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Radiological investigations in the Rum Jungle and East Finniss River areas 2009

A Hughes & A Bollhöfer

November 2010

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Executive summary

Mining and mineral processing activities were undertaken in the Rum Jungle area from the early 1950s to the early 1970s. Mineralisation included complex sulfidic ores that also contained uranium and uranium radioactive decay progeny.

Waste and contaminated water from these mining and processing activities migrated downstream in the East Branch of the Finniss River (East Finniss) during and subsequent to the Rum Jungle mining operations. Some remediation programs were undertaken on the site during the 1970s and 1980s. Reports on research projects indicate that some of the remediation activities were incomplete and some that were completed may be suffering from deterioration of their performance. A number of review reports note that there was an outstanding need for characterisation of radiological contamination from Rum Jungle operations.

A detailed airborne gamma radiation survey commissioned by the Supervising Scientist Division (SSD) of the Australian Government Department of the Environment, Water, Heritage and the Arts in 2006 confirmed that there are still some areas of elevated gamma activity on and downstream of the minesite. Ground surveys of anomalies on the minesite were undertaken in 2006 to estimate potential gamma dose rates that may result from exposure to these areas. The results of this work were reported in a previous SSD report, Bollhöfer et al 2007. This earlier report did not examine the anomalies that occur downstream of the minesite, nor did the work seek to characterise the source or vertical extent of the source of the anomalism.

In September 2009 SSD undertook further investigations of the radiological anomalies at Rum Jungle and downstream of the Finniss River and East Finniss confluence in the vicinity of Mt Fitch. This work, which includes geochemical sampling of most of the anomalies to determine the nature of the source and its likely thickness, is described in this report.

On the basis of the work reported herein it is concluded that three of four main gamma anomalies in the immediate minesite area are caused by tailings residues that were overlooked in earlier remediation work and the fourth by residual mineralised waste rocks. Three of the downstream anomalies in the Mt Fitch area have similar geochemical and radiological signatures to the Rum Jungle anomalies leading to the conclusion that they were also sourced from the Rum Jungle operations. The fourth Mt Fitch anomaly is attributed to local, naturally occurring mineralisation at the Mt Fitch mine and is not sourced from residues of milling operations at Rum Jungle. Profiling by auger drilling indicates that six tailings-related anomalies have sources with depth extents that are typically between 0.1 and 0.5 metres. Some minor residual deposits of tailings material have also been exposed in a track along the northern boundary of what was the old tailings storage area.

Assessment of possible radiological exposure in these anomalous areas is incomplete as only the external gamma component has been considered to date. The potential contribution of long lived alpha activity from dust, inhalation of radon and its daughter radionuclides and possible ingestion through the consumption of locally sourced food also need to be considered when making dose assessments.

The sources of the gamma anomalies tested typically contain elevated base metal concentrations in addition to uranium and its decay progeny and it is concluded that the distribution of the gamma anomalism provides an effective indication of the distribution of other heavy metal contamination in sediments on and downstream of the site.

Radiological investigations in the Rum Jungle and East Finniss River areas 2009

A Hughes & A Bollhöfer

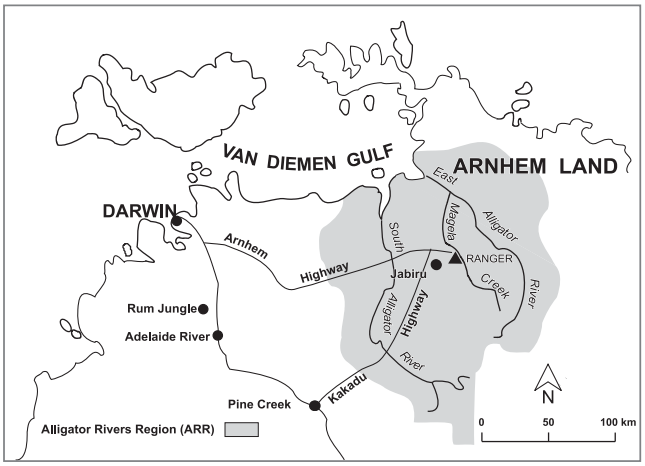
1 Introduction

Copper and uranium mining was undertaken in the Rum Jungle area from 1952 with processing from 1954 until the cessation of production in 1971 (Verhoeven 1988). Ore from four main deposits was processed at a single facility which is generally known as Rum Jungle. Tailings from the processing of the ore were stored in a low depression (Old Tailings Dam) located to the north of the processing plant until 1961, following which tailings were deposited into Dyson's pit until 1965 and White's open cut from 1965 until cessation of milling in 1971 (Davy 1975). The Old Tailings Dam drained into the East Finniss River. Although there was some bunding of the tailings in the Old Tailings Dam there were numerous recorded breaches of the containment and direct deposition into the Tailings Creek North, resulting in the erosion of tailings into the East Finniss and the transport of this material downstream to, and beyond, the confluence of the East Finniss with the main branch of the Finniss River (Davy 1975; Rum Jungle Working Group 1978; Lowson et al 1987). In addition to the contamination of the river system by remobilised tailings and associated process waters, acid drainage with elevated levels of heavy metals, most notably copper, mainly sourced from stockpiled waste rock and ore and the copper heap leach area, also contributed to significant environmental degradation downstream of Rum Jungle during and subsequent to its period of operations. The location and general layout of the site are shown in Figure 1.

In 1977 the Commonwealth Government commenced a clean up program of the site to manage safety risks and set up a working group of interested parties convened by the Department of the Northern Territory to investigate rehabilitation options for the site. Following a report from the working group in 1978 (Rum Jungle Working Group 1978) a decision was made to proceed with a recommended rehabilitation program for the site and an agreement to undertake the work was signed by the Commonwealth and the Northern Territory. Significant rehabilitation works were undertaken between 1983 and 1986 (Allen & Verhoeven 1986). Monitoring to 1988 confirmed that the project achieved major reductions in water pollution, public health risks and radiation levels on the site (Kraatz & Applegate 1992). The main features of the rehabilitation program were the consolidation and capping of the waste rock dumps to minimise the production of acid drainage, the relocation of low grade copper ore from the heap leach pad and most of the remaining tailings from the Old Tailings Dam in Dyson's open cut, capping of this open cut and the treatment of water in the remaining open voids (Whites and Intermediate open cuts) to improve the quality of water being flushed into the East Finniss each wet season.

Subsequent to 1988 the level of monitoring of the environmental performance of the rehabilitation was reduced but over the following ten or so years it became apparent that the performance of the capping of the waste rock dumps was diminishing (Pidsley 2002). In 2001 the Commonwealth commissioned a review of the status of the site. The resultant report concluded that the capping of the waste dumps had been failing to meet design criteria since the mid 1990's and that there were insufficient data to undertake a complete radiological

assessment of the site (SSD & Sulphide Solutions 2002.). A further review and scoping study report prepared in 2004 reiterated that the radiological status of the site remained a knowledge gap (Kraatz 2004).



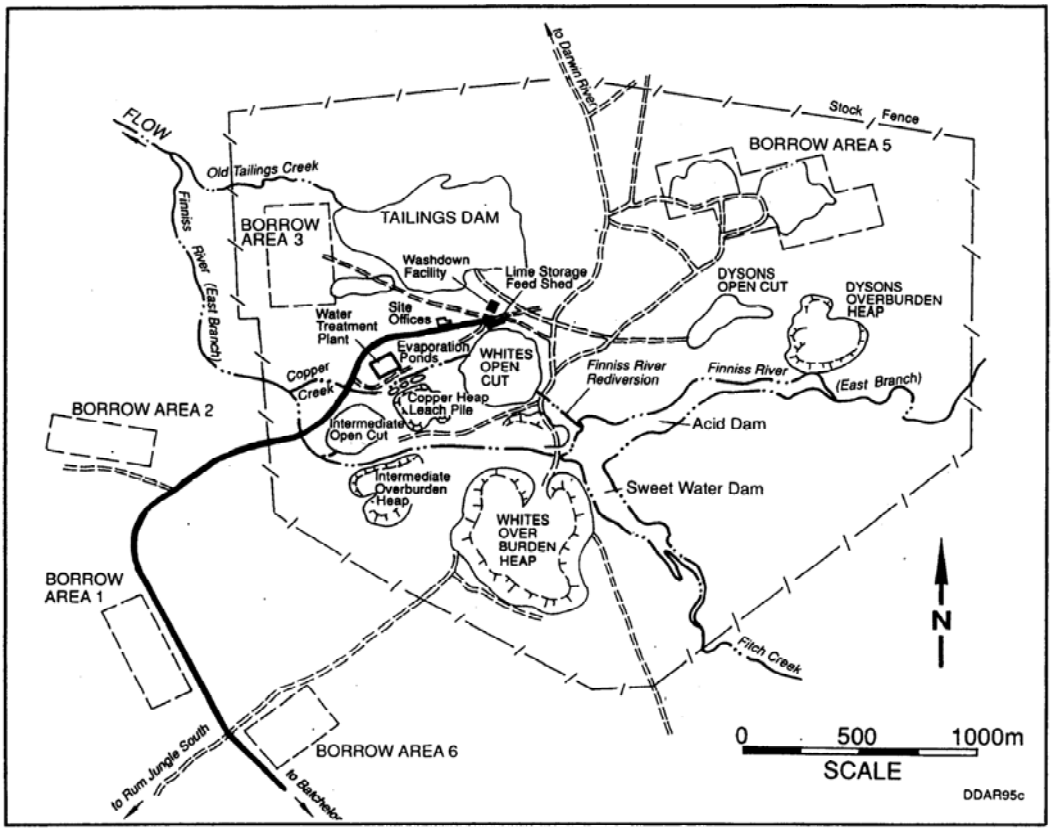


Figure 1 Rum Jungle location plan

In 2006 a detailed airborne gamma survey was flown over the Rum Jungle site and this survey included the East Finniss River downstream from the site beyond its junction with the Finniss River (Figure 2). Ground follow up surveying was undertaken by SSD over three areas of elevated gamma radiation within the Rum Jungle minesite, defined by the fenced area comprising Section 2968, Hundred of Goyder, and a report on the findings of this survey indicated that these anomalies were unsuitable for permanent habitation on the basis of expected annual radiation doses received (Bollhöfer et al 2007). This SSD investigation aimed at characterising only the Rum Jungle site from a radiological point of view for various

occupation scenarios and did not consider radiological anomalies located outside of the immediate Rum Jungle fenced area, nor did it seek to characterise the nature or depth extent of the radioactive materials at each of the sites studied.

In 2009 the Australian Government announced that funding had been made available over a period of four years to ascertain the environmental status of the site and to develop and recommend a further program of rehabilitation at Rum Jungle. This funding is being managed by the Northern Territory under a National Partnership Agreement between the Australian and Northern Territory Governments. A working group including NT Department of Natural Resources, Environment, the Arts and Sport (NRETAS) and the NT Department of Resources (DoR), Australian Government Department of Resources, Energy and Tourism (RET) and the Supervising Scientist Division (SSD) of the then Department of the Environment, Water, Heritage and the Arts (DEWHA), (now Department of Sustainability, Environment, Water, Population and Communities) and the Northern Land Council (NLC) is overseeing the technical aspects of the program and the project works are being managed by DoR.

As a natural follow on from the 2006 SSD investigations into radiological aspects of the minesite (Bollhöfer et al 2007), further investigations of the radiological anomalies identified in the 2006 airborne survey were undertaken in 2009. This work has included identification of a fourth anomaly in the Rum Jungle area, just outside the NT Portion 2968 fence near the confluence of the old Tailings Creek and the East Finniss River within NT Portion 2940. Four additional anomalies were identified in the Mt Fitch area downstream of Rum Jungle, near the Finniss River Junction.

This report describes the 2009 investigations and observations relating to the eight main radiometric anomalies (RJ1 to RJ4 and MFA to MFD) that were detected by the 2006 airborne radiometric survey and are shown in Figure 2.

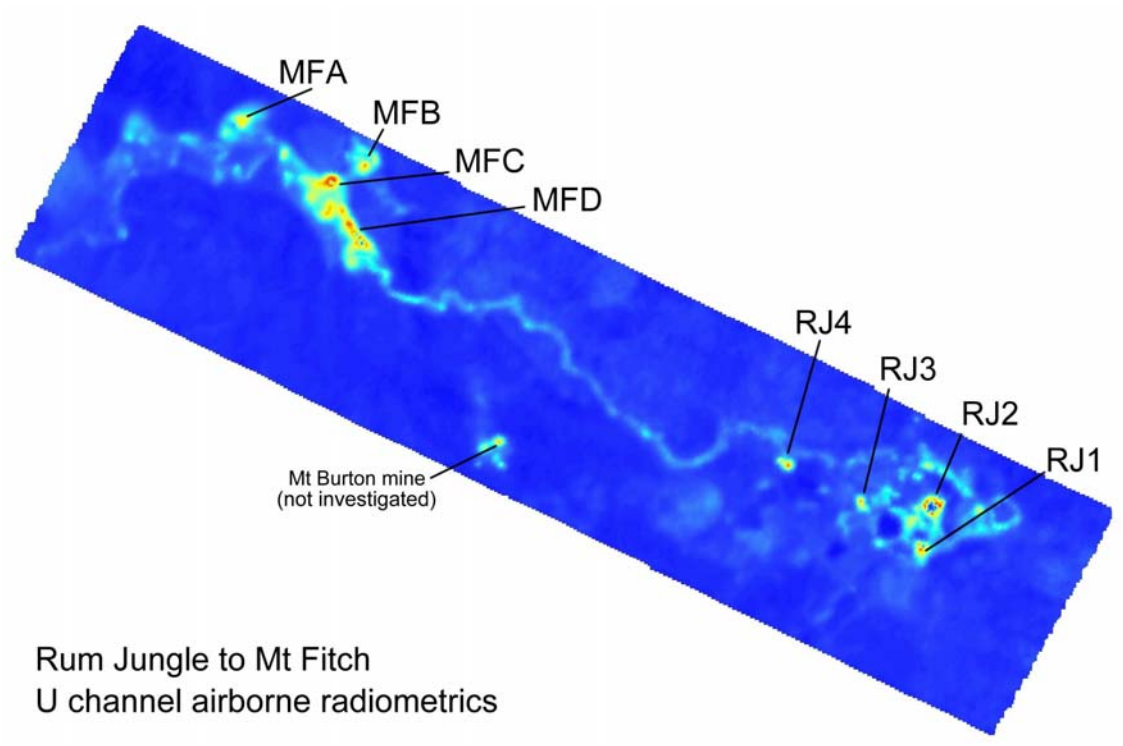


Figure 2 Anomaly locations and uranium channel counts from the airborne gamma survey. Red is highest, blue is lowest.

2 Methods

2.1 Fieldwork

Figure 2 shows the counts in the uranium channel from the 2006 airborne gamma survey with the designated locations of the uranium anomalies identified. Locations of the RJ and MF anomalies and sample locations are shown on Figures 3 and 4 respectively. Anomalies RJ1, RJ2 and RJ3 were the sites of ground follow-up surveying, which was reported by SSD to the Northern Territory Government (Bollhöfer et al 2007). In addition, Mt Fitch anomaly MFD was previously surveyed using the same methodology as the three Rum Jungle anomalies. The results of the MFD traverse were not previously reported and are included in this report.

The previous survey work confirmed that the anomalies could be readily located on the ground using a GPS receiver to navigate to coordinates derived from the airborne survey. Once in the area, the peak of the anomaly was located on the ground by traversing and monitoring gamma count rates using a scintillometer and a Mini Instruments 6-80 environmental dose rate meter fitted with a Geiger Müller tube.

At anomalies RJ1, RJ3, RJ4 and MFA, MFC and MFD a soil profile was obtained using a hand auger and samples were collected at 10 cm intervals down hole. Typical hole depths were around 0.5 m. In addition, two samples of residual tailings were collected from the north eastern and northerly edges of where the old TSF had previously been located to provide reference samples for comparison purposes. A single composite grab sample of soil and gravel was collected at anomaly MFB, which coincided with stockpiled rock adjacent to a small open cut at the Mt Fitch mine.

Each sample was split in three in the laboratory: one split was used for visual inspection using a Wild MZ8 binocular microscope, one for geochemical analysis by inductively coupled plasma mass spectrometry (ICPMS) at an external chemical laboratory and one for gamma spectrometry analysis at the ***eriss*** laboratory in Darwin. In addition, general observations of ground conditions and geomorphology were recorded at each site. Sample ledgers with details of the sampling are included in the Appendix, Tables A1 and A2.

In November 2006 a 150 m transect was surveyed at Mt Fitch anomaly MFD, in a southwest-northeast direction, to measure the gamma dose rate 1 m above the ground, and to groundtruth the airborne gamma survey for the downstream areas of Rum Jungle. The transect was surveyed at a resolution of ~10 m, and included the hotspot at MFD. A Mini Instruments 6-80 environmental dose rate meter fitted with a Geiger Müller tube was used for the survey. The instrument was calibrated in June 2006, and the results of this calibration complied with the manufacturer's specifications for the instrument. The results of this gamma survey are included in the Appendix, Table A3.

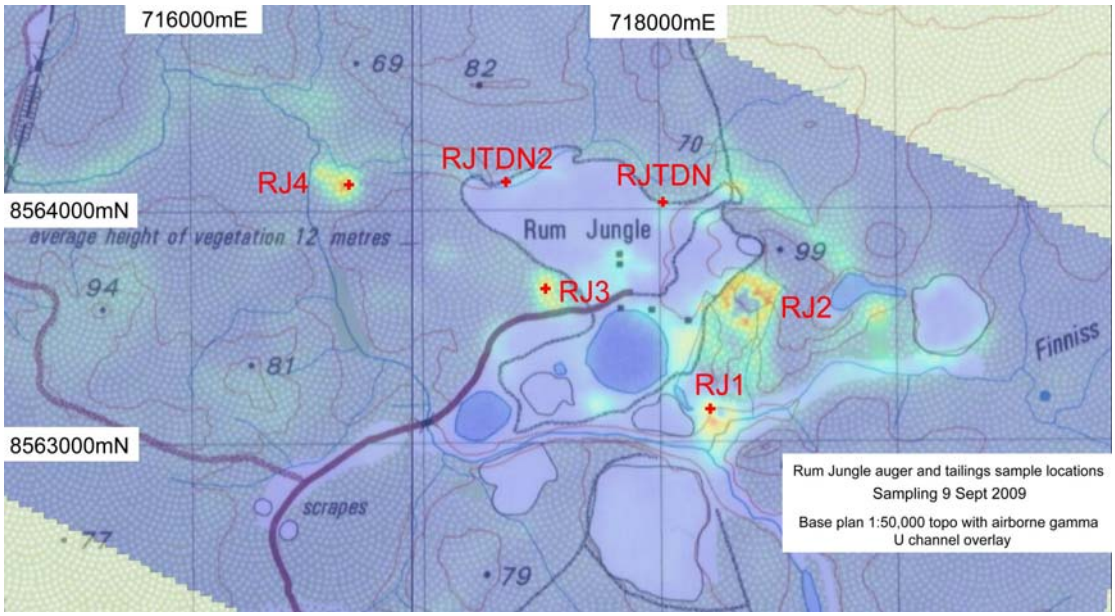


Figure 3 Sample locations – RJ series anomalies

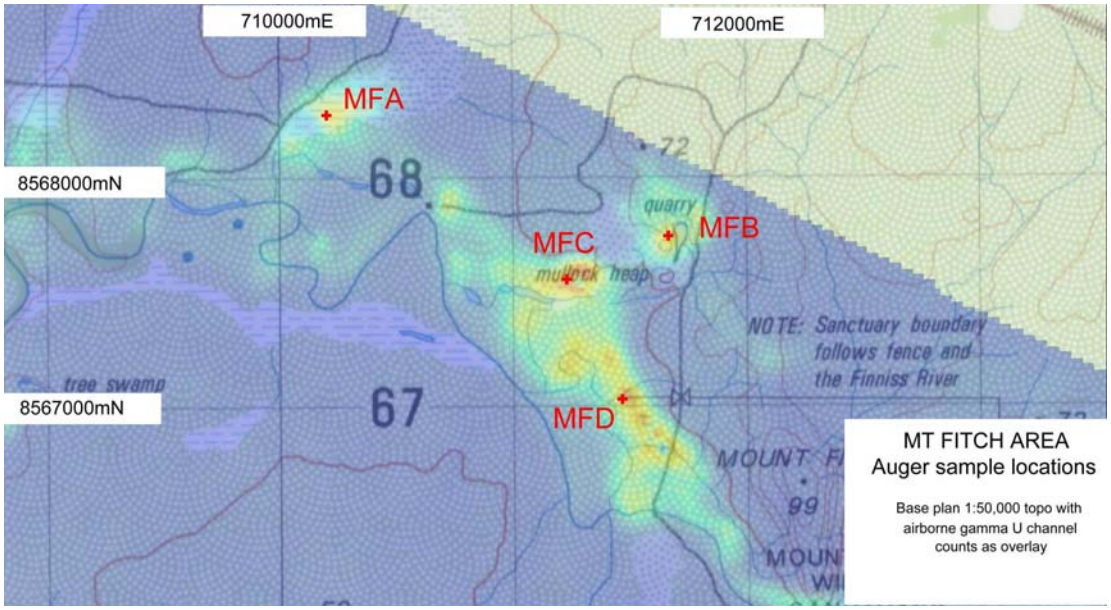


Figure 4 Sample locations – MF series anomalies

2.2 Gamma spectrometry

Soil samples were measured using the eriss high resolution High Purity Germanium (HPGe) gamma detectors. These detectors are capable of measuring the radioactive decays of various uranium-series (^{235}U, ^{234}Th, ^{230}Th, ^{226}Ra, ^{210}Pb) and thorium-series (^{228}Ra, ^{228}Th) elements, as well as ^{40}K and anthropogenic radionuclides such as ^{137}Cs.

After collection, soil samples were dried at 60°C and ground using an agate ring mill. Around 15 g of the ground material was then pressed into a standard geometry used at ***eriss*** for direct gamma spectrometry. Radon progeny were allowed to reach secular equilibrium with ^{226}Ra in the sample for ~24 days before the samples were counted for one day.

Detailed procedures for sample preparation and measurements of radionuclide activities via gamma spectrometry at ***eriss*** are described in Murray et al (1987), Marten (1992) and Esparon

and Pfitzner (2010). The counting system has been calibrated for the respective geometries, using certified uranium and thorium standards. Detection limits for the geometry used are approximately 10 Bq kg^{-1} for ^{210}Pb and approximately 5 Bq kg^{-1} for ^{226}Ra, ^{228}Ra and ^{228}Th.

For the measurements of soil radionuclide activity concentrations ***eriss*** detectors, N, G, O, P and S were used. A multi-element standard containing elements of the uranium and thorium decay chains is measured fortnightly on every detector to check the stability of the detectors. In addition, the accuracy of the measurement system is checked monthly using International Atomic Energy Agency (IAEA) reference material 315 (IAEA 2000). Results of the measurements of the reference material are generally within two standard deviations of the certified radionuclide activity concentrations.

Results of the gamma analyses are shown in Appendix 1 and contain the radionuclide activities of the long-lived progeny of the uranium and thorium series as well as ^{40}K and ^{137}Cs. Reported uncertainties are 2 standard deviations based on counting statistics only.

2.3 Metals analysis by ICPMS

A subsample of the ground soil was sent to the Northern Territory Environmental Laboratories. Soil samples were digested using a 4 acid digest (HCl, HNO_3, $HClO_4$ & HF) and subsequently diluted for measurement using an AGILENT 7500A inductively coupled plasma mass spectrometer (ICPMS).

Samples were analysed for silver, arsenic, cadmium, cobalt, copper, iron, manganese, nickel, lead, uranium and zinc. These elements were considered to be likely indicators of Rum Jungle sourced material, based on previously reported data.

3 Results and observations

3.1 Anomaly RJ1

This anomaly is situated in the old Acid Dam area near the former Rum Jungle processing plant. Records indicate that process water was stored in the Acid Dam during the dry season while the processing plant was operational. A fine grained, laminated muddy layer between 10 and 15 cm thick observed near the centre of the anomaly is interpreted to be a residue that settled from this process water. This fine-grained material with elevated radionuclide activity and base metal concentrations overlies coarse sandy sediments thought to be the natural substrate of the stream that existed prior to mining. In addition, a drain from the old stockpile area also feeds into this area and is likely to have contributed some particulate mineralisation and dissolved heavy metals into the same impoundment during the wet season each year.

Figure 5 is a photograph of the soil profile of the anomaly depicting the fine laminated material overlying the sandy alluvium. Some contamination of the lower layer occurred during sampling as it was raining at the time of collection. Samples from 10–60 cm were consequently combined for analysis.

Figure 6 shows the soil concentrations of lead, copper, uranium nickel, arsenic and cobalt measured in core RJ1, plotted versus the depth in the core, Figure 7 shows the soil $^{226}Ra/^{238}U$ activity ratio. In natural soils and sediments this ratio is expected to be close to unity, whereas tailings typically exhibit $^{226}Ra/^{238}U$ activity ratios that are much larger than one.

Figure 5 Anomaly RJ1 – fine, laminated sediment overlying sandy alluvium

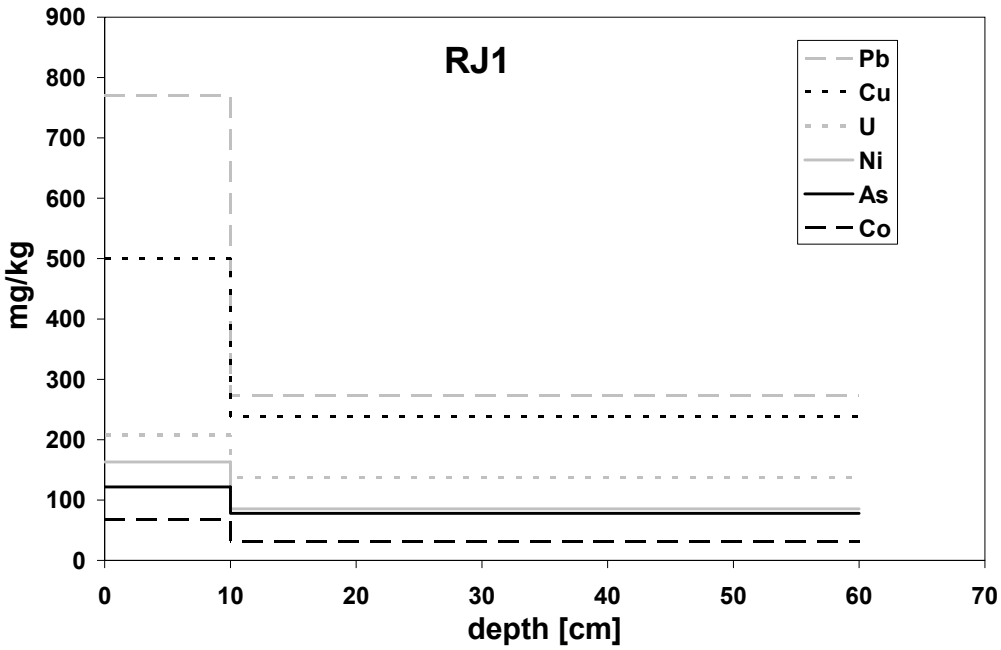


Figure 6 Pb, Cu, U, Ni, As and Co concentrations in Rum Jungle core RJ1

Note: Material from 10–60 cm was combined into a single sample for analysis.

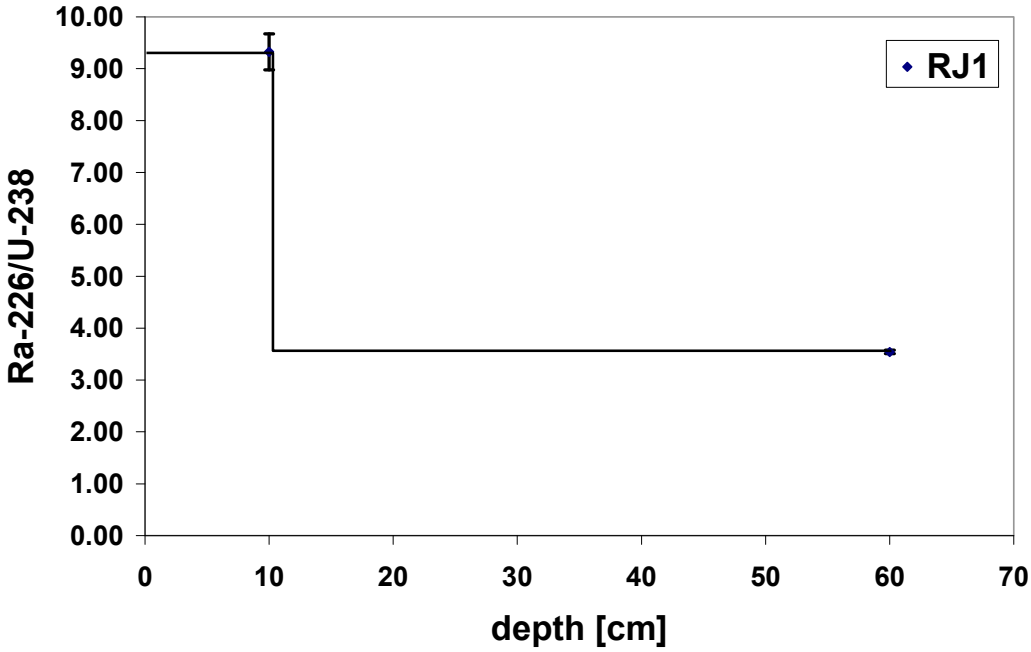


Figure 7 $^{226}Ra/^{238}U$ activity ratio in Rum Jungle core RJ1

Figures 6 and 7 show that although there is a drop of metal concentrations and also the $^{226}Ra/^{238}U$ activity ratio, they are still relatively high below 10 cm depth, potentially due to contamination of the lower layer during sampling. Core lithology and geochemistry suggest that the contamination with tailings extends to at least 10–15 cm depth in this area.

3.2 Anomaly RJ2

Inspection of the area revealed no evidence of tailings but a wide range of mineralised material varying from soil to large boulders and weathered to unweathered rocks (Figure 8). The area has been subject to a lot of earthmoving and indications are that the area was used for stockpiling prior to cessation of operations. It appears that some residues from the stockpiles have been pushed to the NW and SE from a central ridge resulting in wedges of rocks that could be up to 3 or 4 metres thick away from the central ridge. Further detailed ground surveys would be required to get a better estimate of the amount and depth extent of mineralised material that forms the source of this anomaly.

Due to the extreme heterogeneity of the material no sampling was undertaken during the soil sampling program as it was considered that many samples would be required to provide a representative sample for geochemical characterisation. However, the 2006 airborne survey has provided good results for radiological dose estimation purposes. Given that there is a good correlation between radionuclide activity concentrations and base metal mineralisation, use of the radiological footprint determined in the 2006 airborne gamma survey (Bollhöfer et al 2007) to calculate volumes is justifiable and would minimise the need for extensive sampling and analytical programs. However the depth extent of the source material at this site will require further investigation before a reasonable volumetric estimation can be made.

Figure 8 Anomaly RJ2 – heterogeneous mineralised material assumed to be from old stockpiles

3.3 Anomaly RJ3

Anomaly RJ3 is situated immediately to the south of the old TSF. A thin layer of fine grained material with an appearance and occurrence that is consistent with it being an overflow of fines from the TSF is located at the centre of the anomaly. The material thins out and disappears to the south and west, the northern boundary is marked by a built up berm on the edge of what was the TSF. The eastern side of the anomaly is obscured by a 2 to 3m thick layer of heterogeneous fill that includes mine waste rock and other rubbish (Figure 9).

Figure 9 Anomaly RJ3 – fine tailings residue (foreground) covered by waste and land fill material

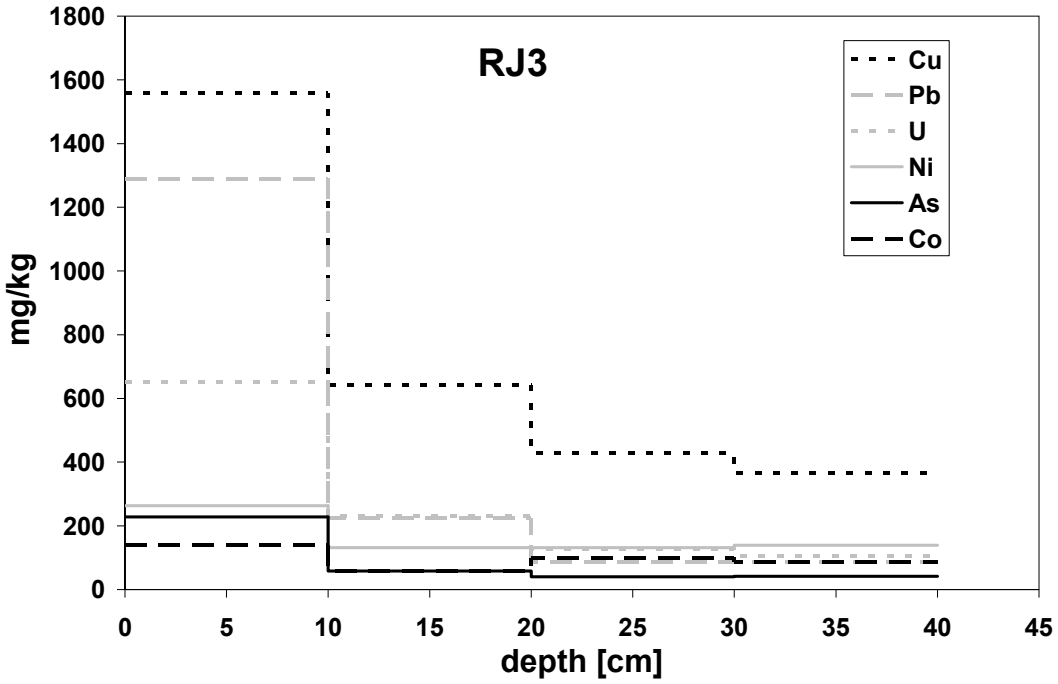


Figure 10 Pb, Cu, U, Ni, As and Co concentrations in Rum Jungle core RJ3

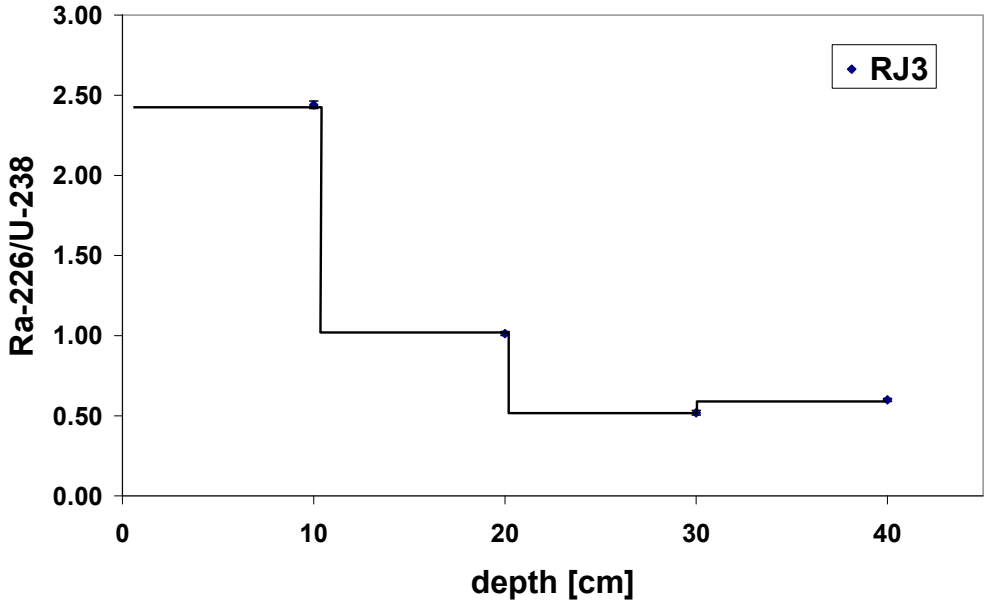


Figure 11 $^{226}Ra/^{238}U$ activity ratio in Rum Jungle core RJ3

Figure 10 shows the Pb, Cu, U, Ni, As and Co concentrations in Rum Jungle core RJ3. Figure 11 shows the soil $^{226}Ra/^{238}U$ activity ratio plotted versus the depth. In natural soils and sediments this ratio is expected to be close to unity, whereas tailings typically exhibit $^{226}Ra/^{238}U$ activity ratios that are much larger than one. It appears that the influence of tailings and/or process water is largely confined to the top 10–20 cm of the core. Consequently, the contaminated residues are likely to be only a small volume that could be readily excavated and removed for disposal or covered in situ. Any that extends to the east beneath the fill materials appears to be adequately covered and is unlikely to pose any environmental risk.

3.4 Anomaly RJ4

At RJ4 there is a low rise of approximately 80 m x 15 m in dimension. Fallen trees in the area have identifiable tailings exposed in the upturned roots (Figure 12). There is substantial evidence of earthmoving around the area. An aerial photograph that predates the 1980s tailings clean up clearly depicts extensive tailings having flooded over the area. It appears that RJ4 is a small residual area of tailings that was missed when the clean up was undertaken.

Figure 12 Anomaly RJ4 tailings in tree roots

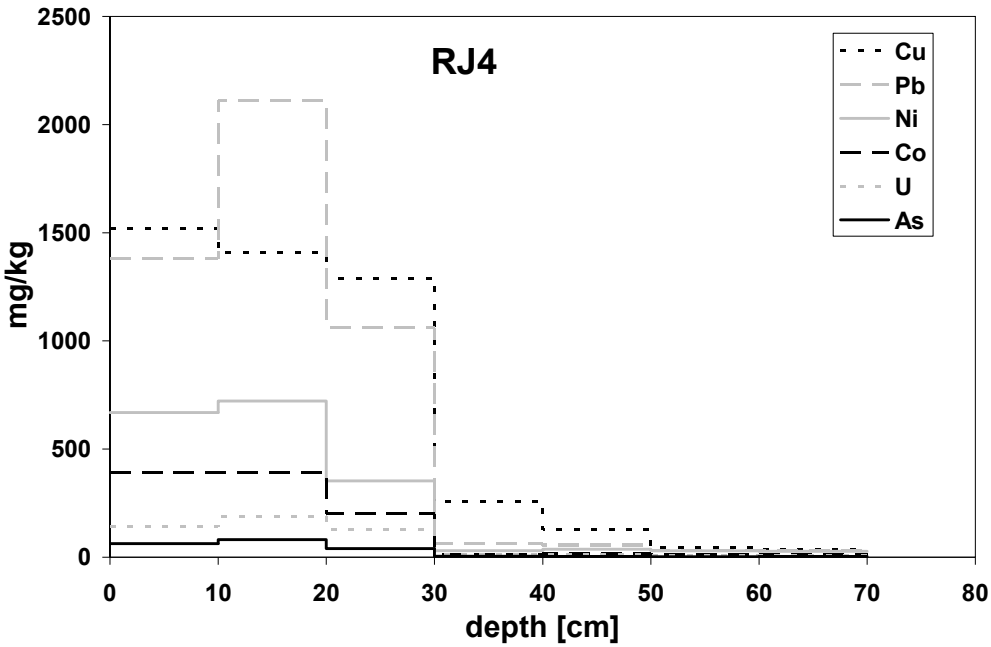


Figure 13 Pb, Cu, U, Ni, As and Co concentrations in Rum Jungle core RJ4

Figures 13 and 14 show the Pb, Cu, U, Ni, As and Co concentrations in Rum Jungle core RJ4 and the soil $^{226}Ra/^{238}U$ activity ratio plotted versus the depth. It appears that the contamination extends to at least 30–40 cm depth in the area that was augered (close to a tree root in a depression where the tailings collected). A few auger traverses supported by ground radiometric surveying would permit an accurate estimate of the volume of remnant tailings.

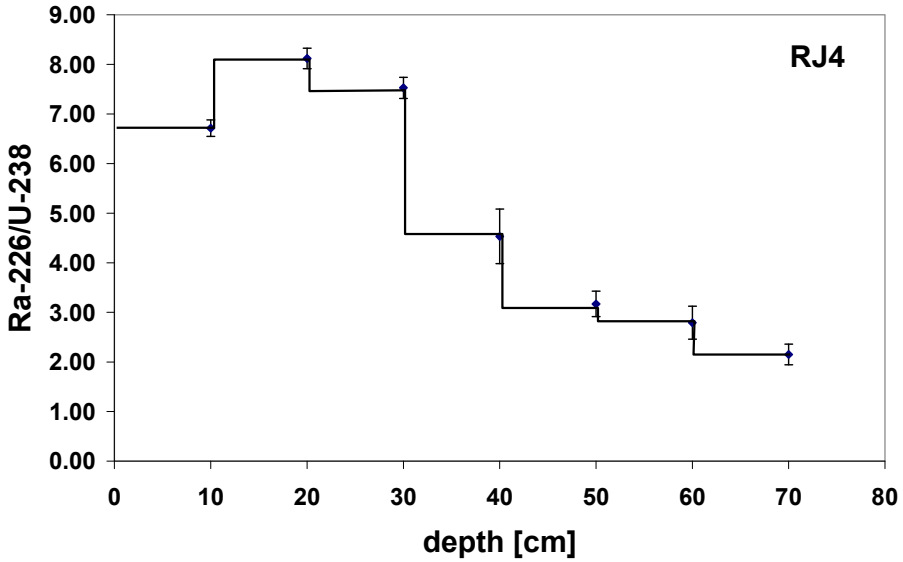


Figure 14 $^{226}Ra/^{238}U$ activity ratio in Rum Jungle core RJ4

3.5 Remnant patches of tailings

The airborne gamma survey results show above background levels of gamma radiation along the northern edge of what was the Old Tailings Dam adjacent to the drainage line that is referred to as Tailings Creek. The material is typically patchy and thin and sometimes obscured by thin cover materials. Where it surfaces it is readily recognisable by its relatively uniform mid grey colour and sandy texture (Figure 15).

Figure 15 Anomaly RJTDN2 – tailings exposed in track to the north of Tailings Creek

If further clean up and disposal of tailings is intended then this material should be collected as well, to minimise potential dust hazards along tracks which are currently accessible by vehicle. Volumetrically these remnant patches are likely to be small and dilution with uncontaminated material would be difficult to avoid while attempting to collect the tailings. Geochemically the two samples collected (RJTDN and RJTDN2) differ from one another, but this is not unexpected given their spatial (and therefore likely temporal) separation and the fact that a number of different ores were processed at Rum Jungle over time.

3.6 Anomaly MFA

This anomaly is located downstream of Rum Jungle and Mt Fitch mines and upstream of the confluence of the East Finniss and main branch of the Finniss Rivers. It is located on a flood plain where all exposed sediments and those intersected by auger drilling are fine grained.

The geochemical and radionuclide fingerprint of the sediments at this location is similar to that of anomalies MFC and MFD (Sections 3.8 and 3.9 below). The profile of anomaly MFA is a little different from that at MFC and MFD however, in that it appears to have two horizons of elevated metals as opposed to one at the two latter sites (Figure 16).

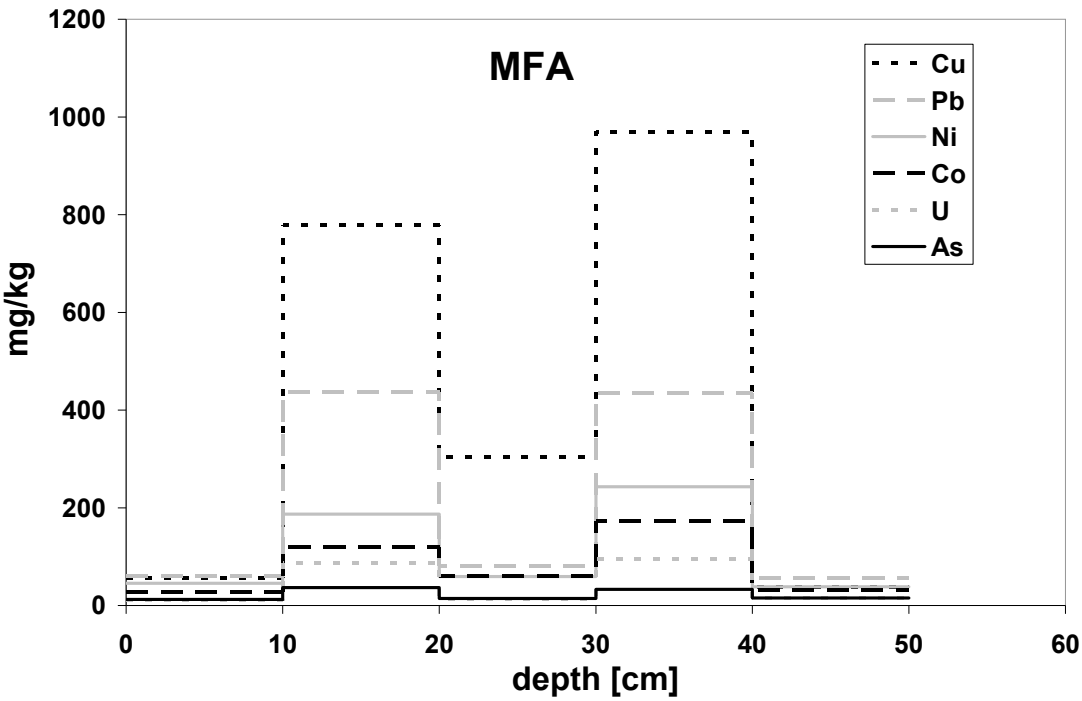


Figure 16 Cu, Pb, Ni, Co, U and As concentrations in Mt Fitch core MFA

Notably all three of these anomalies exhibit similar geochemical patterns and radiological disequilibrium to those observed at the contaminated Rum Jungle sites, leading to the conclusion that the elevated metal concentrations observed in the sediments are mainly attributable to Rum Jungle. While some may be natural and predate mining, the radiological signature is indicative of tailings (relative U depletion against Ra) (Figure 17).

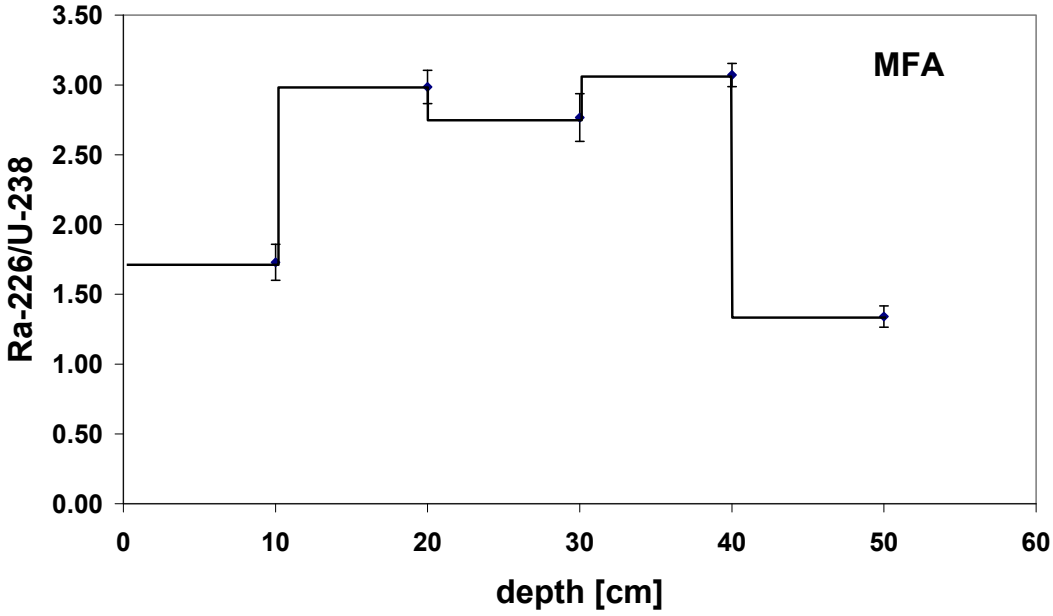


Figure 17 $^{226}Ra/^{238}U$ activity ratio in Mt Fitch core MFA

3.7 Anomaly MFB

Field traversing confirmed that the anomaly is related to stockpiled spoil from a small open cut identified as the Mt Fitch mine. Sampling at this site comprised a composite surface grab of fine grained weathered rocks and soil. The sampled material had high radionuclide activity concentrations, but in contrast to Rum Jungle samples lower levels of metals other than U. The U concentration in this sample of about 800 mg/kg is the highest measured of all samples collected during this study. The $^{226}Ra/^{238}U$ ratio in this sample is 0.84, which is indicative of uraniferous material that has not been exposed to a leaching process.

3.8 Anomaly MFC

Anomaly MFC is located on the floodplain immediately downstream of Mt Fitch mine. Its geochemical signature is, however, very similar to that of Rum Jungle tailings and that of MFD, both of which are located upstream of Mt Fitch mine. It appears that despite its general proximity to Mt Fitch mine, anomaly MFC is mainly derived from contamination from Rum Jungle. Figures 18 and 19 show that the contamination in this area extends to 20–30 cm depth.

3.9 Anomaly MFD

Being generally located upstream of Mt Fitch mine this anomaly is even less likely than MFC to have a local source. As noted, the geochemical profiles of both MFC and MFD are similar to the RJ1, RJ3 and RJ4 anomalies, which have tailings and/or other process residues as their principal source. Figures 20 and 21 show that the contamination at MFD extends to about 20 to 30 cm depth in this core.

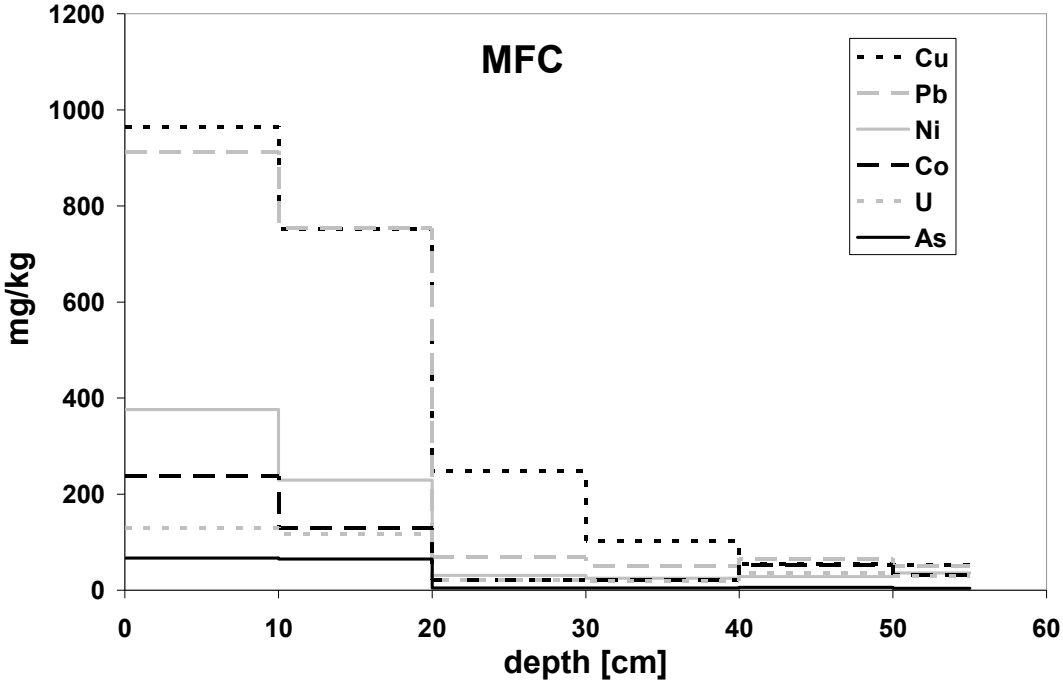


Figure 18 Cu, Pb, Ni, Co, U and As concentrations in Mt Fitch core MFC

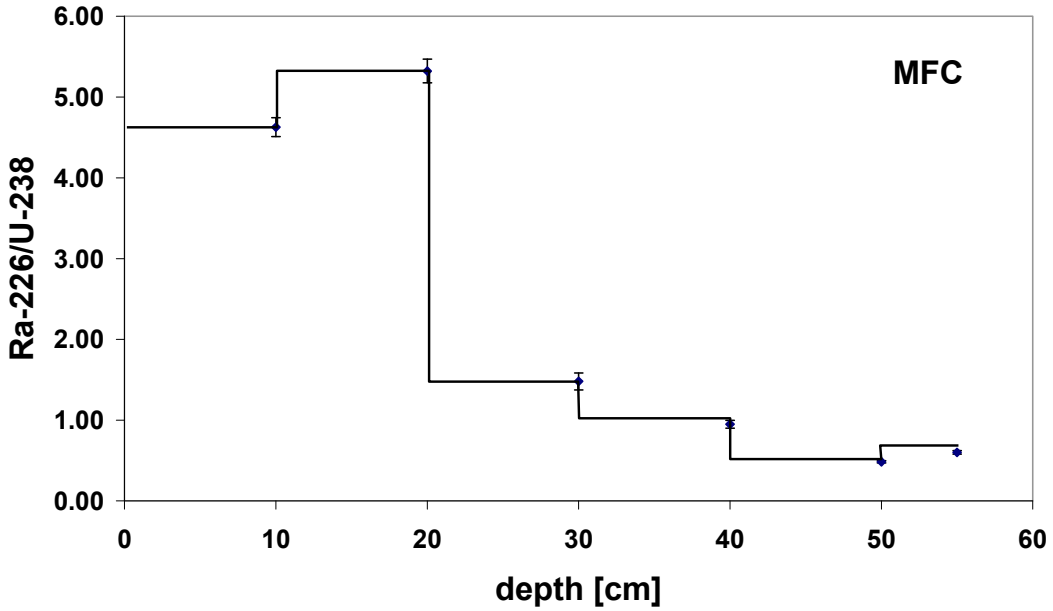


Figure 19 $^{226}Ra/^{238}U$ activity ratio in Mt Fitch core MFC

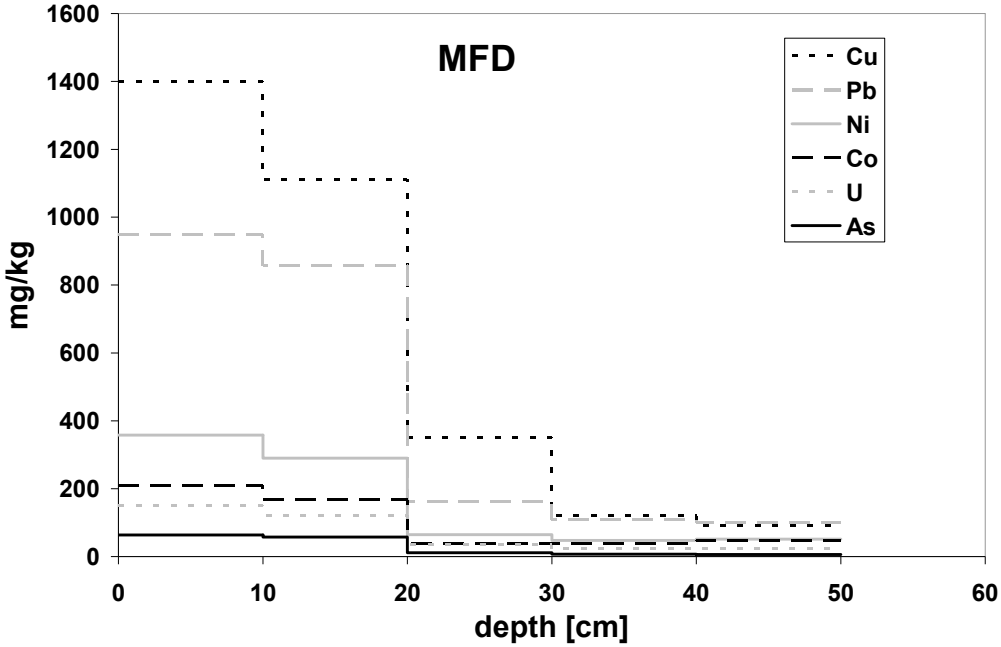


Figure 20 Cu, Pb, Ni, Co, U and As concentrations in Mt Fitch core MFD

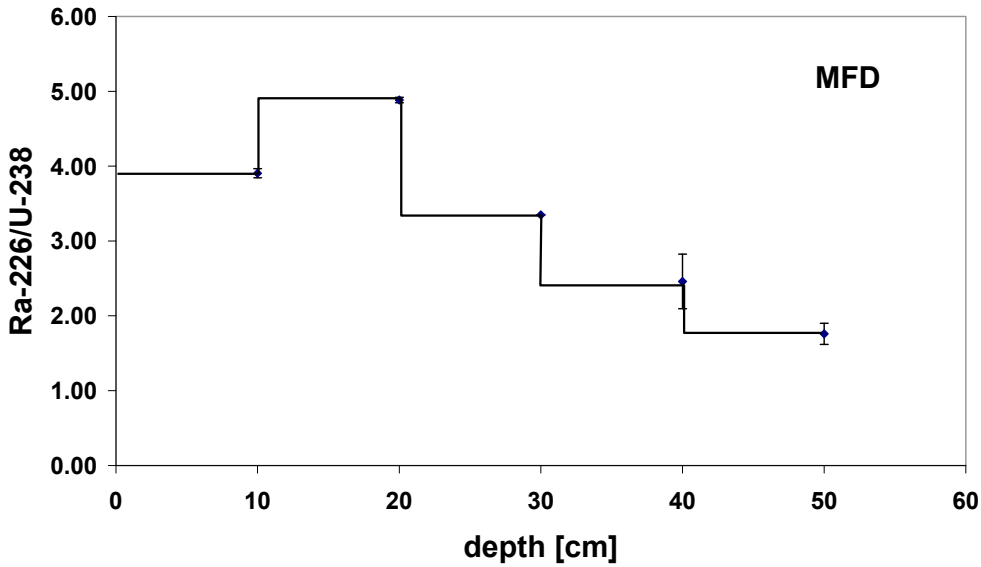


Figure 21 $^{226}Ra/^{238}U$ activity ratio in Mt Fitch core MFD

3.10 Geochemistry

Results of the geochemical and gamma spectrometry analysis of all samples are given in tables in Appendix 1, Table A2.

U concentration [mg/kg] can be calculated from the gamma spectrometry ^{238}U analyses by multiplying the ^{238}U activity concentration [$Bq \cdot kg^{-1}$] by 0.080993 $mg \cdot Bq^{-1}$. A comparison of the ICPMS and gamma spectrometry results is shown in Figure 22. It is obvious that there is an excellent agreement between the two methods ($p << 0.001$).

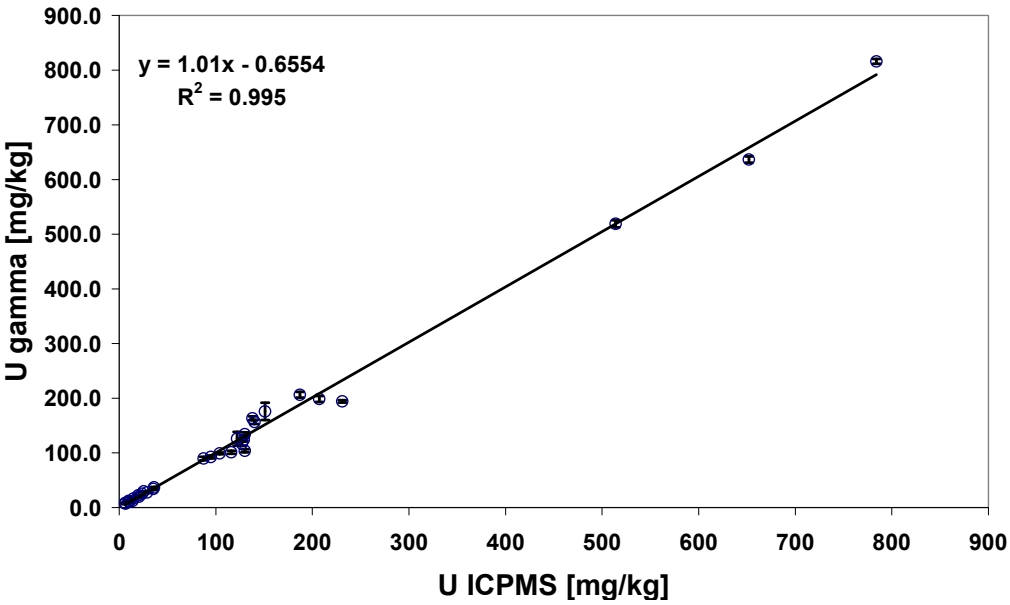


Figure 22 U concentration measured via gamma spectrometry plotted versus ICPMS results

Figure 23 shows the profiles (U, Cu and Pb) of all samples taken for this study. It appears that downstream anomaly MFD is the most contaminated of the downstream sites with a signature similar to RJ3 and RJ4.

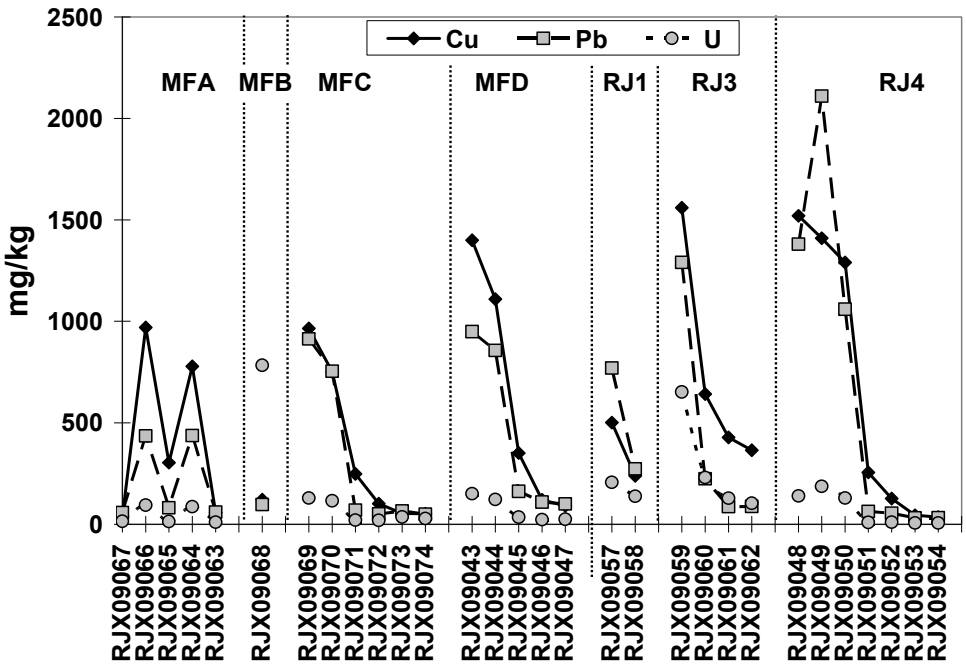


Figure 23 Geochemical profiles of the radiometric anomalies

Not surprisingly, as the Rum Jungle ores were known to have complex mineralogy, there is a significant correlation between As, Co, Cu, Ni, Pb, U and Zn concentrations in the samples as those elements are considered to represent contamination by mine-derived materials (cadmium was below the detection limit of 0.05 mg/kg in most samples). Table 1 shows the Pearson correlation coefficients and p-values for As, Co, Cu, Ni, Pb, U and Zn.

Table 1 Pearson correlation coefficients and p-values (*italics*) for As,Ca, Cu, Ni, Pb, U and Zn

	As	Co	Cu	Ni	Pb	U
Co	0.34					
	0.057					
Cu	0.573	0.701				
	0.001	*< 0.001*				
Ni	0.409	0.991	0.743			
	0.02	*< 0.001*	*< 0.001*			
Pb	0.416	0.55	0.902	0.589		
	0.018	*0.001*	*< 0.001*	*< 0.001*		
U	0.788	0.342	0.483	0.384	0.442	
	< 0.001	*0.056*	*0.005*	*0.03*	*0.011*	
Zn	0.416	0.525	0.9	0.55	0.949	0.435
	0.018	*0.002*	*< 0.001*	*0.001*	*< 0.001*	*0.013*

There is also a positive correlation between U and Ra activity concentrations. Generally ^{226}Ra (a ^{238}U decay product) is larger than the ^{238}U activity concentration. This indicates radiochemical disequilibrium with either preferential removal of ^{238}U, or enrichment of ^{226}Ra. While there may be a range of reasons for this pattern, the most likely is that the nature of the disequilibrium is typical of a tailings signature, resulting from relative depletion of the U content in tailings due to processing of the uranium ore for extraction of uranium. Similar relative enrichment of Ra has been observed at other locations with tailings at rehabilitated and disused uranium mining and milling sites in northern Australia (Hancock et al 2006, Tims et al 2000).

For most of the Rum Jungle anomalies the existence of a tailings signature in the samples is supported by field observations of the material present at the site of the anomalies. However, at the Mt Fitch area anomalies MFA, MFC and MFD , the surface and depth profiles were much more uniform and visual observation under a microscope was not able to identify obvious fragments of unweathered schist, which were evident in, and characteristic of, the tailings materials in the reference samples from Rum Jungle. The geochemical and radiochemical trends are similar to those of the Rum Jungle tailings anomalies and it is concluded that Mt Fitch area anomalies MFA, MFC and MFD have a significant component of Rum Jungle tailings and/or process water as their origin.

This conclusion is supported by the data plotted in Figure 24. In this figure the ^{226}Ra/^{238}U activity ratio in the soil samples is plotted versus their ^{210}Pb/lead ratios. In such a plot, natural uranium mineralised samples will be characterised by a ^{226}Ra/^{238}U activity ratio of approximately 1, and a high ^{210}Pb/lead ratio, due to the high ^{210}Pb activity concentration (which is expected to be in equilibrium with ^{238}U and ^{226}Ra, respectively) in the sample. Typical environmental background samples will also exhibit ^{226}Ra/^{238}U activity ratios close to unity, but smaller ^{210}Pb/lead ratios due to the smaller ^{210}Pb activity concentration compared to uranium mineralised materials. In tailings, the ^{226}Ra/^{238}U activity ratio will be much larger than 1, and the ^{210}Pb/Pb ratio relatively small, due to the high concentrations of lead in the tailings at Rum Jungle (see Table A2 in Appendix).

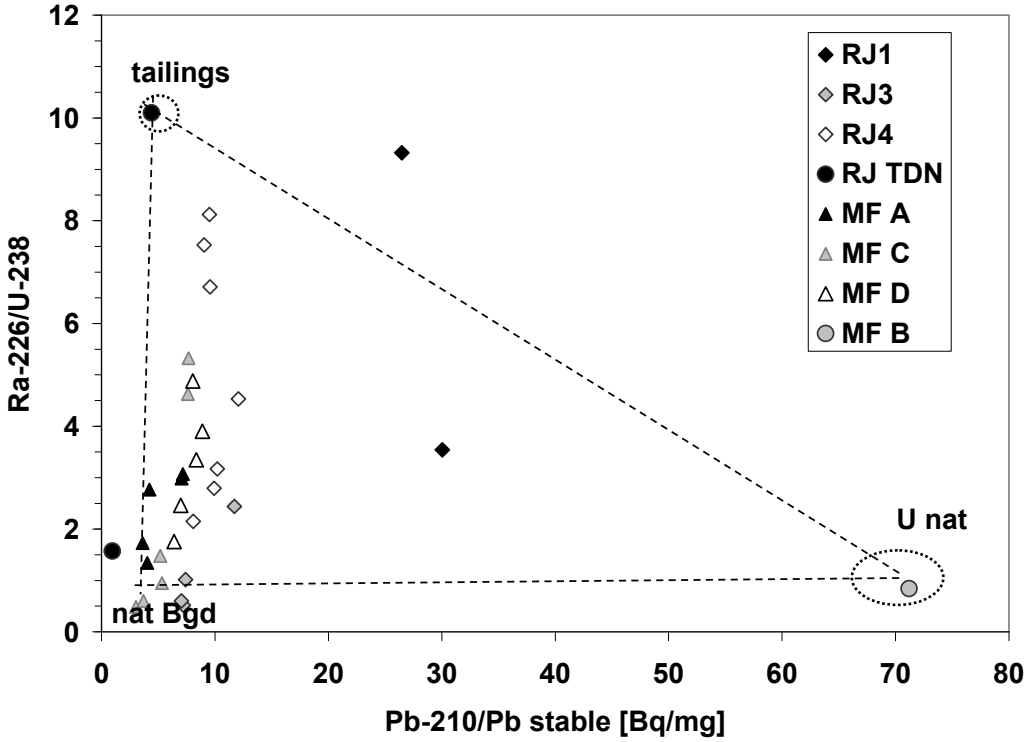


Figure 24 $^{226}Ra/^{238}U$ activity ratios plotted versus ^{210}Pb/lead ratios in the samples collected

Sample MFB represents a material with a signature typical for uranium mineralised material. It has the highest U concentration (~ 800 mg/kg), and the sample represents a single composite grab sample of soil and gravel that was collected in the vicinity of stockpiled rock adjacent to the small open cut at the Mt Fitch uranium mine. This material has not been processed and thus the $^{226}Ra/^{238}U$ activity ratio is close to one, and the ^{210}Pb/lead ratio is elevated.

A sample collected north of the Old Tailings Dam at Rum Jungle (RJTDN) exhibits a ^{226}Ra activity concentrations which is in excess of the ^{238}U activity concentrations. This is a typical signature for uranium tailings that had most of the uranium removed during the extraction process.

The deeper sections of the cores taken at Anomalies RJ3 and MFC represent signatures that can be considered typical environmental background (although activity concentrations are still rather large, due to the general uranium mineralised nature of the Rum Jungle and Mt Fitch areas).

Figure 24 shows the soil cores collected at the Rum Jungle anomalies 1, 3 and 4 are contaminated by tailings to variable extents. The top of RJ1, taken from the Acid Dam area, appears to be contaminated the most by tailings. However, there also appears to be an influence from contamination with unprocessed (natural) uranium as values are tending towards high ^{210}Pb/lead ratios. This is in agreement with field observations at this site, which identified a drain from the old stockpile area which feeds into this area. The top of core RJ4 is also contaminated by tailings to a relatively high degree. In the RJ3 core the degree of contamination is slightly less but still significant.

The samples from anomalies MFA, MFC and MFD have relatively low ^{210}Pb/lead ratios. The top sections of MFC and MFD show high $^{226}Ra/^{238}U$, as do the samples from 10–40 cm depth

in MFA. This supports the conclusion that tailings originating from Rum Jungle have contaminated areas downstream in the vicinity of these anomalies. In contrast, the source of contamination at MFB is clearly due to remnant mineralisation from mining activities at Mt Fitch mine.

3.11 Groundtruthing of the airborne gamma survey

Figure 25 shows a comparison of the total counts in the 2006 airborne gamma survey with the gamma dose rate measurements made on the ground at MFD in November 2006. The dose rate measurements on ground have then been smoothed using a three point average along the transect, resulting in a resolution similar to that of the airborne gamma survey (~30–35 m). This approach has been used previously and is discussed in Martin et al (2006) and Bollhöfer et al (2008). The results of the smoothed ground data have been compared with the total count results from the nearest pixels airborne gamma survey, and a conversion factor has been calculated (Figure 26). This conversion factor, 0.0406 ± 0.0064 nGy·hr^{-1}·s (95% confidence interval), is similar to, but slightly higher than, the conversion factor previously determined for the Rum Jungle site of 0.028 ± 0.004 nGy·hr^{-1}·s (Bollhöfer et al 2007).

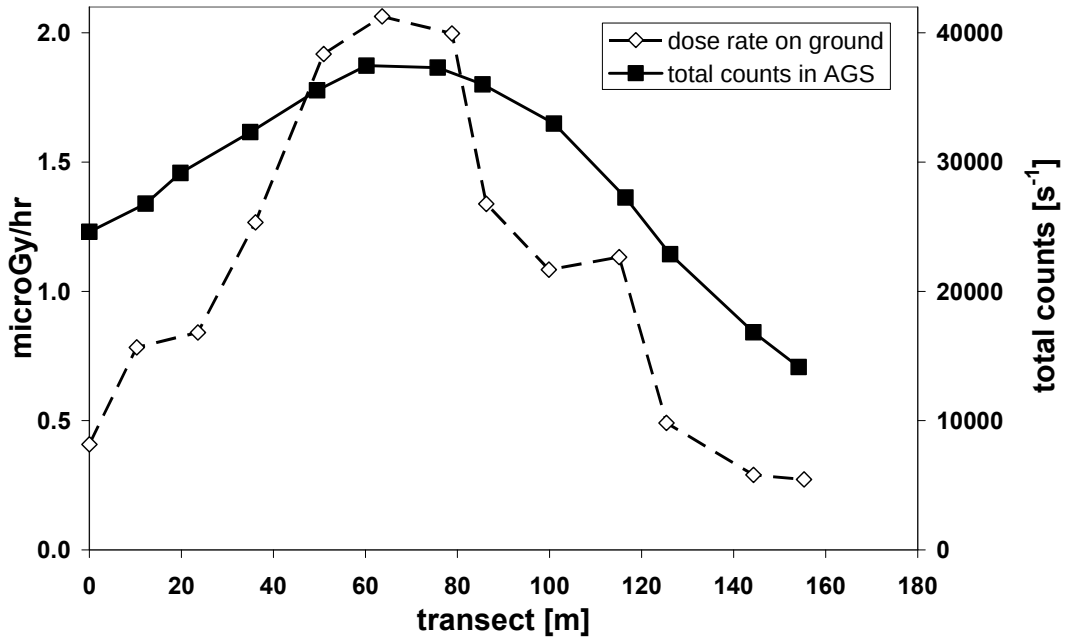


Figure 25 Dose rates measured on the ground at MFD and a comparison with counts in the nearest pixel of the 2006 airborne gamma survey

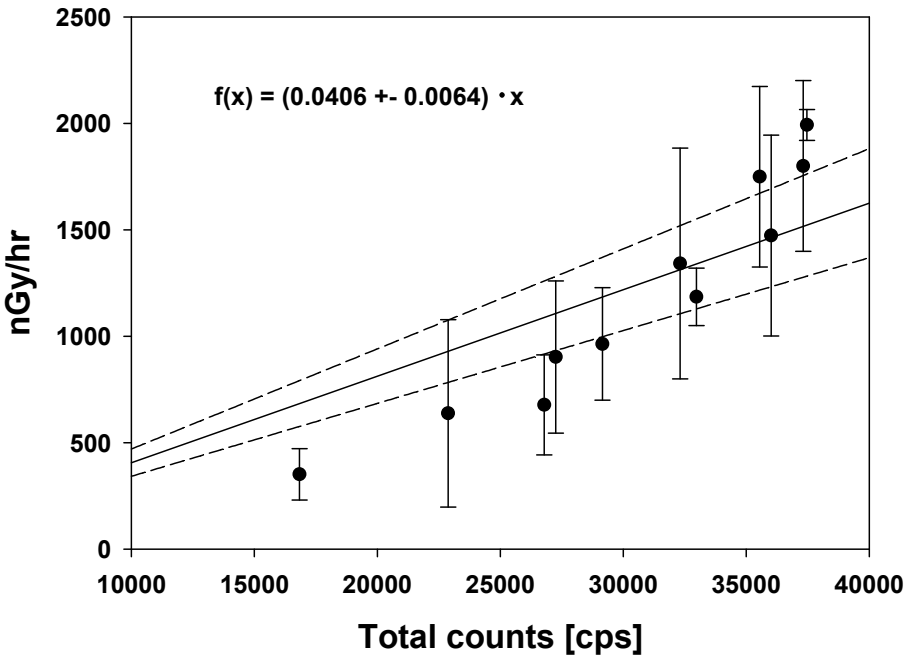


Figure 26 Correlation of the gamma dose rates measured on the ground (3 point averages) and total counts in the 2006 airborne gamma survey of the nearest pixel

After a comparison with the detailed ground radiological surveys previously reported for anomalies RJ1 to RJ3 (Bollhöfer et al 2007), the airborne gamma counts for each anomaly and the conversion factor above have been used to estimate average gamma dose rates for the Mt Fitch anomalies downstream of Rum Jungle.

Because the airborne survey was flown at a high resolution (25m nominal line spacing) area calculations at a given threshold gamma dose rate value provide a reasonable approximation of the extent of the anomalies to assist in making decisions about possible rehabilitation options. On this basis estimates of the area of each anomaly is provided in Table 1 and displayed in Figure 27 for the Mt Fitch subset, and for the whole area surveyed in 2006 (Figure 28).

Table 2 Area of the main Mt Fitch series radiometric anomalies. An estimate of the areas of the Rum Jungle anomalies are given in Bollhöfer et al (2007). Mean annual effective gamma dose was calculated for a child using a conversion factor from measured absorbed dose to effective whole body dose of 0.79 Sv·Gy^{-1} (UNSCEAR 2000).

μGy·hr^{-1} threshold	total counts in AGS (range)	Anomaly	Area (ha)	Mean (TC)	mean γ μGy·hr^{-1}	mean mSv/a
$0.5 < H_E < 1.0$	12315–24630	MFA	11.44	16148	0.66	4.6
$H_E > 1.0$	24630–36945	MFA	0.82	26417	1.07	7.4
$0.5 < H_E < 1.0$	12315–24630	MFB	9.32	16337	0.66	4.6
$H_E > 1.0$	24630–36945	MFB	0.58	27342	1.11	7.7
$1.0 < H_E < 1.5$	24630–36945	MFC	3.86	29076	1.18	8.2
$H_E > 1.5$	36945–40639	MFC	0.24	37980	1.54	10.7
$1.0 < H_E < 1.5$	24630–36945	MFD	8.69	28525	1.16	8.0
$H_E > 1.5$	36945–40639	MFD	0.07	37618	1.53	10.6
$0.5 < H_E < 1.0$	12315–24630	MFC + MFD	49.6	17848	0.72	5.0

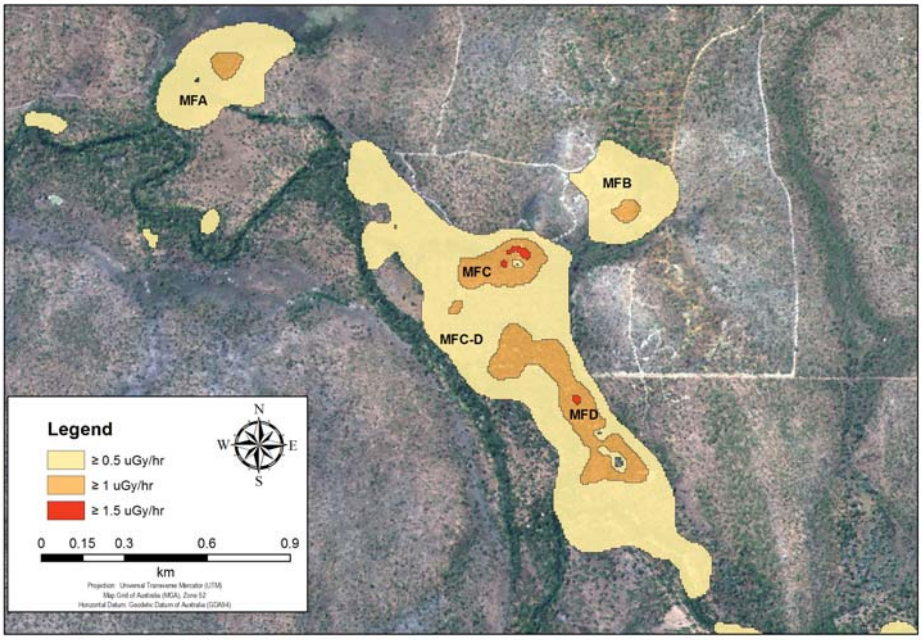


Figure 27 Areal extent for various threshold values at the Mt Fitch area anomalies

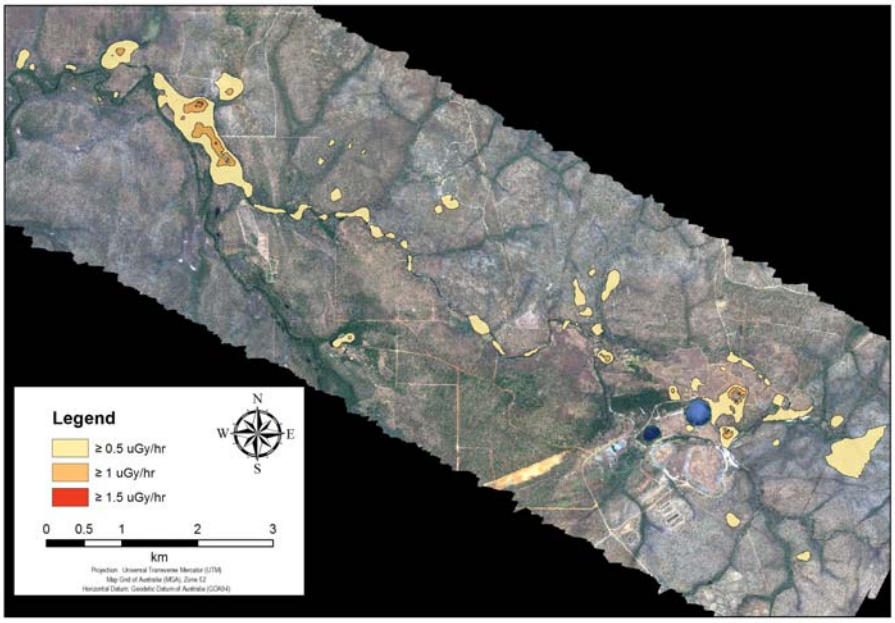


Figure 28 Areal extent for various threshold values for the whole area surveyed in the 2006 airborne gamma survey

An approximate value for the thickness of the source of each anomaly can be made on the basis of the results of the soil augering in each case (Figures 16–21). From these area and depth figures an estimate can be made of the approximate volume of material that comprises the source of each radiometric anomaly.

In detail the RJ anomalies differ from the MF anomalies in that they are discrete bodies with locally variable levels of contaminants. Although they have similar average levels of total radioactivity to the MF anomalies they are considered to potentially comprise a more acute health and environmental risk due to small but higher grade patches located within the broader anomalies.

Conclusion

Investigation of the four Rum Jungle and four Mt Fitch anomalies indicate that six (RJ1, RJ3, RJ4, MFA, MFC and MFD) comprise thin layers (approximately 10–30 cm) of soil containing radioactive process residues, mainly tailings. One anomaly at Mt Fitch itself (MFB) is locally derived mineralised spoil from the Mt Fitch mine and one at Rum Jungle (RJ2) appears to be caused by residual mineralised stockpile material. Lower levels of gamma anomalism are apparent along the course of the East Finniss drainage system downstream of Rum Jungle that are obviously sourced from the site.

The radiological contamination at Rum Jungle and downstream in the East Finniss and Finniss Rivers has a major component due to historic mining activities. The proposed action of rehabilitating the area should be regarded as an intervention (NHMRC 1995). This is because the sources of exposure and exposure pathways are already present due to earlier practices that preceded regulatory control. It is thus an *existing exposure situation*.

For these situations the International Commission on Radiological Protection (ICRP) currently recommends a reference level for the restriction on dose or risk, above which it is judged inappropriate to plan to allow exposures to occur. This reference level is 1–20 mSv per year for existing exposure situations involving naturally occurring radioactive materials in the human habitat (ICRP 2008). In its previous recommendations the ICRP recommended that doses be optimised below a dose constraint (ICRP 1999, paragraph 4.1):

> An existing annual dose approaching about 10 mSv may be used as a generic reference level below which intervention is not likely to be justifiable for some prolonged exposure situation.

Using the ICRP System of Radiological Protection, one can compare the dose constraint of 10 mSv per year with the gamma doses received, assuming the unlikely scenario that the areas are occupied permanently. Gamma dose rates would be at a maximum at the anomalies identified from the 2006 airborne survey. At the Rum Jungle and Mt Fitch anomalies theoretical gamma doses could be up to 10 mSv per annum for relatively small areas. However this does not include the radon and dust inhalation or the ingestion pathways, which would add to the dose. Further work is required to estimate the contributions from these pathways. It should be noted that these theoretical maxima will be reduced due to the improbability of permanent occupation at any of these sites, particularly at the Mt Fitch anomalies, which are located on the floodplain and are subject to seasonal inundation.

In addition to the radiological aspects of this study, the geochemical results of the sampling indicate that most sediment quality guidelines pertaining to a range of base metals, in particular copper, nickel and lead, are likely to be exceeded downstream of Rum Jungle, with a probable significant contribution from mine-derived contamination.

Table 3 compares geochemical results for each of the anomalies to three sediment quality guidelines values, where available. These guidelines are:

1. ANZECC/ARMCANZ sediment quality guideline trigger value (SQG TV)

2. National Environmental Protection Measures Ecological Investigation Level (NEPM EIL)

3. ANZECC/ARMCANZ sediment quality guideline – high (SQG-high)

In most cases (but not always) this order represents the lowest to highest in terms of the guideline values. The SQG-high typically represents a concentration at which there is considered to be a high probability of detectable environmental effects.

Table 3 Comparison of geochemical results with sediment quality guidelines

Anomaly	Depth from (cm)	Depth to (cm)	Ag	As	Cd	Co	Cu	Fe	Mn	Ni	Pb	U	Zn
			ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
MFA	0	10	0.1	12.5	0.05	28.2	56.8	37400	1070	45.6	60.4	10.6	24
MFA	10	20	0.9	37	<0.05	119	778	38500	468	187	437	87.4	52
MFA	20	30	0.2	14.5	0.05	59.8	304	38700	1180	59.4	81.8	13.7	45
MFA	30	40	0.9	33.5	0.15	173	970	35100	385	243	435	94.9	83
MFA	40	50	0.1	15.5	<0.05	31.8	37.4	41300	1570	38.4	57.4	14.9	21
MFB	0	5	0.1	80	<0.05	221	121	231000	93	353	97	784	27
MFC	0	10	2	67	<0.05	238	965	42800	223	376	913	130	56.5
MFC	10	20	1.3	65	<0.05	129	751	37200	190	229	754	116	39.5
MFC	20	30	0.1	4.5	<0.05	20.4	248	20400	212	30.8	69.4	20.4	14.5
MFC	30	40	0.05	4.5	<0.05	21.7	102	34000	316	25	51	19.9	15
MFC	40	50	<0.05	6	<0.05	52.3	53.8	53600	1270	28	65.6	36.1	17
MFC	50	55	<0.05	4	<0.05	32.1	51.6	34800	599	35.6	50	28.9	20.5
MFD	0	10	1.75	63.5	<0.05	211	1400	39400	163	358	949	151	86.5
MFD	10	20	1.2	58	0.05	167	1110	39200	189	290	857	122	60
MFD	20	30	0.35	11	<0.05	39.2	351	27400	182	64.6	162	35.3	28
MFD	30	40	0.15	7	<0.05	37.9	120	45100	341	47.6	109	23.6	31.5
MFD	40	50	0.1	6.5	<0.05	47.6	90.6	42800	471	51.6	100	25.3	32.5
RJ1	0	10	1	122	0.05	67.8	501	84700	160	163	770	207	49.5
RJ1	10	60	0.4	78	0.05	32.3	239	72700	97	85.4	273	138	22
RJ3	0	10	5.1	228	<0.05	139	1560	101000	2310	263	1290	652	52.5
RJ3	10	20	0.8	58.5	<0.05	58.4	642	196000	12600	132	224	231	26.5
RJ3	20	30	0.3	40.5	0.05	99.6	428	205000	15800	132	87.4	129	22
RJ3	30	40	0.25	41.5	0.05	85.9	365	211000	16500	139	87.6	104	23.5
RJ4	0	10	3.05	63	<0.05	392	1520	33900	110	669	1380	140	63.5
RJ4	10	20	4.5	81.5	<0.05	394	1410	41000	106	722	2110	187	59.5
RJ4	20	30	2.9	40.5	<0.05	201	1290	21700	74	353	1060	130	34.5
RJ4	30	40	0.2	4	<0.05	14.9	256	7180	44	30.4	62.6	9.6	4
RJ4	40	50	0.1	3.5	<0.05	16.8	127	9860	62	36.6	54.6	9.77	6
RJ4	50	60	0.05	2.5	<0.05	11.1	44.8	14400	72	29.4	31.8	6.46	1.5
RJ4	60	70	0.05	3.5	<0.05	9.2	35.4	19000	87	27.6	32.8	6.34	6
RJTDN	0	10	4.3	108	<0.05	265	3560	117000	500	487	8640	514	284
RJTDN2	0	10	4.45	36.5	<0.05	658	1810	25200	201	1010	3060	127	98

Key		Cu	Pb	As	Cd	Mn	Ni	Zn	Ag
	> SQG TV								
	also >	NEPM EIL	SQG-high	NEPM EIL	NEPM EIL	NEPM EIL	SQG-high	NEPM EIL	
	also >	SQG-high	NEPM EIL	SQG-high	SQG-high		NEPM EIL	SQG-high	SQG-hig
	No Guidelines								

Guidelines

(mg/kg)	Cu	Pb	As	Cd	Mn	Ni	Zn	Ag
SQG TV	65	50	20	1.5		21	200	1
NEPM EIL	100	600	20	3	500	60	200	
SQG-high	270	220	70	10		52	410	3.7

Given that there would have been some exposure of ore in the catchment prior to mining there is also an unknown natural pre-mining component in the area of these anomalies.

Additional work would be required to determine whether the levels observed pose a level of risk that would justify rehabilitation actions. It is considered improbable that there will be any exposed areas of significant heavy metal contamination from Rum Jungle that do not exhibit a coincident radiometric anomaly.

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Appendix 1

Table A1 General description of the samples collected for this study

Surface uSv/hr	Anomaly	Easting	Northing	Zone	Depth from (cm)	Depth to (cm)	Sample number	Field observations	Sample description (optical binocular microscope observation)
1	MFA	710179	8568130	52	0	10	RJX09067	Anomaly on clayey alluvial plain	Tan to light grey clay with rare dark larger fragments
	MFA	710179	8568130	52	10	20	RJX09066		Grey silty clay with very rare dark specks
	MFA	710179	8568130	52	20	30	RJX09065		Grey silty clay with rare dark specks and some orange staining
	MFA	710179	8568130	52	30	40	RJX09064		Grey silty clay with some coarser quartz grains and rare dark fragments
	MFA	710179	8568130	52	40	50	RJX09063		Grey silty clay with increased orange stained quartz grains and rare dark fragments
3	MFB	711648	8567621	52	0	5	RJX09068	Scrape sample of soil and rock chips adjacent to Mt Fitch open cut. Sample dominated by ferruginous fine grained rock.	Weathered and fresh quartz and schistose and ferruginous rock fragments
2	MFC	711214	8567428	52	0	10	RJX09069	Anomaly on clayey alluvial plain	Fine silt with some dark micaceous flecks and dark rock fragments like in tailings sample
	MFC	711214	8567428	52	10	20	RJX09070		As above but much less black fragments
	MFC	711214	8567428	52	20	30	RJX09071		As above but lighter in colour, more clayey and damp
	MFC	711214	8567428	52	30	40	RJX09072		Yellow and cream clayey silt with no unweathered rock fragments
	MFC	711214	8567428	52	40	50	RJX09073		As above but with some weathered rock fragments and minor black specks
	MFC	711214	8567428	52	50	55	RJX09074		Less clayey weathered fine sand and ferruginous-stained sand
2	MFD	711472	8566932	52	0	10	RJX09043	Anomaly located on alluvial flat, with higher	Mid grey clayey sand with rare black rock fragments
	MFD	711472	8566932	52	10	20	RJX09044	count rates on areas approximately 1m lower	Mid grey clayey sand but with no black rock fragments or unweathered chips
	MFD	711472	8566932	52	20	30	RJX09045	than the average level of the plain.	Grey and cream clayey silt
	MFD	711472	8566932	52	30	40	RJX09046		Cream and orange silty clay with some ferruginisation
	MFD	711472	8566932	52	40	50	RJX09047		Cream and orange silty clay with some ferruginisation
5	RJ1	718218	8563149	52	0	10	RJX09057	Looks like fine tailings deposit sloping gently SE	Finely laminated clayey micaceous silt with coarser orange and fresh rock fragments
	RJ1	718218	8563149	52	10	60	RJX09058	Tailingss 15-20cm thick, probably contaminating the sandy material beneath during the sampling, hence 10-60cm combined	Medium grained orange sand with coarse fresh and weathered rock fragments
3	RJ3	717523	8563655	52	0	10	RJX09059	Fine tailings, probably slimes. Bounded by 2 to 3m of waste	Fine grey micaeous silty clay - most probably tailings
	RJ3	717523	8563655	52	10	20	RJX09060	rock and other materials to the E and by cover from the TD	10% as above, mostly gritty red soil with ferruginous fragments
	RJ3	717523	8563655	52	20	30	RJX09061	rehab works to the N. Probably thins out to nothing the W and S.	Red brown ferruginous soil with ironstone fragments and some chips of the surface tailings
	RJ3	717523	8563655	52	30	40	RJX09062		As above, the tailings are probably contamination washed from the surface as it was raining
5	RJ4	716692	8564089	52	0	10	RJX09048	Anomaly is associated with a low sandy ridge	Mid grey silt with coarse black rock fragments - tailings
	RJ4	716692	8564089	52	10	20	RJX09049	of material that looks like tailings. Approx	As above - these samples are very like RJX09056 which is clearly residual tailings
	RJ4	716692	8564089	52	20	30	RJX09050	dimensions are about 15x80m, up to 0.5m thick?	As above
	RJ4	716692	8564089	52	30	40	RJX09051	There is evidence of earthmoving around the area	Less mica and more quartz sand
	RJ4	716692	8564089	52	40	50	RJX09052	It could have been tailings overlooked in the 1980s	Mostly fine quartz sand/silt
	RJ4	716692	8564089	52	50	60	RJX09053	rehab program when Tailings Creek was cleaned up.	Clayey grey and ferruginous silt and fine sand, maybe some schist from uphole contamination
	RJ4	716692	8564089	52	60	70	RJX09054		As above
1	RJTDN	718004	8564024	52	0	10	RJX09056	Thin layer of tailings exposed in track	White and grey mica and white grey and orange quartz, fine silt
1	RJTDN2	717362	8564100	52	0	10	RJX09055	Thin layer of tailings exposed in track	White and grey mica and white grey and orange quartz, fine silt. Some coarser rock fragments including fresh black (biotite schist?) rock fragments. These dark fragments and fresh schist are typical of samples noted as probable tailings

Sampling undertaken with hand auger by Andreas Bollhoeffer and Alan Hughes 9 September 2009.
Surface dose rates measured approximately 1 m above ground with small handheld instrument fitted with GM tube.
Location according to Magellan …….. hand held GPS using WGS84 datum
Chemistry results by ICPMS
Gamma activity determinations by ERISS laboratory Darwin

Table A2 ICPMS and gamma spectrometry results

			ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	[Bq/kg]	[Bq/kg]	[Bq/kg]	[Bq/kg]	[Bq/kg]	[Bq/kg]	Ratio	Ratio	Ratio	Ratio
Anomaly	**Depth from (cm)**	**Depth to (cm)**	Ag	As	Cd	Co	Cu	Fe	Mn	Ni	Pb	U	Zn	U-238	Ra-226	Pb-210	Ra-228	Th-228	K-40	Ra226 / U238	Pb210 / Ra226	Ra228 / Ra226	Ra226 / 228
MFA	0	10	0.1	12.5	0.05	28.2	56.8	37400	1070	45.6	60.4	10.6	24	205	276	231	135	137	424	1	0.84	0.49	2
MFA	10	20	0.9	37	<0.05	119	778	38500	468	187	437	87.4	52	1143	3511	3115	116	120	856	3	0.89	0.03	30
MFA	20	30	0.2	14.5	0.05	59.8	304	38700	1180	59.4	81.8	13.7	45	154	425	346	116	123	365	3	0.81	0.27	4
MFA	30	40	0.9	33.5	0.15	173	970	35100	385	243	435	94.9	83	1107	3305	3087	122	124	749	3	0.93	0.04	27
MFA	40	50	0.1	15.5	<0.05	31.8	37.4	41300	1570	38.4	57.4	14.9	21	137	236	219	136	136	408	2	0.93	0.58	2
MFB	0	5	0.1	80	<0.05	221	121	231000	93	353	97	784	27	10075	8491	6906	90	80	339	1	0.81	0.01	95
MFC	0	10	2	67	<0.05	238	965	42800	223	376	913	130	56.5	1658	7673	6960	113	127	1032	5	0.91	0.01	68
MFC	10	20	1.3	65	<0.05	129	751	37200	190	229	754	116	39.5	1249	6648	5782	131	115	844	5	0.87	0.02	51
MFC	20	30	0.1	4.5	<0.05	20.4	248	20400	212	30.8	69.4	20.4	14.5	246	364	360	165	169	709	1	0.99	0.45	2
MFC	30	40	0.05	4.5	<0.05	21.7	102	34000	316	25	51	19.9	15	276	262	271	200	201	811	1	1.04	0.76	1
MFC	40	50	<0.05	6	<0.05	52.3	53.8	53600	1270	28	65.6	36.1	17	455	220	199	190	199	667	0	0.91	0.86	1
MFC	50	55	<0.05	4	<0.05	32.1	51.6	34800	599	35.6	50	28.9	20.5	345	207	185	187	189	679	1	0.89	0.90	1
MFD	0	10	1.75	63.5	<0.05	211	1400	39400	163	358	949	151	86.5	2171	8472	8440	166	148	958	4	1.00	0.02	51
MFD	10	20	1.2	58	0.05	167	1110	39200	189	290	857	122	60	1557	7598	6899	150	139	887	5	0.91	0.02	51
MFD	20	30	0.35	11	<0.05	39.2	351	27400	182	64.6	162	35.3	28	420	1405	1354	193	206	718	3	0.97	0.14	7
MFD	30	40	0.15	7	<0.05	37.9	120	45100	341	47.6	109	23.6	31.5	311	759	762	204	214	766	2	1.00	0.27	4
MFD	40	50	0.1	6.5	<0.05	47.6	90.6	42800	471	51.6	100	25.3	32.5	368	647	641	208	215	699	2	0.99	0.32	3
RJ1	0	10	1	122	0.05	67.8	501	84700	160	163	770	207	49.5	2454	22881	20387	267	69	332	9	0.89	0.01	86
RJ1	10	60	0.4	78	0.05	32.3	239	72700	97	85.4	273	138	22	2016	7138	8202	86	44	229	4	1.15	0.01	83
RJ3	0	10	5.1	228	<0.05	139	1560	101000	2310	263	1290	652	52.5	7860	19184	15103	143	101	790	2	0.79	0.01	134
RJ3	10	20	0.8	58.5	<0.05	58.4	642	196000	12600	132	224	231	26.5	2397	2430	1659	97	105	88	1	0.68	0.04	25
RJ3	20	30	0.3	40.5	0.05	99.6	428	205000	15800	132	87.4	129	22	1534	796	630	112	122	86	1	0.79	0.14	7
RJ3	30	40	0.25	41.5	0.05	85.9	365	211000	16500	139	87.6	104	23.5	1225	734	616	137	133	66	1	0.84	0.19	5
RJ4	0	10	3.05	63	<0.05	392	1520	33900	110	669	1380	140	63.5	1934	12987	13205	105	69	1233	7	1.02	0.01	123
RJ4	10	20	4.5	81.5	<0.05	394	1410	41000	106	722	2110	187	59.5	2549	20698	20082	113	93	1523	8	0.97	0.01	183
RJ4	20	30	2.9	40.5	<0.05	201	1290	21700	74	353	1060	130	34.5	1284	9663	9595	77	60	778	8	0.99	0.01	125
RJ4	30	40	0.2	4	<0.05	14.9	256	7180	44	30.4	62.6	9.6	4	137	622	756	72	81	180	5	1.21	0.12	9
RJ4	40	50	0.1	3.5	<0.05	16.8	127	9860	62	36.6	54.6	9.77	6	150	476	558	92	104	219	3	1.17	0.19	5
RJ4	50	60	0.05	2.5	<0.05	11.1	44.8	14400	72	29.4	31.8	6.46	1.5	88	247	315	93	98	203	3	1.28	0.38	3
RJ4	60	70	0.05	3.5	<0.05	9.2	35.4	19000	87	27.6	32.8	6.34	6	104	224	265	111	116	185	2	1.19	0.50	2
RJTDN	0	10	4.3	108	<0.05	265	3560	117000	500	487	8640	514	284	6409	10052	8312	109	88	656	2	0.83	0.01	92
RJTDN2	0	10	4.45	36.5	<0.05	658	1810	25200	201	1010	3060	127	98	1442	14560	13507	84	67	1467	10	0.93	0.01	174

Table A3 Results of the groundtruthing of the 2006 airborne gamma survey

Longitude and UTM coordinates				distance along transect								
WGS84 datum		52L							closest AGS pixel			
line	**pos.**	**easting**	**northing**		**comments**	**uGy/hr**	**+-**		**easting**	**northing**	**transect**	**Total counts**
line 6 d/s	1	711417	8566894	0	next to river bank	0.41	0.02	P01	711416.5	8566895.5	0.0	24598
line 6 d/s	2	711422	8566903	10.3		0.78	0.03	P02	711426.5	8566902.5	12.2	26786
line 6 d/s	3	711431	8566913	23.6		0.84	0.03	P03	711430.5	8566909.5	19.8	29153
line 6 d/s	4	711442	8566920	36.1		1.27	0.04	P04	711444.5	8566916.5	35.0	32312
line 6 d/s	5	711454	8566929	50.9		1.92	0.04	P05	711451.5	8566930.5	49.5	35548
line 6 d/s	6	711468	8566932	63.6	depression	2.06	0.05	P06	711465.5	8566930.5	60.2	37466
line 6 d/s	7	711481	8566940	78.8	depression	2.00	0.05	P07	711479.5	8566937.5	75.7	37313
line 6 d/s	8	711488	8566943	86.3		1.34	0.04	P08	711486.5	8566944.5	85.4	36010
line 6 d/s	9	711499	8566951	99.9		1.08	0.03	P09	711500.5	8566951.5	101.0	32974
line 6 d/s	10	711512	8566959	115.1		1.13	0.03	P10	711514.5	8566958.5	116.5	27257
line 6 d/s	11	711519	8566967	125.4		0.49	0.02	P11	711521.5	8566965.5	126.2	22878
line 6 d/s	12	711529	8566985	144.3		0.29	0.02	P12	711528.5	8566986.5	144.3	16837
line 6 d/s	13	711535	8566995	155.3	fence ~ 20 m	0.27	0.02	P13	711535.5	8566993.5	154.2	14146