed material on contaminated sites commonly contains higher contents of lithophile elements. Pairs of plant samples (pepper tree *Schinus* spp., saltbush *Atriplex* spp.), growing on substrates with high contents of lithophile elements, show a distinct increase in the uptake of these elements (in ashed material) from contaminated substrates (Table 1). Ashed plant materials from the mill site contain significantly lower Ca and Ba values and higher values of lithophile and chalcophile elements (Mo, Pb, Zn) than those of ashed plant materials from the background site (Table 1). Moreover, saltbush growing on contaminated substrate displays distinctly higher Na (12.3 wt%), Ti (0.17 wt%) and lithophile element contents including U than the pepper tree.

DISCUSSION

Primary contamination sources

Contamination of soils by lithophile elements at the Radium Hill mine and processing site is due to two main sources: (i) the use of crushed waste rocks as a ground cover (e.g. around many buildings) and for roads; and (ii) the erosion of steep waste rock dumps and tailings repositories and physical dispersion of mine waste particles into local soils. In particular, the waste rock dumps and tailings storage facilities have acted as point sources of contamination and have affected the immediate area. At the mine and processing site, the significant correlation of Cs, Rb and Sc (>+0.9) and, to a lesser degree, between U, La and Ce (>+0.6) in the highly contaminated soils highlight the physical dispersion of fine-grained tailings from the main tailings storage facility into local soils. This transfer of contaminants from the main tailings storage facility into soils largely occurred prior to capping of the main tailings storage facility in the 1980s. Currently, wind and water erosion of tailings repositories and crushed waste rock dumps remains active at covered and uncovered sites (Figure 3c, d).

It is important to note that the waste rock materials and tailings are essentially free of sulfide minerals. It is estimated that sulfides constitute <0.1% by volume of these materials. With the prevailing low rainfall and high evaporation rates, infiltration of rain and surface waters into the dumps is probably low, with leaching reactions and seepages of leachate solutions being minimal. Sparsely disseminated fresh pyrite occurs on waste rock dumps and has essentially remained unoxidised after several decades' exposure to the atmosphere.

Dispersion into soils and vegetation

Windblown tailings material up to tens of centimetres thick is common up to 80 m away on the northeast and southeast sides of the main tailings storage facility, but thinner further away and on the northwest and southwest sides. Small amounts of windblown tailings remain evident for at least 500 m distant on the southeast side of the main tailings storage facility (Figure 4). The dispersion to the northeast and southeast reflects the direction of the prevailing strong winds, although east of the main tailings storage facility, the dispersion plume has probably been largely removed by subsequent flooding of a wide stream channel (Figure 2). Contaminated soils at the mine and processing site have acquired their trace-element contents from the windborne and waterborne erosion of fine-grained ore particles and their subsequent dispersion into local soils. Currently, contaminants are not dispersed into stream channels because the geochemical composition of stream sediments downstream of the mine and processing site does not exceed background values.

The correlation matrices of log-normalised data of background soils and stream sediments reveal nonsignificant correlation coefficients between U and most other elements. Thus, in background soils and stream sediments, U is probably adsorbed on to mineral grains. Sorption plays an important role in determining the fate of U in the aquatic and soil environment (Elless & Lee 1998). Radium Hill tailings display strong correlations of U with lithophile elements, reflecting the presence of primary uranium ore mineral aggregates. Also, the regional contaminated and highly contaminated soils still display significant, yet slightly diminished correlations of U with other lithophile elements. Therefore, breakdown of windborne and waterborne uranium ore minerals, through the actions of oxygen, water and catalytic bacteria, is limited in the U contaminated topsoils. Yet, during rare rainfall events, the leaching of U in uncapped waste rock dumps and contaminated soils is likely to occur. Oxidation and leaching of the uranium ore minerals would lead to the limited liberation of trace elements from their host minerals. Lithophile (e.g. Cr, Rb, REE, Sc, Th, Ti, U, V) and chalcophile elements (e.g. Mo, Pb, Zn) would slowly dissolve during rainfall events, with these elements being chemically mobilised into soils, thus becoming bioavailable to vegetation.

The biogeochemical data clearly show that significant bioaccumulation of lithophile elements occurs in plants growing in the disturbed sites. In particular, the LREE contents of ashed saltbush from the crushed waste rock dumps are highly anomalous and well above ($100\times$) published values for LREE contents in plants growing on contaminated soils (Pfeifer et al. 1994). In addition, there is significant enrichment of U in saltbush (V2, Table 1).

The major land use of the rehabilitated Radium Hill site is low-density grazing, and a consequence of U uptake into vegetation is that there is the potential to transfer toxicants into grazing animals. A risk assessment is required to determine the potential impact of U enriched topsoils and vegetation on grazing animals. However, the uptake of U into plants is probably restricted in area to no more than 1 km^2.

Rehabilitation

The mean exposure rate calculated from 38 individual geophysical traverses from the mine and processing site amounts to 0.67 μSv/h. Australian Radiation Protection Standards (ARPANSA 1995) limit the exposure to ionising radiation, and the dose limit for the public has been set at 1 mSv/year. Also, radiation levels from most sample media are not significant, bearing in mind the remote location and good ventilation. Thus, visitors to the Radium Hill site will not be exposed to excessive radiation levels. However, exposure of mill tailings by future erosion could become a more substantial issue as tailings generally have the highest radiation dose. The current covered tailings storage facilities do not have long-term geomorphic stability and are already subject to rill erosion, and in the future might be subject again to significant wind erosion. A long-term management strategy must require capping of waste dumps and reconfiguration of the main tailings dam to a stable landform.

CONCLUSIONS

The Radium Hill uranium mine in South Australia ceased operations in 1961 and underwent rehabilitation in the 1980s. The mine area now consists of numerous waste rock dumps, several tailings storage facilities and numerous relics and foundations of buildings and other structures. The waste dumps are prone to physical erosion involving wind and seasonal rain. Physical dispersion of mineralised particles from waste rock dumps and tailings repositories, has led to local enrichment of lithophile elements (Ce, Cr, La, Lu, Rb, Sc, Th, U, V, Y, Yb) in adjacent soils. Plants (pepper tree, saltbush), growing on contaminated soil, display enhanced uptake of lithophile elements. The enrichment in common species implies that there is potential for transfer of U into grazing animals and their bioaccumulation. Additional capping and landform design of the crushed waste and tailings repositories are required in order to minimise erosion and impacts on surrounding soils and sediments.

ACKNOWLEDGEMENTS

REFERENCES

ABDELOUAS A., LUTZE W. & NUTALL E. 1998. Chemical reactions of uranium in ground water at a mill tailings site. *Journal of Contaminant Hydrology* **34**, 343–361.

ARPANSA (AUSTRALIAN RADIATION PROTECTION AND NUCLEAR SAFETY AGENCY) 1995. Recommendations for limiting exposure to ionizing radiation. *Radiation Protection Series Publication* **1**.

BLISSETT A. H. 1975. Willyama Mount Painter and Denison Inliers. Sundry mineralisation in South Australia. *In*: Knight C. L. ed. *Economic Geology of Australia and Papua New Guinea 1. Metals*, pp. 498–505. Australasian Institute of Mining and Metallurgy Monograph **5**.

BUREAU OF METEOROLOGY 2005. Wind roses for selected locations in Australia. Online <http://www.bom.gov.au/climate/averages/wind/selection_map.shtml>

CONOR C. H. H. 2000. Definition of major sedimentary and igneous units of the Olary Domain, Curnamona Province. *MESA Journal* **19**, 51–56.

ELLESS M. P. & LEE S. Y. 1998. Uranium solubility of carbonate-rich uranium-contaminated soils. *Water, Air, & Soil Pollution* **107**, 147–162.

FORBES B. J. 1991. *Olary, South Australia, Sheet SI 54–2, 1:250 000 Series Explanatory Notes*. Geological Survey of South Australia, Adelaide.

LOTTERMOSER B. G. 2003. *Mine Wastes: Characterization, Treatment and Environmental Impacts*. Springer, Berlin.

LOTTERMOSER B. G. & ASHLEY P. M. 2005. Tailings dam seepage at the rehabilitated Mary Kathleen uranium mine, Australia. *Journal of Geochemical Exploration* **85**, 119–137.

MAWSON D. 1906. On certain new mineral species associated with carnotite in the radioactive ore body near Olary. *Transactions of the Royal Society of South Australia* **30**, 191.

McKAY A. D. & MIEZITIS Y. 2001. Australia's uranium resources, geology and development of deposits. *Geoscience Australia Mineral Resource Report* **1**.

MENZIES N. W. & MULLIGAN D. R. 2000. Vegetation dieback on clay-capped pyritic mine wastes. *Journal of Environmental Quality* **29**, 437–442.

MORIN K. A. & HUTT N. M. 1997. *Environmental Geochemistry of Minesite Drainage*. MDAG Publishing, Vancouver.

PARKIN L. W. 1965. Radium Hill uranium mine. *In*: McAndrew J. ed. *Geology of Australian Ore Deposits: Proceedings of the 8th Commonwealth Mining and Metallurgical Congress*, vol. 1, pp. 312–313. Australasian Institute of Mining & Metallurgy, Melbourne.

PARKIN L. W. & GLASSON K. R. 1954. The geology of the Radium Hill uranium mine, South Australia. *Economic Geology* **49**, 815–825.

PEACEY V., YANFUL E. K. & PAYNE R. 2002. Field study of geochemistry and solute fluxes in flooded uranium mine tailings. *Canadian Geotechnical Journal* **39**, 357–376.

PFEIFER H. R., VUST M., MEISSNER N., DOPPENBERG R., TORTI R. C., DOMERGUE F. L., KELLER C. & HUNZIKER J. 1994. Uranium-enrichment in soils and plants in the vicinity of a pitchblende vein at La Creusaz/Les Marecottes (W of Martigny, Valais, Switzerland). *Eclogae Geologicae Helvetiae* **87**, 491–501.

RICHARDS R. J., APPLEGATE R. J. & RITCHIE A. I. M. 1996. The Rum Jungle rehabilitation project. *In*: Mulligan D. ed. *Environmental Management in the Australian Minerals and Energy Industries*, pp. 530–553. University of New South Wales Press, Sydney.

RITCHIE A. I. M. & BENNETT J. W. 2003. The Rum Jungle mine—a case study. *In*: Jambor J. L., Blowes D. W. & Ritchie A. I. M. eds. *Environmental Aspects of Mine Wastes*, pp. 385–405. Mineralogical Association of Canada, Ottawa.

SMITH K. S. & HUYCK H. L. O. 1999. An overview of the abundance, relative mobility, bioavailability, and human toxicity of metals. *In*: Plumlee G. S. & Logsdon M. J. eds. *The Environmental Geochemistry of Mineral Deposits. Part A: Processes, Techniques and Health Issues*, pp. 29–70. Reviews in Economic Geology **6A**.

TAYLOR G., SPAIN A., TIMMS G., KUZNETZOV V. & BENNETT J. 2003. The medium-term performance of waste rock covers—Rum Jungle as a case study. *In*: Farrell T. & Taylor G. eds. *6th International Conference on Acid Rock Drainage*, pp. 383–397. Australasian Institute of Mining and Metallurgy, Melbourne.

VAN LOON J. C. & BAREFOOT R. R. 1989. *Analytical Methods for Geochemical Exploration*. Academic Press, San Diego.

WHITTLE A. H. G. 1959. The nature of davidite. *Economic Geology* **54**, 64–81.