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Ground truthing of an airborne gamma survey and assessment of the radiological conditions of the Sleisbeck mine area

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Executive summary

This report describes the results of the radiological characterisation of the Sleisbeck mine, one of the many small abandoned uranium mine sites located in and around the South Alligator River Valley in the remote Northern Territory of Australia. The mine site is situated in the Katherine River catchment, ~30 km south east of Coronation Hill. This report is part of a larger study aimed at characterising the extent and intensity of radiological contamination in the area as a result of mining in the 1950s and 60s, and to assist in determining rehabilitation requirements. Although there is no reason for intervention on radiological grounds as annual radiation doses are low, the area is sparsely populated and access to many of the sites, including Sleisbeck, is restricted on cultural grounds, rehabilitation works have begun at the request of the Traditional Owners of the area.

A high resolution airborne gamma survey (AGS) of the Sleisbeck site was commissioned in 2002 to provide information about the extent of residual radiological contamination. The survey resulted in the collection of airborne radiometric data (eU, eTh, K and total count rates), magnetic, and digital elevation data. A NaI(Tl) detector with a 48 litre detector volume was used, with sampling occurring every 1 second. A flight line spacing of 25 m, with 250 m tie line spacing, and an aircraft height of 40 m were chosen for the survey, providing unusually high spatial resolution of the images.

Emphasis was given on the evaluation of the equivalent uranium (eU) data from the AGS. This channel represents gamma rays detected from the 1.73-1.76 MeV decay of ^{214}Bi. As ^{214}Bi is a radioactive progeny of ^{226}Ra, elevated count rates indicate the presence of ^{226}Ra in the soil, rather than uranium. This point was especially important during the project, because of the possible presence of uranium mill tailings in the South Alligator River Valley close to the old South Alligator mill. Count rates at Sleisbeck in the eU channel ranged from 17-2182 counts per second. High levels of radioactivity are confined to the abandoned mine and associated with the pit area and three low grade ore truck dumps. Quickbird satellite data was also acquired to relate the airborne count rates to the land cover features.

Based on the anomalously high regions identified from the airborne survey, ground-based gamma radiation surveys were conducted in 2003, and a detailed survey in 2006, to correlate count rates measured from the airborne platform with soil activity concentrations and gamma dose rates on ground, respectively. Two transect were chosen for ground truthing at 10-15 m resolution.. The ground-based gamma measurements were performed in the mid dry season when surface soil moisture content is very low. A portable 3’×3’ NaI(Tl) spectrometer collected 512 channel gamma data over the energy range 0–3 MeV. External gamma dose rates were measured using environmental dose rate meters. Groundbased measurements were averaged to result in a resolution similar to the airborne gamma survey (~50 m). Terrestrial gamma dose rates and soil eU activity concentrations along the transects follow the trend of the AGS signal, with AGS pixels exhibiting high count rates represented by elevated dose rates and activity concentrations on the ground.

Conversion factors to estimate terrestrial gamma dose rates from the airborne counts have been calculated. These conversion factors have been used to determine area wide terrestrial gamma dose rates. Typical terrestrial background gamma dose rates have been determined from the ground truthed AGS data to 0.1–0.14 μGy per hour, whereas the area around Sleisbeck is characterised by values between 0.6–0.8 μGy per hour. Maximum values from the AGS amounted to 2.3 μGy per hour, but measurements on the ground indicate that this value is exceeded at localised areas within the old truck dumps at Sleisbeck.

Radiological guidelines have been adopted for the rehabilitation of the old mine sites in the South Alligator River Valley. Our measurements indicate that the guideline value of 7.5 μGy per hour is exceeded only at a few localised areas within the old truck dumps at Sleisbeck. The agreed rehabilitation strategy for the site is to remove the dumps, place the material back into the original pit and then cover it with one metre of compacted clean fill. Higher activity concentration material should be removed first, successively followed by lower activity concentration material.

Given that the dumps have been weathering on the land surface for decades it is possible that radionuclides have been leached into the underlying soil profile and the volume of material needing to be excavated could be much larger than indicated by the surface extent. Hence, trenches were dug at the identified hot spots and samples were taken down the wall of the trenches to determine the extent of leaching of radionuclides into the soil profile. This strategy is important from a remediation point of view to ensure that all of the contaminated material is removed and that any residual contamination of the underlying soil profile is also taken out.

The investigation of the soil profiles showed that the maximum penetration depth of radionuclides is 5–10 cm below the waste rock – top soil interface. If 5 cm of the underlying topsoil is shifted during the removal of the mineralised material, this would result in an additional 600 m^3 of material.

Plain English summary

Gamma radiation is the radiation that is coming from the ground, from rocks and soils. It is much like an X-ray that you may have when you go to the doctors. The X-rays and the gamma radiation pass straight through your body. The gamma radiation is everywhere you go and it has always been on the land, and it is not harmful in nature. But sometimes there can be more radiation from rocks that have some uranium in them. The more uranium is in the rock, the higher is the gamma radiation.

At Sleisbeck, people were looking for uranium and were digging up the ground 50 years ago. Because there was not so much uranium around they left the area but did not clean up. Parks Australia wants to clean up the area now, and have asked ***eriss*** to look where there is much radiation so they can pick it up and put it back in the old pit again and cover it with rock and soil, so that the area is like bushland again, much like the area around the old mine.

eriss has looked at the radiation coming from the ground around the Sleisbeck mine. We measured the radiation from a plane flying back and forth across the old mine site, and also across other areas to see how much natural radiation is there. We looked from a plane, because we can look at a much bigger area compared to when we measure on foot. We only found higher radiation where the old pit and the truck dumps are. Eriss has then measured the radiation on the ground and we have determined where exactly the higher radiation is coming from so Parks Australia know which rocks to shift back into the pit.

Eriss also dug three holes with a backhoe into the dumped rocks, to test whether the uranium from the rocks has been washed into the soil that is under the rocks by the rain. There is a little bit in the top 5 cm of the soil, but below that the soil is clean. So the top 5 cm of the soil needs to be scraped off and put in the pit as well, to make the land like it was before the Sleisbeck mine started.

When all the rock and soil has been shifted back into the pit, the area will be safe again for people to access. A little bit of extra radiation from the ground may still be there because of the uranium rocks that have been lying around on the ground for so long, but there will not be much. For example, the extra radiation from the ground that you may get when you camp next to the cleaned up mine for a whole week after it has been cleaned, is like the radiation you get when you have a chest X-ray or when you fly from Darwin to Perth. It is only a little bit more radiation than what you get naturally.

Ground truthing of an airborne gamma survey and assessment of the radiological conditions of the Sleisbeck mine area

A Bollhöfer, K Pfitzner, B Ryan & M Fawcett

1 Introduction

This Internal Report describes the results of the radiological characterisation of the abandoned Sleisbeck uranium mine. It is part of a larger study aimed at characterising the extent and intensity of radiological contamination in the South Alligator River Valley and areas in the vicinity as a result of mining in the 1950s and 60s, and to assist in determining rehabilitation requirements.

1.1 Site description

The Sleisbeck mine is one of the many small abandoned uranium mine sites located in the south of World Heritage listed Kakadu National Park. It is situated in the Katherine River catchment, ~30 km south east of Coronation Hill (Figure 1). Sleisbeck differed markedly from other uranium mines of the region in that it lies away from the Palette Fault, and is hosted by the Kapalga Formation (Stuart-Smith et al 1988).

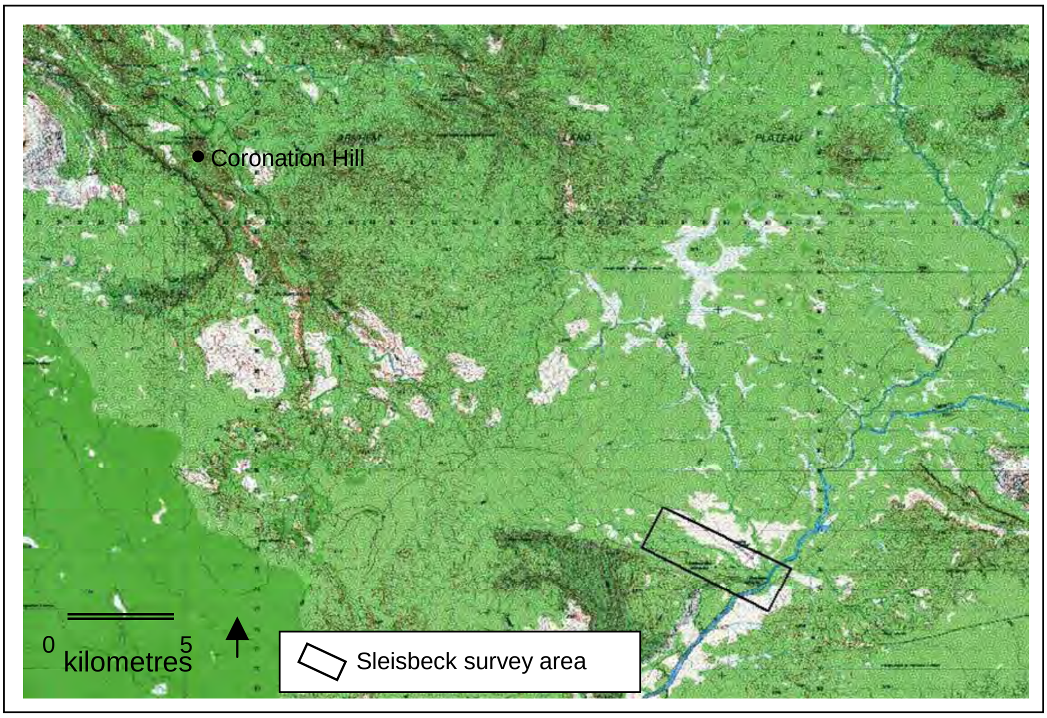


Figure 1 Location of the Sleisbeck survey area

George Sleis, a Czechoslovakian geologist discovered the Sleisbeck ore body in 1954 (Annabell 1977). It was subsequently worked in 1957 and owned by the North Australian Uranium Corporation. Although it was thought to be a major find at first, only 3 tonnes of

U_3O_8 were produced at Rum Jungle, from ~600 tonnes of uranium ore mined at Sleisbeck. The Sleisbeck mine workings consisted of an open pit approximately 100 m x 30 m in dimensions. The pit retains water throughout the year. A 5 m high wall with residual exposed uranium mineralisation is located on its eastern side. This mineralisation is largely confined to a small (~1.5 m x 4 m) hollow in the wall, which currently can only be accessed by boat from the pit. There are three major 'truck dumps' approximately 100 m to the south western side of the pit (Figure 2). They contain overburden and waste rock with low grade uranium mineralisation (Pfitzner et al 2003).

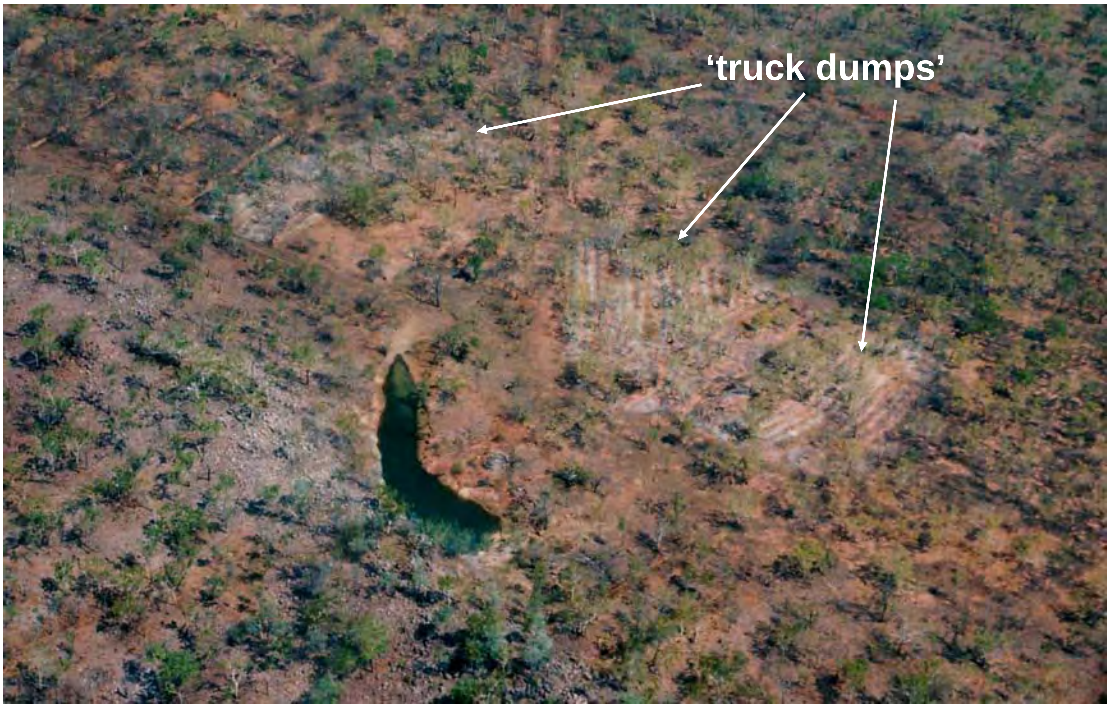


Figure 2 Aerial view of the Sleisbeck pit and waste rock dumps ('truck dumps'), 2002

1.2 Background

In 1997 a preliminary radiological survey was conducted by ***eriss*** at the request of Parks Australia North and Internal Report 284 was produced (Tims & Ryan 1998). Subsequently SSD and PAN commissioned UTS Geophysics to conduct a low-level airborne geophysical radiometric survey over the abandoned Sleisbeck mine on 30^{th} July 2002 (Pfitzner et al, 2003). Data were collected in the AGD84 coordinate system, within Zone 53 with a central meridian of 135 degrees. The boundary coordinates for the survey were: 263050 8477960, 268850 8475020, 267900 8473150 and 262100 8476090. The data were then reprojected to UTM GDA94, Zone 53.

Airborne radiometric data (eU, eTh, K and total count measures), magnetic, and digital elevation data were collected. A total of 650 line km of data was obtained. The airborne gamma survey results are summarised in Pfitzner et al (2003). Quickbird high resolution satellite data were also acquired (Figure 3) in order to relate the airborne count rates to land cover features. A ground gamma radiation survey was carried out by SSD staff on June 23 2003, to obtain more accurate data for the 'hot spot' areas identified by the airborne gamma survey and to develop a correlation to transform the airborne data to terrestrial gamma dose rates and soil radionuclide activity concentrations, respectively. A final ground survey was conducted on 18 July 2006. The results of the ground truthing are summarised in this report.

A rehabilitation strategy has been agreed on by Parks Australia and stakeholders and is reported in Part A of the rehabilitation plan for the South Alligator River Valley sites (Stockton et al 2003). At Sleisbeck it is planned to remove the dumps, place the material back into the original pit and then cover with compacted clean fill. A key aspect of planning for rehabilitation is to determine the volume of material that needs to be relocated to the pit and covered, in order to lower radiation doses received when accessing the area. Given that the dumps have been weathering on the land surface for decades it is possible that radionuclides have been leached into the underlying soil profile and the volume of material needing to be excavated could be much larger than indicated by the surface radiometric signature. Hence, trenches were dug at the identified hot spots in September 2006, and samples were taken down the wall of the trenches to determine the vertical extent of leaching of radionuclides into the soil profile.

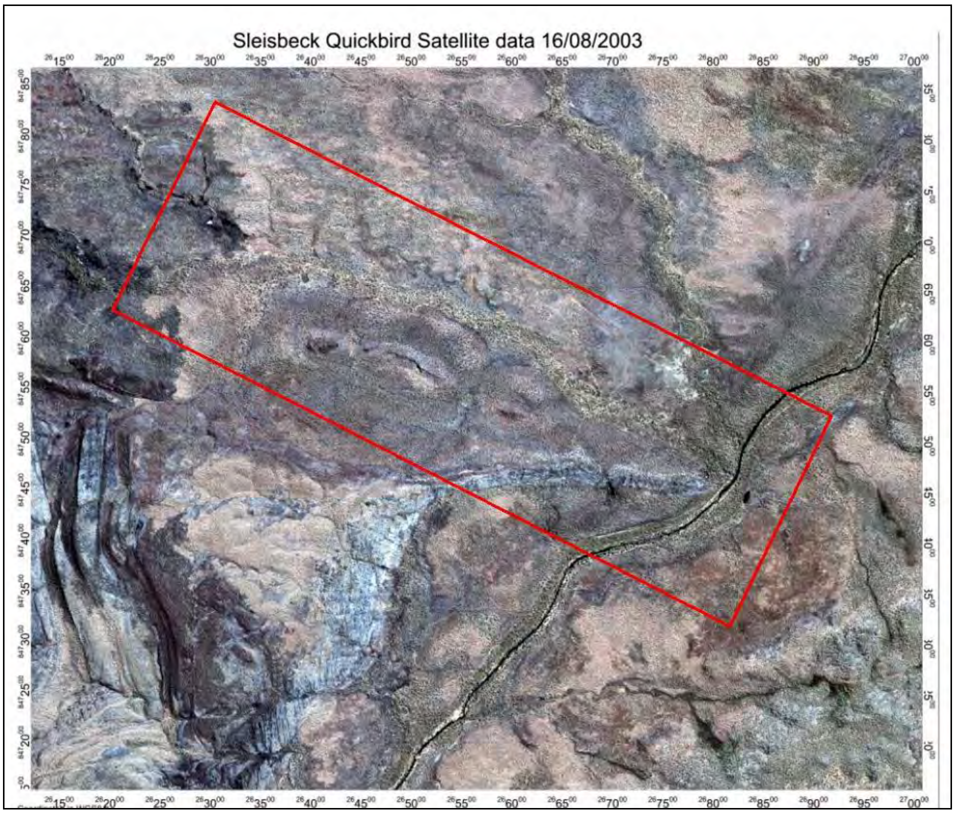


Figure 3 Quickbird satellite data coverage (with airborne gamma survey extent in red overlaid)

1.3 Radiological guidelines

The IAEA Safety Guide (No WS-R-3) recommends (IAEA 2003):

> 3.2 A generic reference level for aiding decisions on remediation is an existing annual effective dose of 10 mSv from all sources, including the natural background radiation. This will normally be assessed as the mean dose for an appropriately defined critical group. Remedial measures would often be justified below the generic reference level and national authorities may define a lower reference level for identifying areas that might need remediation.
>
> 3.3 If remediation is justified for dose levels below the generic reference level to reduce a dominant component of an existing annual dose, a reference level specific to particular components can be established on the basis of appropriate fractions of the generic reference level. Such specific reference levels (such as intervention levels and action levels) shall be subject to the

> approval of national authorities for particular situations of prolonged contamination that are amenable to intervention on the basis of the optimisation process specified in para. 3.1. Specific reference levels can be expressed in terms of the avertable annual dose or a subsidiary quantity such as activity concentration (Bq/g) or surface contamination density (Bq/cm^2).

Guideline values for rehabilitation of the South Alligator River Valley area have been recommended, and were subsequently approved by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) in 2006. These values are an external gamma dose rate of 7.5 μGy·hr^{-1} per hour, 35 Bq·g^{-1} soil uranium activity concentration and less then 10 mSv annual dose to an average member of the critical group, respectively (Stockton et al 2003). It has previously been shown for sites in the South Alligator River valley that there is no reason for intervention on radiological grounds alone, as annual radiation doses are low (Bollhöfer et al 2002a,b), the area is sparsely populated and access to many of the sites, including Sleisbeck, is restricted due to the remoteness and/or on cultural grounds. Nonetheless rehabilitation works have begun at the request of the Traditional Owners of the area.

2 Method

2.1 Remote sensing

Previous research at Nabarlek (Martin 2000, Martin et al 2006) and the South Alligator River Valley (Pfitzner et al 2001a,b) has shown the usefulness of high resolution airborne gamma survey (AGS) data for providing a radiological perspective at the landscape scale and for identifiying anomalously high gamma radiation areas for detailed gamma field-based work. Consequently, UTS Geophysics was commissioned to conduct a low-level airborne geophysical survey over the abandoned Sleisbeck mine. The geophysical data were collected along 25 m spaced flight lines, with 250 m tie line spacing. An Exploranium GR820 spectrometer was used, characterised by 48 litre detector volume, with a sampling frequency of 1 Hz. The altitude readings were collected with a radar altimeter, at a reported accuracy of 0.3 m, resolution of 0.1 m and sampling rate of 0.1 seconds.

A detailed description of the processing undertaken for the airborne gamma data can be found in Pfitzner et al (2003). Emphasis was given to the evaluation of the equivalent uranium (eU) data from the AGS. This channel represents gamma rays detected from the 1.73-1.76 MeV decay of Bi-214. As Bi-214 is a radioactive progeny of Ra-226, elevated count rates indicate the presence of Ra-226 in the soil, rather than uranium. Because it is the eU channel that is important for abandoned uranium minesite applications, a brief summary of the data analysis method applied to this channel is provided here. The eU channel is displayed as a ‘rainbow colour table’ and contrast stretched to emphasise the higher counts. Basic statistics are generated from the U channel data and used as a threshold into ten class ranges (counts/second), highlighting areas of higher counts.

Table 1 summarises the ranges used in the threshold (counts/s), the colour assigned, and the number of pixels associated with the particular threshold. Figure 4 illustrates these ranges, with counts less than 200 being displayed as grey scale. Figure 5 shows the Quickbird data acquired over the area in 2003 with the AGS data > 200 counts per second overlaid.

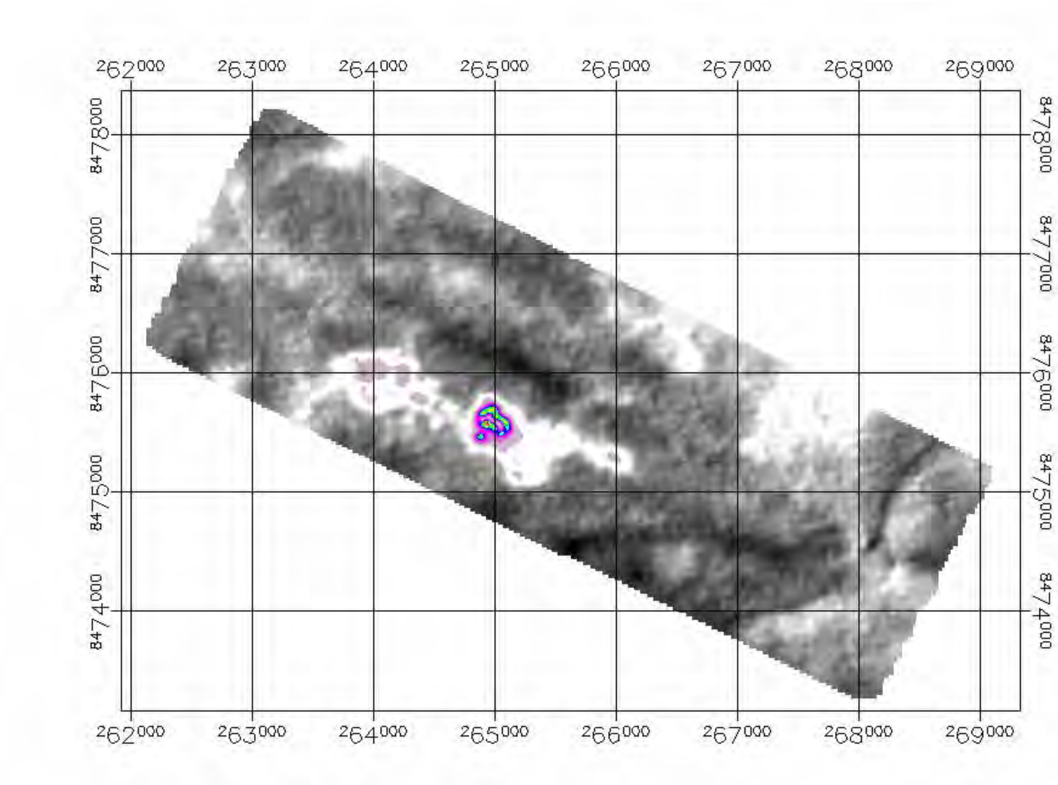


Figure 4 U Channel threshold of highest counts per second, with values of less than 200 counts per second, displayed as grey scale

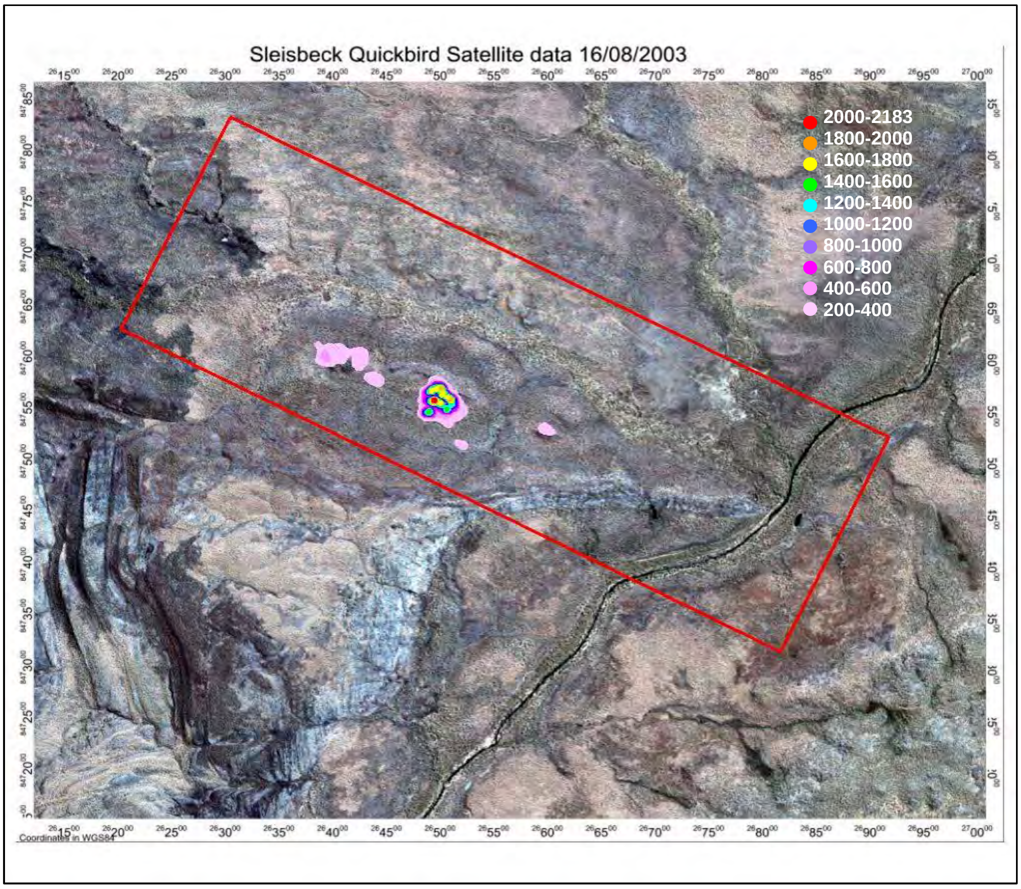


Figure 5 Quickbird satellite data coverage with airborne gamma > 200 counts per second overlaid

Table 1 U Channel thresholds associated with figures 4 and 5

Digital number range (counts/second)	Colour assigned	Number of pixels
2000-2183	Red	4
1800-2000	Orange	9
1600-1800	Yellow	48
1400-1600	Green	69
1200-1400	Cyan	88
1000-1200	Blue	112
800-1000	Purple	117
600-800	Magenta	160
400-600	Orchid	263
200-400	Violet	1367

2.2 Field work

2.2.1 Ground truthing, 26/27thJune 2003

During this first ground truthing excercise some preliminary readings of soil radionuclide activity concentrations and external gamma dose rates were taken, for comparison with the AGS results. The greater Sleisbeck area and in particular areas of higher airborne gamma signals were inspected visually.

The airborne survey results showed that areas of higher activity are primarily confined to the abandoned Sleisbeck mine, specifically the pit area and waste overburden dumps (Pfitzner et al 2003). The area in the vicinity of the pit and the truck dumps was surveyed at a relatively coarse resolution. In addition, other anomalies in the vicinity of the minesite (see Figure 5) were investigated. These areas were inspected visually and check measurements were performed. The areas are mostly associated with historic exploration activity around the old minesite, such as trenches (costeans) into naturally occurring uranium anomalies.

The ground-based gamma measurements were performed in the mid dry season when surface soil moisture content was very low. The portable 3’×3’ NaI(Tl) spectrometer collected 512 channel gamma data over the energy range 0–3 MeV. Three regions of interest were investigated, giving results for K-40, eU and eTh.

The hand held gamma spectrometer was refurbished and calibrated in October 2003 in Brno, Czech Republic, by SatisGeo s.r.o. Calibration constants were determined by the manufacturer using standard test pads. These calibration constants are used to convert count rates to nominal activity concentrations for K-40, eU (equivalent uranium) and eTh (equivalent thorium). The new calibration has shown that calibration constants had not changed significantly since the instrument has been acquired in 1999. A more detailed description of the hand held NaI detector and further information on the method of operation of the system is given in Lawrence (2005) and Geofizika (1998).

External gamma dose rates were measured using a Mini Instruments (6-80/MC-71) Environmental Radiation Meter. This instrument was calibrated by Australian Radiation Services Pty Ltd, by testing the response of the monitor to a collimated beam of gamma rays from a ^{137}Cs source. The results obtained in the calibration were typical for this type of instrument and complied with manufacturer’s specifications.

2.2.2 Ground truthing, 18th July 2006

Two transects (Line 2 and 3) were investigated in detail at the truck dump areas. These transects were chosen to count the greatest expected activity concentration gradients identified by the AGS. Both transects were approximately 300 m in length. Figure 6 shows an aerial view of the Sleisbeck mine, with the AGS eU data overlaid, and the location of the two transects and trenches A, B and C. Soil radionuclide activity concentration measurements, using the GS512 hand-held NaI gamma spectrometer, and external gamma dose rate measurements, using a Mini Instruments (6-80/MC-71) Environmental Radiation Meter, were taken approximately every 10–15 m.

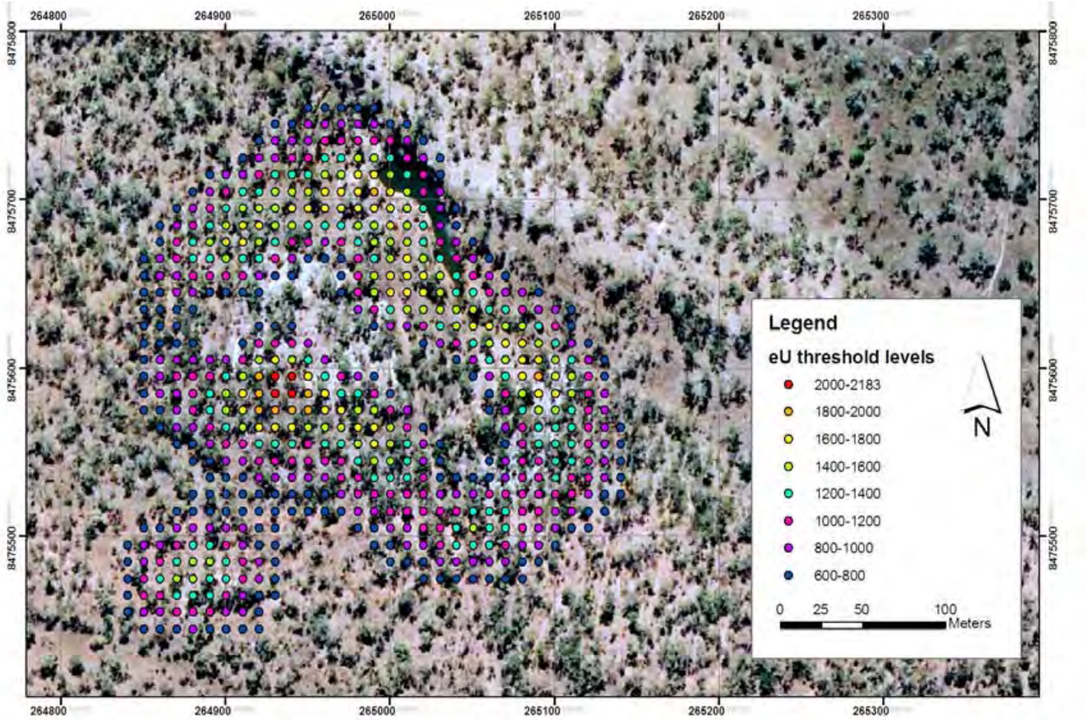


Figure 6 Aerial view of the Sleisbeck pit and waste rock dumps, 2002, with AGS eU data, location of the transects (Lines 2 and 3) and trenches A, B and C

Three major truck dumps (dumps #1–3) were identified immediately to the south of the pit. Additionally, two further dump areas (dumps #4,5) further south were identified from elevated gamma counts in the airborne uranium channel (cyan colour to the south in Figures 2 & 4), and during the 2006 field investigations. Figures 7 and 8 indicate the aerial extent of these areas. In addition, Figure 8 shows the location of transect lines 2 and 3.

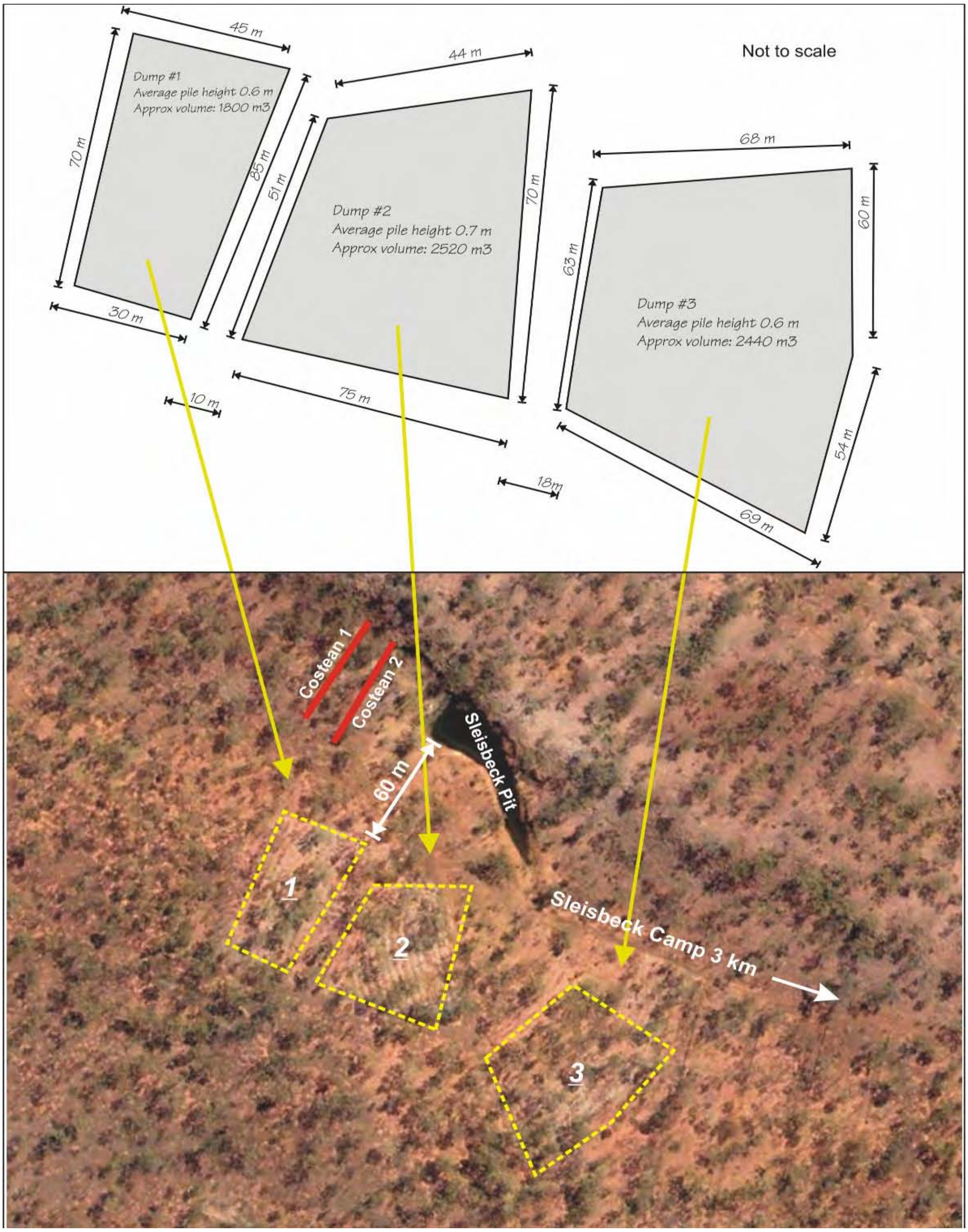


Figure 7 Approximate location and extent of truck dumps 1, 2, and 3, respectively. Satellite data from Google Earth 2005.

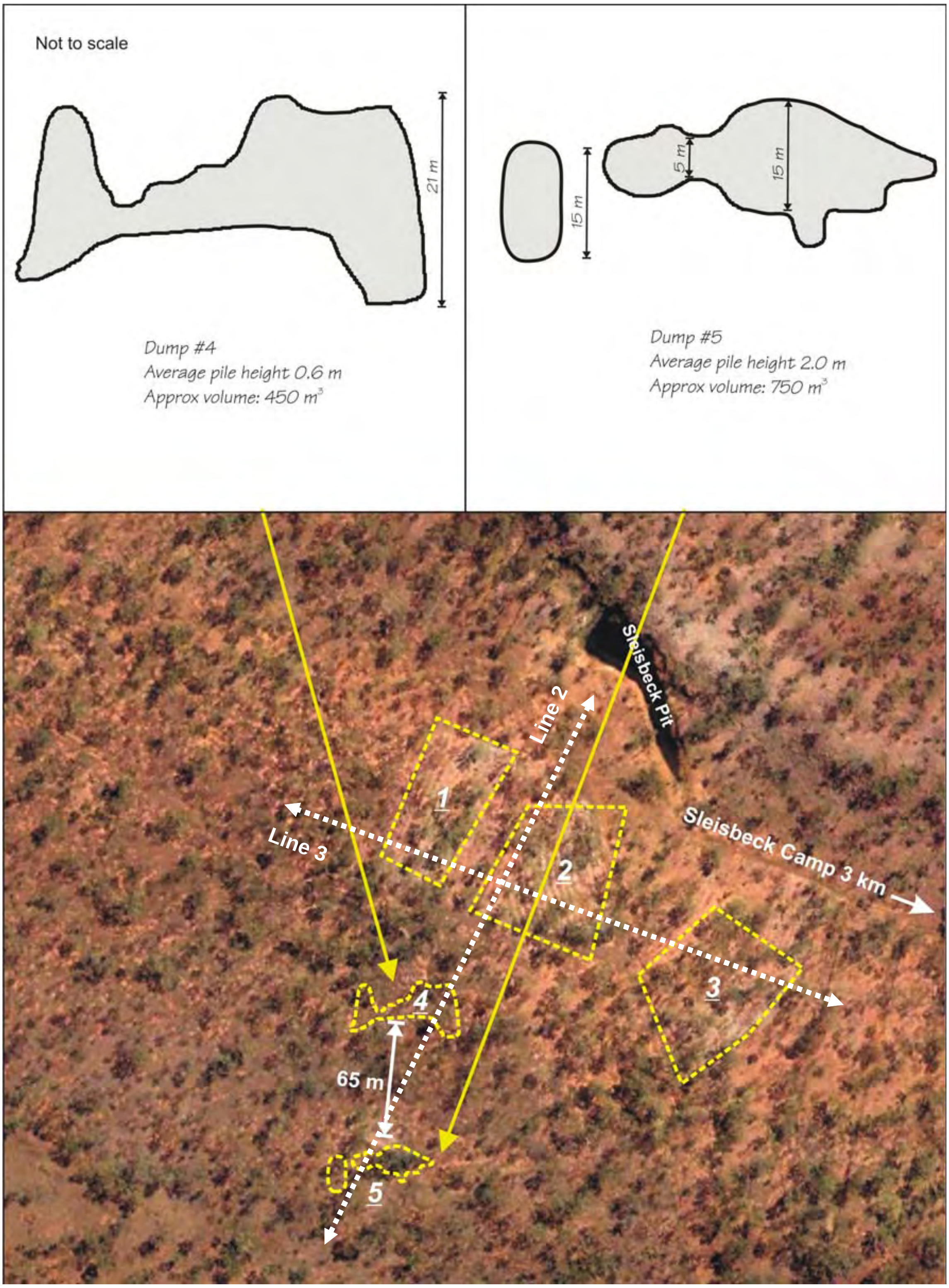


Figure 8 Location and extent of truck dumps 4 and 5, and transect lines 2 and 3, respectively. Satellite data from Google Earth 2005.

2.2.3 Fieldwork, 7th September 2006

During the fieldwork in July 2006, it was attempted to take three soil cores in the area of highest readings on the truck dumps using ***eriss***'s hand auger coring equipment. However, no cores could be obtained by this method owing to the hard hard ferricrete near surface layer.

Consequently, a back-hoe was used to dig three trenches (at sites A, B and C in figure 6) and samples were taken along the walls of the trenches, to investigate leaching of radionuclides from the overlying waste into the underlying soil profile. Figure 9 shows a photo of the soil profile in trench A. The height of the dumped material is between 0.5–0.7 m above original ground surface at the areas investigated.

Figure 9 Trench A

Qualitative measurements of surface radioactivity along the trench walls were performed in the field, using an Automess Model 6150 AD5/H Dose Rate Meter with a 6150AD-17 Alpha-beta-gamma contamination probe. These measurements were performed to get information on the required sampling depth along the trench walls. Figure 10 shows the measured activities, in counts per second, along the trench walls. These measurements indicated that horizons of high radioactivity do not extend much further beyond the dump-soil interface.

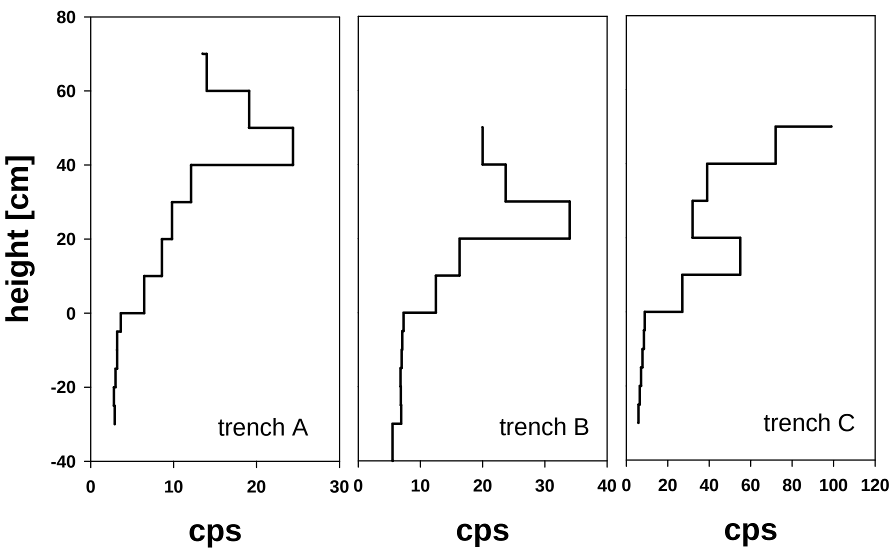


Figure 10 Surface activity readings (counts per second) in trenches A, B and C

2.3 Gamma spectrometry of soil samples

Scrape samples were taken along the walls of the trenches and characterised using gamma spectrometry. ^{238}U, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{210}Pb and ^{40}K activities in the samples were determined using the High Purity Germanium (HPGe) gamma detectors in the Environmental Radioactivity section at ***eriss***. Procedures for measurements of radionuclide activity concentrations via gamma spectroscopy at the Environmental Radioactivity laboratory are described in Marten (1992a). Samples are dried, milled, and pressed into standard geometries using a hydraulic press. The measured and background-corrected count rates are compared to measurements of standards with known activity concentrations, to determine the activity concentration of the samples. The stability of the detectors is checked fortnightly with a multi isotope standard containing radionuclides of the uranium and thorium decay chains. Detection limits for the geometry used are approximately 15 Bq/kg for ^{238}U and ^{210}Pb and approximately 3.5 Bq/kg for ^{226}Ra, ^{228}Ra and ^{228}Th (Marten, 1992a).

Results calculated using in-house software contain the radionuclide activity concentrations of the long-lived progeny of uranium series, thorium series and miscellaneous other photo peaks, such as ^{40}K.

3 Results

3.1 Airborne gamma survey

Data evaluation and results of the airborne gamma survey are discussed in detail in Pfitzner et al (2003). Measurements are taken at a frequency of 1 Hertz, which results in measurements taken at approximately every 50 metres along the flight line. Hence, the best true spatial resolution that can be expected from the AGS is 25–50 m. Areas in between the measurements are interpolated, to result in a 7 x 7 m pixel grid.

Figure 5 shows the AGS eU counts per second > 200 overlaid on the Quickbird data. In summary, the highest counts are observed around the pit, with count rates up to 2183 counts per second surrounded by lower count rates. A closer look at the pit area and the location of field-based measurements from 2003 are provided in Figure 11 (which is a subset of Figure 5). Figure 12 shows an enlargement of the area to the east, and Figure 13 shows an enlargement of the area to the north west of the pit, respectively, where count rates up to the 400–600 counts per second threshold are observed.

3.2 Ground-based measurements

Tables 2 and 3 give a summary of the near surface soil radionuclide activity concentrations measured in 2003 and 2006. Activity concentrations are given in $Bq \cdot kg^{-1}$ and have been calculated using the calibration constants determined by the manufacturer of the GS-512 portable gamma spectrometer. External gamma dose rates were determined using the Mini Instruments (6–80/MC-71) Environmental Radiation Meter. Terrestrial gamma dose rates were calculated by subtracting a value of 0.07 $\mu Gy \cdot hr^{-1}$ for the cosmic ray background, which has previously been obtained for the Alligator Rivers Region (Marten 1992b).

Two transects on site were chosen in 2006 for ground truthing of the airborne gamma survey data. The transects included areas with specifically high readings in the eU channel of the airborne gamma survey (see Figure 11). They were selected on the basis of greatest expected gradient of soil equivalent uranium activity concentration. Some data from 2003 were included in the 2006 ground truthing of the AGS data as well.

Figure 14 shows the equivalent uranium concentrations measured at areas other than the pit. These areas are shown in figure 12 (L2P1-P3) and figure 13 (L3P1-P4). The sites were investigated in 2003 and the elevated signals in those areas was mostly associated with exploration trenches dug into areas of higher natural radioactivity, and smaller hills and/or dumps. The average whole body external gamma dose rate amounts to 0.11 μSv·hr^{-1} at the Line 2 areas (undisturbed area measured in 2003 along the slope of a small hill), and 0.4 μSv·hr^{-1} at the dumps and trenches along the track.

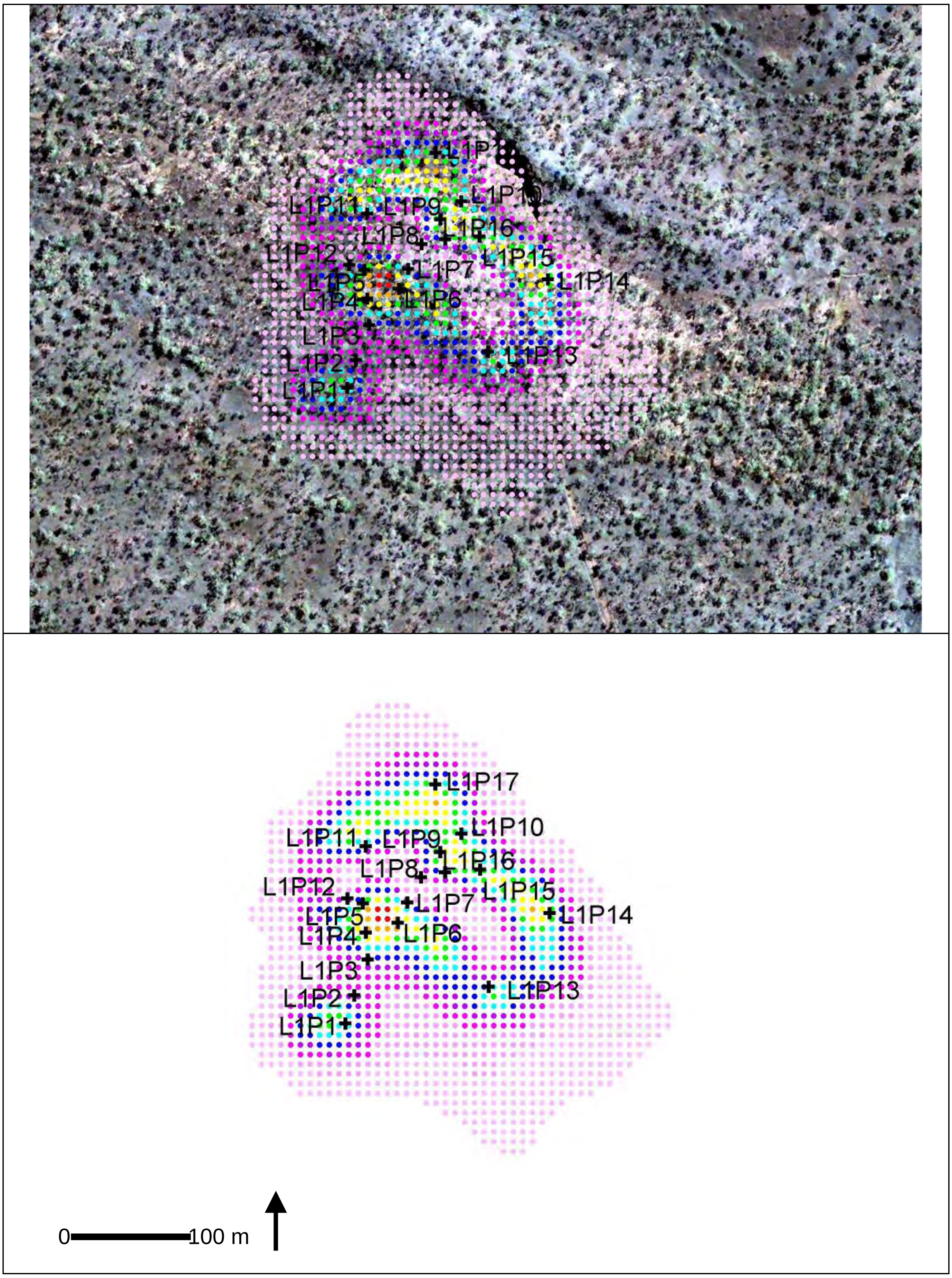


Figure 11 Subset of Figure 4, highlighting the pit and low level dump areas, with airborne gamma > 200 counts per second overlaid, and the location of the 2003 groundbased measurements

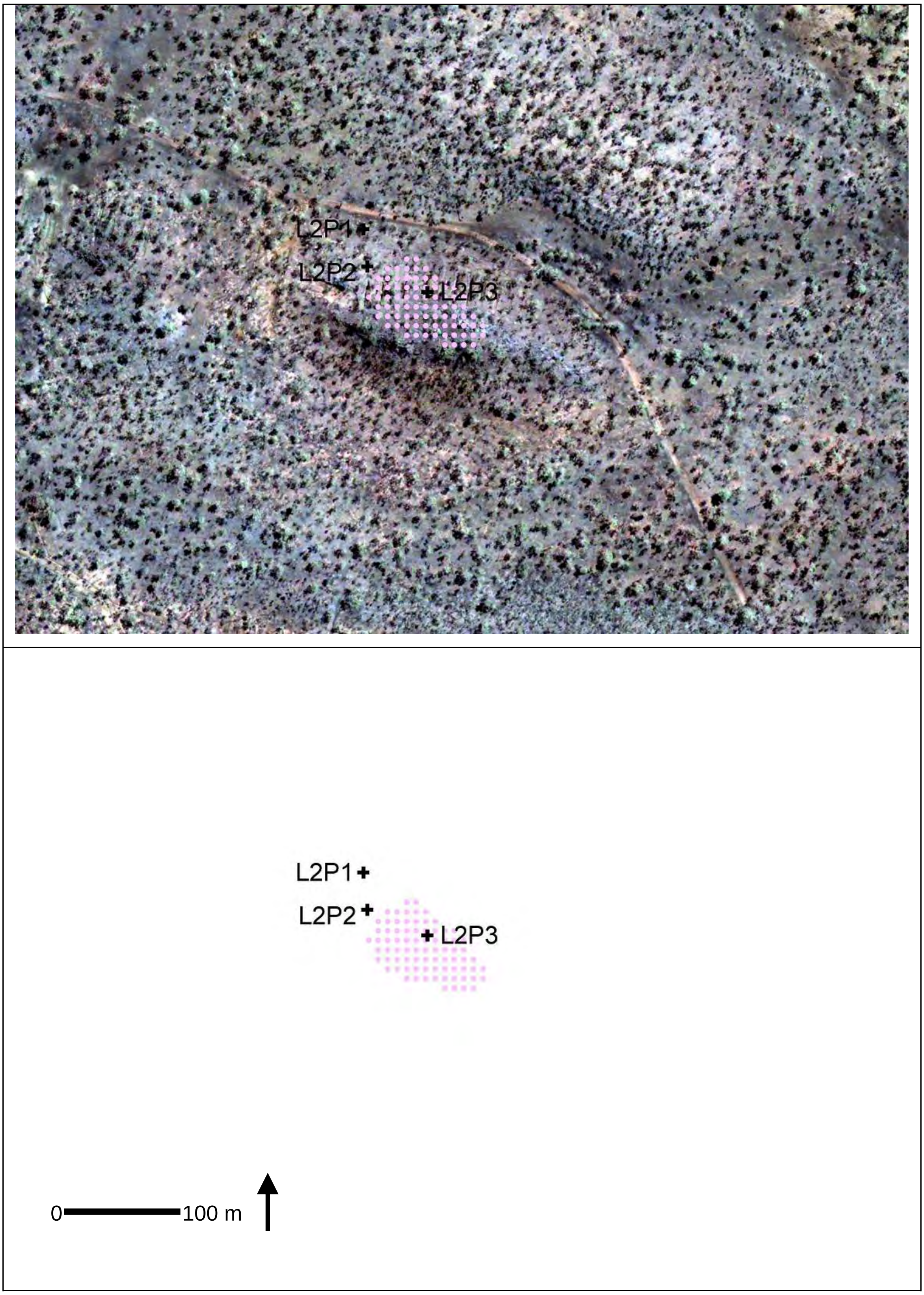


Figure 12 Subset of Figure 4, highlighting the area to the east of the pit, with airborne gamma > 200 counts per second overlaid, and the location of the 2003 groundbased measurements

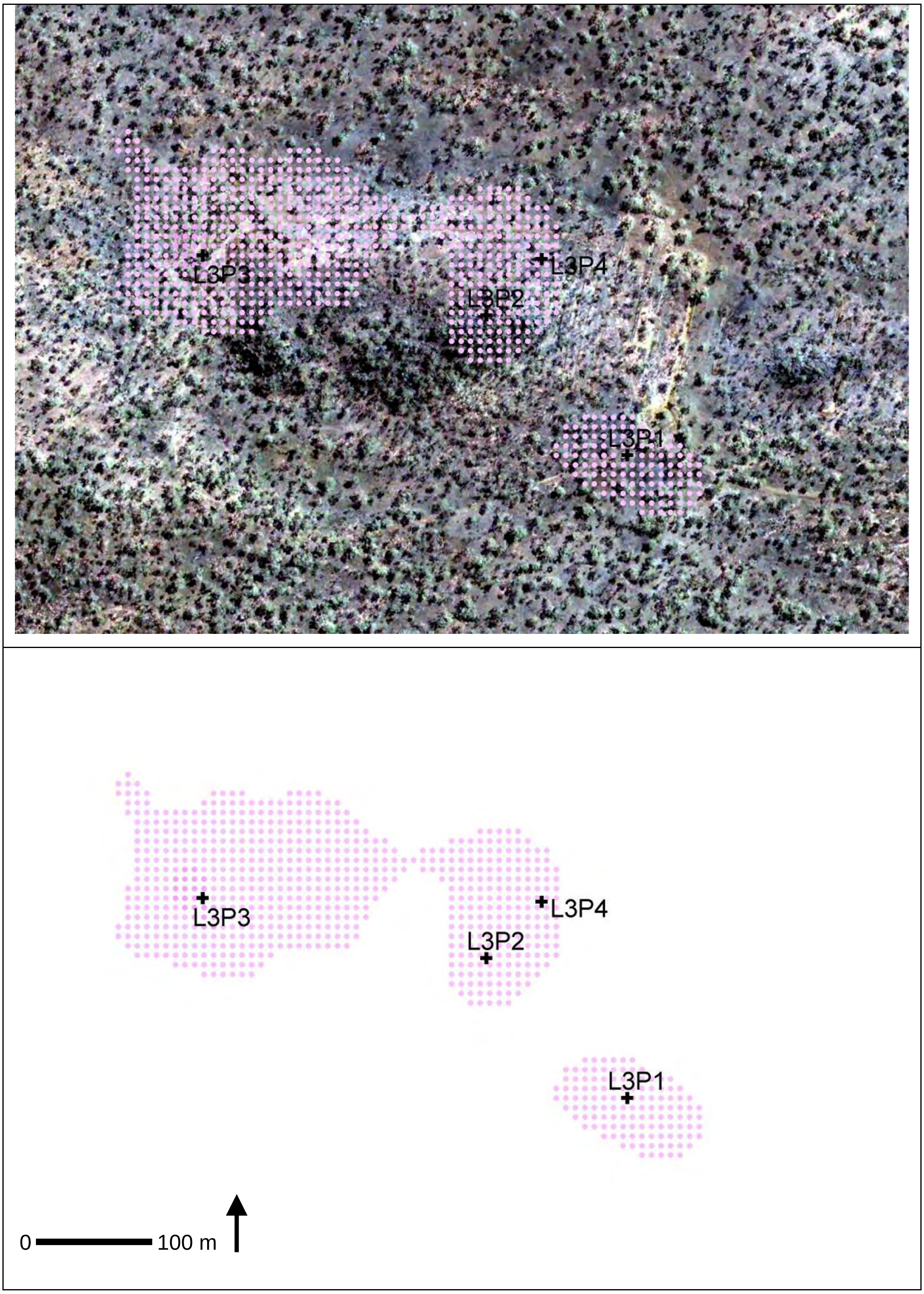


Figure 13 Subset of Figure 4, highlighting the area to the north west of the pit, with airborne gamma >200 counts per second overlaid, and the location of the 2003 groundbased measurements

Table 2 Soil radionuclide activity concentrations and terrestrial gamma dose rates measured 26/27 June 2003 in the Sleisbeck area

	easting	northing	K	+-	U	+-	Th	+-	Dose rate	+-
LINE 1			[Bq·kg^{-1}]		[Bq·kg^{-1}]		[Bq·kg^{-1}]		[µGy·hr^{-1}]	
030626-L1P1	53264897	8475477	656	74	3421	21	70	4	1.74	0.05
030626-L1P2	53264906	8475506	137	17	144	5	19	2	0.13	0.02
030626-L1P3	53264920	8475543	274	51	1660	15	25	3	0.64	0.03
030626-L1P4	53264918	8475571	101	21	254	6	20	2	0.19	0.02
030626-L1P5	53264915	8475601	N/A	N/A	20168	306	1161	74	7.56	0.09
030626-L1P6	53264951	8475581	1116	57	2151	16	57	3	0.88	0.04
030626-L1P7	53264961	8475602	N/A	N/A	16903	280	924	67	6.94	0.09
030626-L1P8	53264975	8475628	1262	586	6399	170	202	34	2.41	0.06
030626-L1P9	53264995	8475654	79	30	540	9	16	2	0.29	0.03
030626-L1P10	53265017	8475673	115	36	833	11	11	2	0.40	0.03
030626-L1P11	53264918	8475660	293	680	8894	200	287	41	3.40	0.07
030626-L1P12	53264899	8475606	N/A	N/A	N/A	N/A	N/A	N/A	3.20	0.06
030626-L1P13	53265045	8475515	1232	645	7803	187	250	38	2.45	0.06
030626-L1P14	53265108	8475591	1050	62	2299	18	56	3	0.87	0.04
030626-L1P15	53265036	8475636	192	27	692	8	17	2	0.35	0.03
030626-L1P16	53265000	8475633	301	42	404	11	23	3	0.28	0.02
030626-L1P17	53264990	8475724	938	0	934	0	46	0	0.53	0.03
LINE 2										
030627-L2P1	53265915	8475386	177	14	58	3	20	2	0.06	0.02
030627-L2P2	53265919	8475347	169	19	74	5	13	1	0.08	0.02
030627-L2P3	53265982	8475320	121	0	184	0	14	0	0.12	0.02
LINE 3										
030627-L3P1	53264375	8475805	563	53	1720	15	43	3	1.14	0.04
030627-L3P2	53264227	8475952	732	32	1326	9	60	2	0.46	0.03
030627-L3P3	53263929	8476015	108	17	626	5	20	2	0.32	0.03
030627-L3P4	53264285	8476011	162	0	127	0	17	0	0.07	0.02

Table 3 Soil radionuclide activity concentrations and terrestrial gamma dose rates measured 18 July 2006 in the Sleisbeck area

LINE 2	easting	northing	K [Bq·kg^{-1}]	+-	U [Bq·kg^{-1}]	+-	Th [Bq·kg^{-1}]	+-	Dose rate [µGy·hr^{-1}]	+-
060718-L2P1	264874	8475438	103	16	143	5	19	2	0.20	0.01
060718-L2P2	264879	8475451	230	37	955	11	24	2	0.68	0.03
060718-L2P3	264885	8475464	525	55	2084	17	51	3	1.01	0.03
060718-L2P4	264890	8475477	1109	68	3178	20	86	4	1.50	0.04
060718-L2P5	264899	8475492	198	22	287	6	26	2	0.25	0.02
060718-L2P6	264902	8475504	194	17	162	5	18	2	0.18	0.01
060718-L2P7	264908	8475523	135	17	152	5	24	2	0.22	0.01
060718-L2P8	264911	8475530	174	18	184	5	22	2	0.23	0.02
060718-L2P9	264918	8475543	457	44	1334	13	35	3	0.71	0.03
060718-L2P10	264922	8475558	152	21	274	6	25	2	0.27	0.02
060718-L2P11	264931	8475571	160	24	366	7	23	2	0.33	0.02
060718-L2P12	264943	8475582	287	32	680	10	27	2	0.44	0.02
060718-L2P13	264947	8475592	1128	46	1298	13	58	3	0.72	0.03
060718-L2P14	264956	8475605	1757	74	7818	22	120	4	3.82	0.07
060718-L2P15	264955	8475608	N/A	N/A	N/A	N/A	N/A	N/A	7.22	0.09
060718-L2P16	264959	8475618	1529	63	2614	19	89	4	1.23	0.04
060718-L2P17	264968	8475627	1638	74	3681	22	113	4	1.63	0.04
060718-L2P18	264977	8475643	731	51	1743	15	44	3	0.60	0.02
060718-L2P19	264982	8475656	279	30	571	9	22	2	0.40	0.02
060718-L2P20	264987	8475668	341	35	804	10	26	2	0.49	0.02
060718-L2P21	264995	8475677	742	50	1676	15	43	3	0.76	0.03
060718-L2P23	264994	8475692	5143	601	6718	174	365	41	3.47	0.06
060718-L2P22	265003	8475695	1002	59	2361	18	54	3	1.13	0.03

Table 3 continued

LINE 3	easting	northing	K [Bq·kg^{-1}]	+-	U [Bq·kg^{-1}]	+-	Th [Bq·kg^{-1}]	+-	Dose rate [μGy·hr^{-1}]	+-
060718-L3P1	264852	8475646	131	16	69	5	17	2	0.16	0.01
060718-L3P2	264881	8475635	171	21	141	6	20	2	0.21	0.01
060718-L3P3	264894	8475632	296	38	569	11	24	3	0.42	0.02
060718-L3P4	264910	8475628	3117	122	5882	36	250	8	2.45	0.05
060718-L3P5	264923	8475621	5710	647	7839	188	412	44	3.60	0.06
060718-L3P6	264941	8475619	443	42	650	12	32	3	0.53	0.02
060718-L3P7	264952	8475614	1224	66	1654	19	67	4	0.91	0.03
060718-L3P8	264965	8475608	1544	87	2984	26	94	5	1.36	0.04
060718-L3P9	264981	8475603	1800	87	2912	25	99	5	1.83	0.04
060718-L3P10	264995	8475599	2491	106	4438	31	157	6	2.01	0.05
060718-L3P11	265010	8475594	1381	97	3890	29	110	6	1.73	0.04
060718-L3P12	265021	8475590	1037	91	3466	28	86	5	1.87	0.04
060718-L3P13	265035	8475585	1274	85	2884	25	86	5	1.12	0.03
060718-L3P14	265048	8475578	755	41	553	11	22	2	0.39	0.02
060718-L3P15	265066	8475576	585	55	1232	16	27	3	0.65	0.03
060718-L3P16	265080	8475569	2778	120	5749	36	206	7	2.91	0.06
060718-L3P17	265093	8475563	1845	100	3987	30	117	6	1.79	0.04
060718-L3P18	265107	8475558	223	36	501	11	24	2	0.35	0.02
060718-L3P19	265122	8475553	144	24	197	7	19	2	0.25	0.02

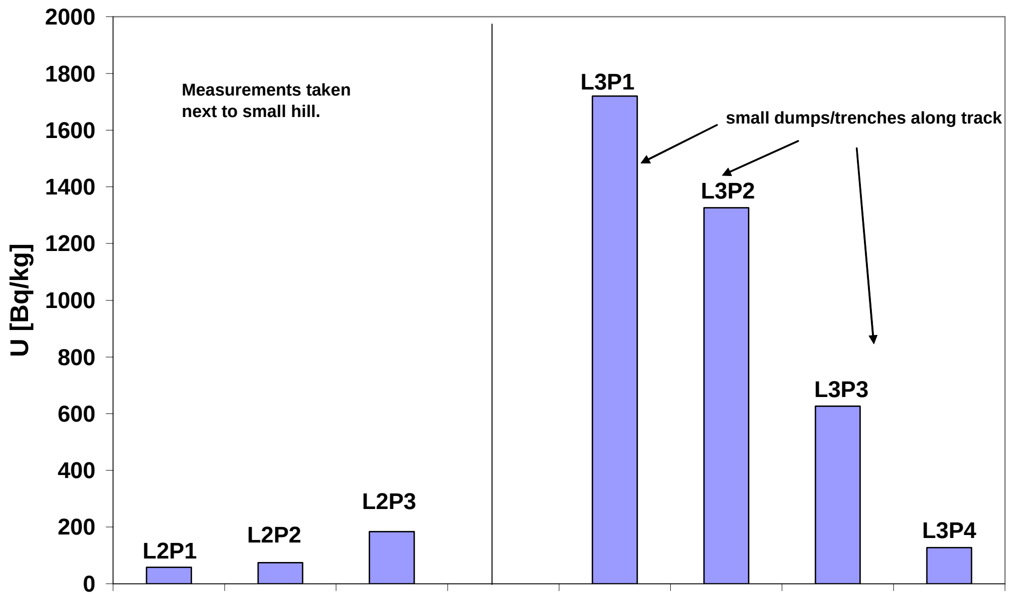


Figure 14 Equivalent uranium activity concentrations measured in 2003 at sites L2P1-L3P4

3.3 Comparison of AGS and ground-based measurements

It is important to note that direct comparison between airborne and ground based readings should be treated with caution, since the measurement footprints of the two methods are quite different (Martin et al 2006). Whereas portable NaI(Tl) and GM tube readings are made at 1 m height and the area that is measured is quite localised, the detector on board the aircraft had an average height above ground of approximately 40 m and flew an average distance of 54 m between measurements.

Table 4 gives a comparison of typical footprints of ground and airborne gamma surveys, assuming that the plane is stationary. Billings and Hovgard (1999) have discussed the effect and mathematical treatment of a moving plane in detail. The table illustrates the large difference in footprints and highlights the need to average ground-based readings for comparison with the aerial measurements.

Table 4 Comparison of typical footprints for ground based and airborne gamma surveys

	Altitude	Footprint, radius R	% signal from within R	Reference
Airborne gamma survey	50 m	50 m	40%	Duval et al 1971
Airborne gamma survey	30 m	36 m	56%	Billings & Hovgard (1999)
Ground gamma survey	1 m	2 m	56%	(IAEA 1989)

The best spatial resolution to be expected from our airborne gamma survey thus amounts to 25 to 54 m. Data along the ground transects were thus combined as five point running means to provide a similar order of magnitude (~45 m) of coverage. Figures 15 and 16 compare the five point running means of the ground-based measurements with the airborne data.

3.3.1 Line 2, 18th July 2006

This transect is 288 m long, and along a SSW-NNE direction. It covered the truck dumps and leads to the edge of the water filled pit. Readings on ground were taken approximately every 10–15 m. Some results from the 2003 ground survey are included in the comparison with the

AGS data as well (L1P1, L1P2, L1P3, L1P6, L1P7, L1P8) as some points from 2003 fell along the 2006 transect or were in close vicinity.

From the airborne gamma survey three areas of comparatively higher readings were expected. (see Figures 6 & 11). These areas were surveyed during the ground truthing in 2006. Looking closely at the raw ground truthed data (dashed lines in figure 15), a shift was observed of approximately 25 m, between the high eU area in the middle of the truck dump identified from the AGS (red pixels in Figure 11) and the actual position of the hot spot on ground.

The reason for this shift is most likely due to post-processing of the data from the AGS. Measurements are taken at a frequency of 1 Hertz, which results in measurements taken at approximately every 50 metres along the flight line. Hence, the best true spatial resolution that can be expected from the AGS is 25–50 m. Small scale variability of radionuclide activity concentrations on ground, much smaller than these dimensions, will not be resolved by the airborne gamma survey. Specifically at the Sleisbeck dumps, the variability of radionuclide activity concentrations is large and frequent, and investigations on ground show that hot spots of elevated gamma readings are common but quite localised.

In addition, individual pixels (7 x 7 m) are interpolated from the actual AGS line data, and the interpolated data may not necessarily indicate the exact position of, especially, localised areas with high count rates. Consequently, to fit the AGS to the groundtruthed data, the data measured along line 2 was shifted by approximately 25 m in between transect section 120–240 m, to optimise the similarity of the AGS with the five point running mean of the groundbased readings.

Figure 15 shows a comparison of the five point running means of the groundtruthed transect with the airborne gamma count rates [s^{-1}] in the eU, eTh and K channels, respectively, of the closest AGS pixel along the transect. Whereas the pattern of eU and ^{40}K in the AGS data closely resembles the ground truthed values, the eTh channel shows a some deviation from the AGS eTh data in the first 130 m of the transect.

3.3.2 Line 3, 18th July 2006

Line 3 is 285 m long and along a WNW-ESE direction. Line 3 crosses Line 2 in the vicinity of the area with highest airborne gamma eU readings.

Figure 16 shows the results and a comparison of the five point running means of the ground truthed transect (Line 3) with the airborne gamma count rates [s^{-1}] in the eU, eTh and K channels, respectively, of the closest AGS pixel along the transect.

It is apparent that Line 3 shows less pronounced variations along the transect compared to Line 2.

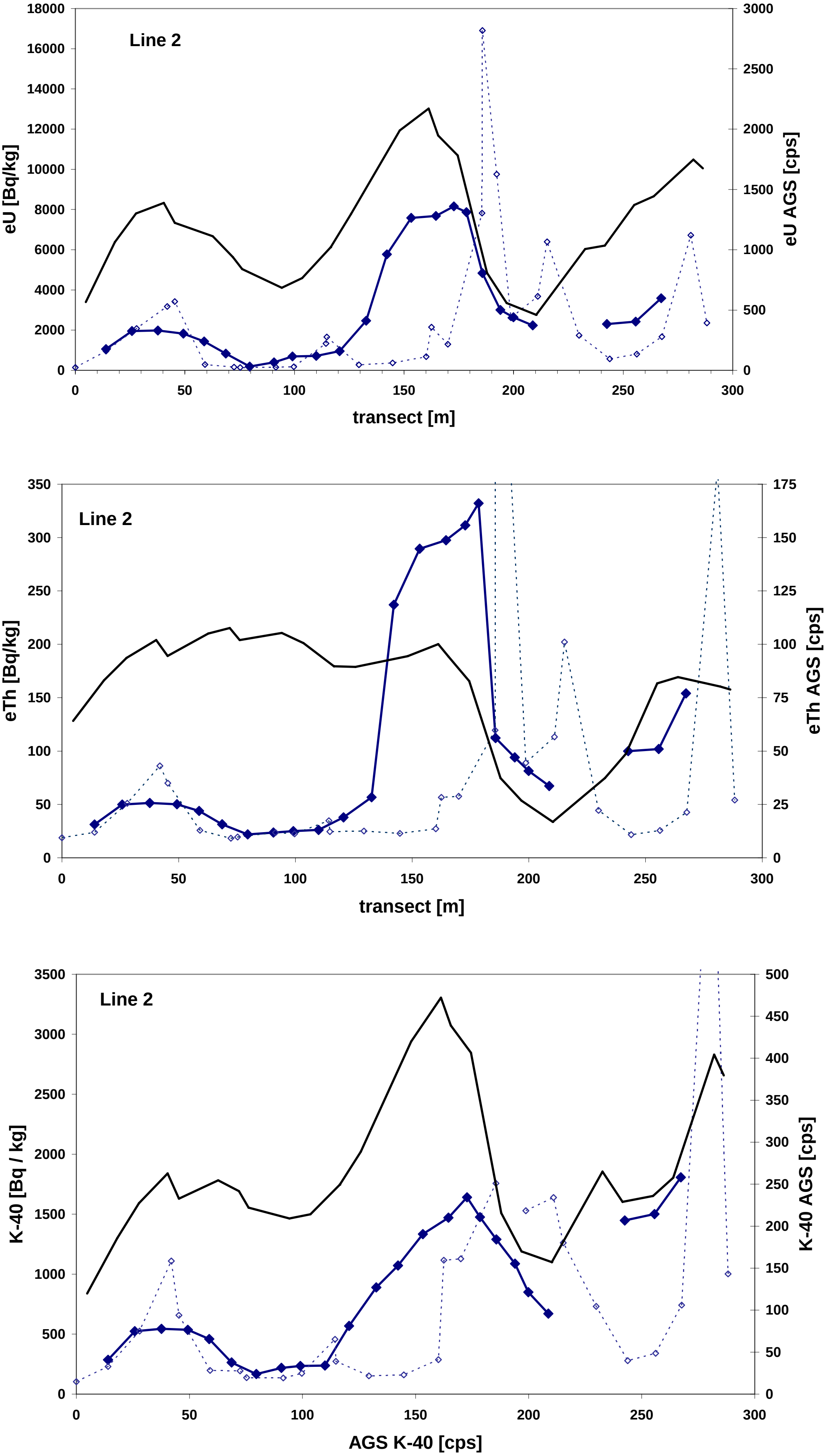
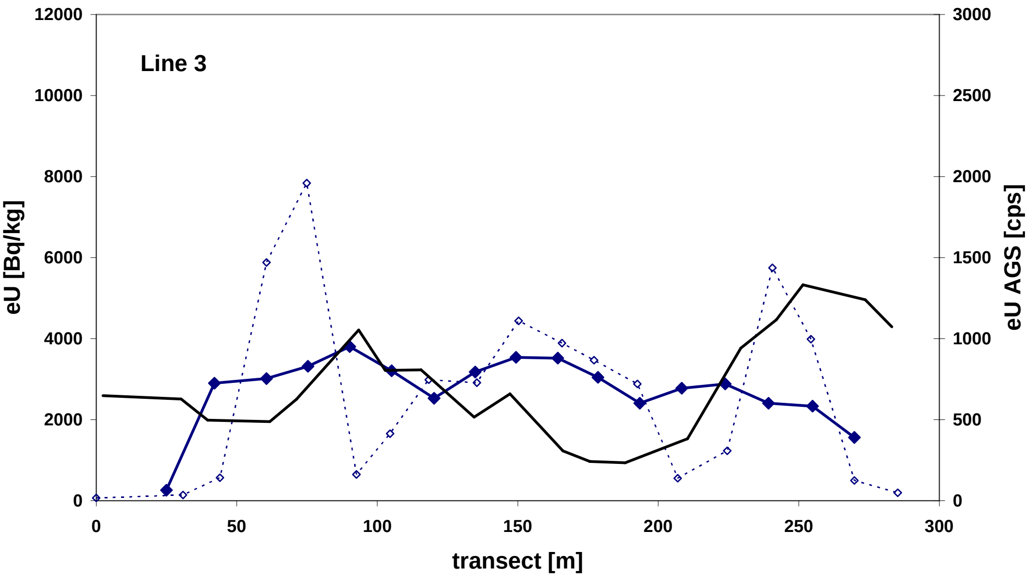
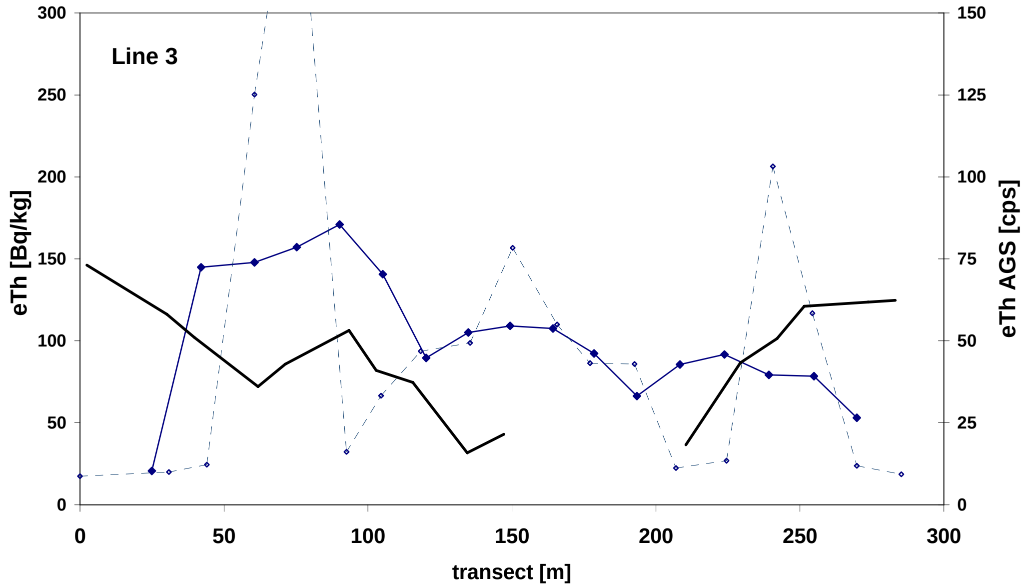


Figure 15 eU, eTh and K-40 for Line 2 (dashed), smoothed and shifted data (solid), and associated AGS data (thick line)





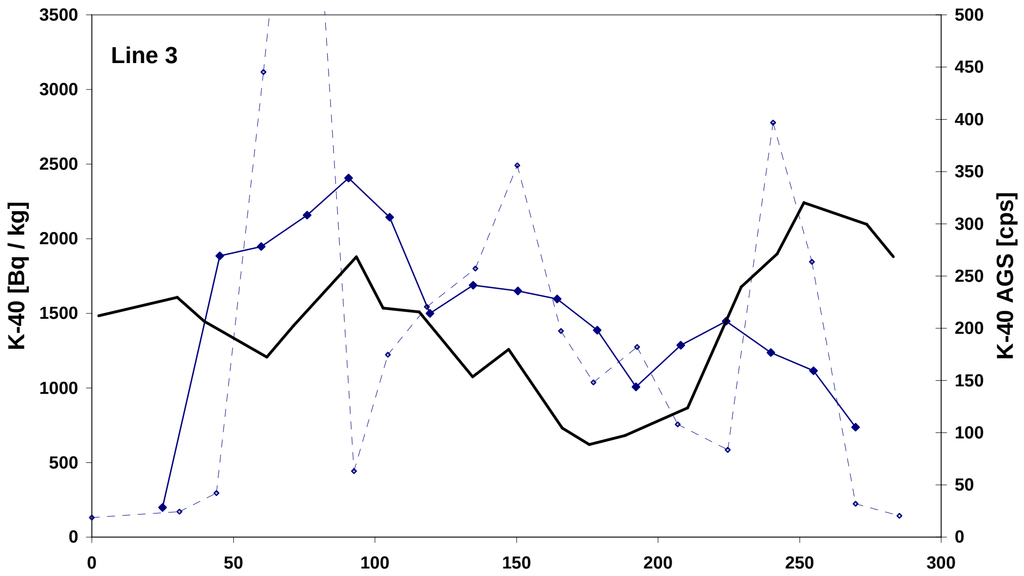


Figure 16 eU, eTh and K-40 for Line 3 and associated AGS data

3.4 Conversion of AGS data to area wide terrestrial gamma dose rate

The level of the terrestrial gamma dose rate in micro Grays per hour [$\mu Gy \cdot hr^{-1}$] can be determined using conventional Geiger Müller tubes, or via the measurement of uranium (^{238}U), thorium (^{232}Th) and potassium (^{40}K) activity concentrations in the soils. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000) recommends equation 1 to be used for the determination of the dose rate H_e in nano Grays per hour [$nGy \cdot hr^{-1}$], from soil activity concentration ($Bq \cdot kg^{-1}$) measurements:

$$H_e = a \cdot eU + b \cdot eTh + c \cdot K \qquad (1)$$

with:

a = 0.462 [$nGy \cdot hr^{-1}$ per $Bq \cdot kg^{-1}$]

b = 0.604 [$nGy \cdot hr^{-1}$ per $Bq \cdot kg^{-1}$]

c = 0.0414 [$nGy \cdot hr^{-1}$ per $Bq \cdot kg^{-1}$].

The conversion factors, a, b and c, are average values, which depend on a number of site specific factors, such as soil moisture, elemental composition of the soil, variability of activity concentration with depth, and disequilibria in the decay chain (Martin et al 2006).

Using equation 1, ground based soil activity concentrations measurements have been converted into terrestrial gamma dose rates. The calculated dose rates have been compared to the terrestrial dose rates that were measured using the Mini Instruments, 6-80/MC-71 Environmental Radiation Meter. Figure 17 shows the results of this comparison. Calculated gamma dose rates are, on average, 9% higher than dose rates measured using the GM tube. This is most likely due to disequilibria in the uranium decay series in the stockpiles, and largely varying activity concentrations with depth (see Figure 20).

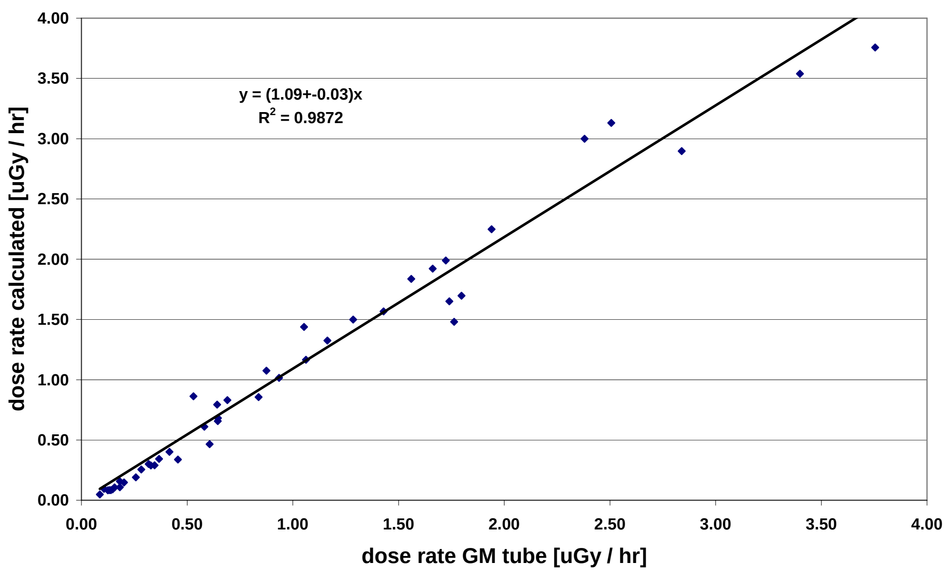


Figure 17 Comparison of calculated (using equation 1) ground based and measured (using Mini Instruments, 6-80/MC-71 Environmental Radiation Meter) gamma dose rates

The similar profiles observed of airborne count rates and groundbased activity concentrations for the transects, allow airborne count rates to be used to quantitatively determine soil activity concentrations and gamma dose rates, respectively, over the entire Sleisbeck area.

Figure 18 shows the five point running means of measured terrestrial gamma dose rates [$\mu Gy \cdot hr^{-1}$] plotted against the total counts [s^{-1}] from the airborne gamma survey for lines 2 and

3. A line was fitted and the 3-sigma test (indicated by the grey shading) was used to remove outliers that exhibited significantly higher dose rates on the ground due to the different footprints, and the line was re-fitted.

Applying this approach to the data, a conversion factor of total AGS counts to terrestrial gamma dose rate measured on ground of (0.060±0.014) nGy·hr^{-1}·s has been determined. An error weighted regression revealed a slope of (0.045±0.005) nGy·hr^{-1}·s, similar to the lower 95% confidence interval. In further discussion, a range of 0.045–0.060 nGy·hr^{-1}·s for the conversion of total counts to terrestrial dose rates has thus been assumed.

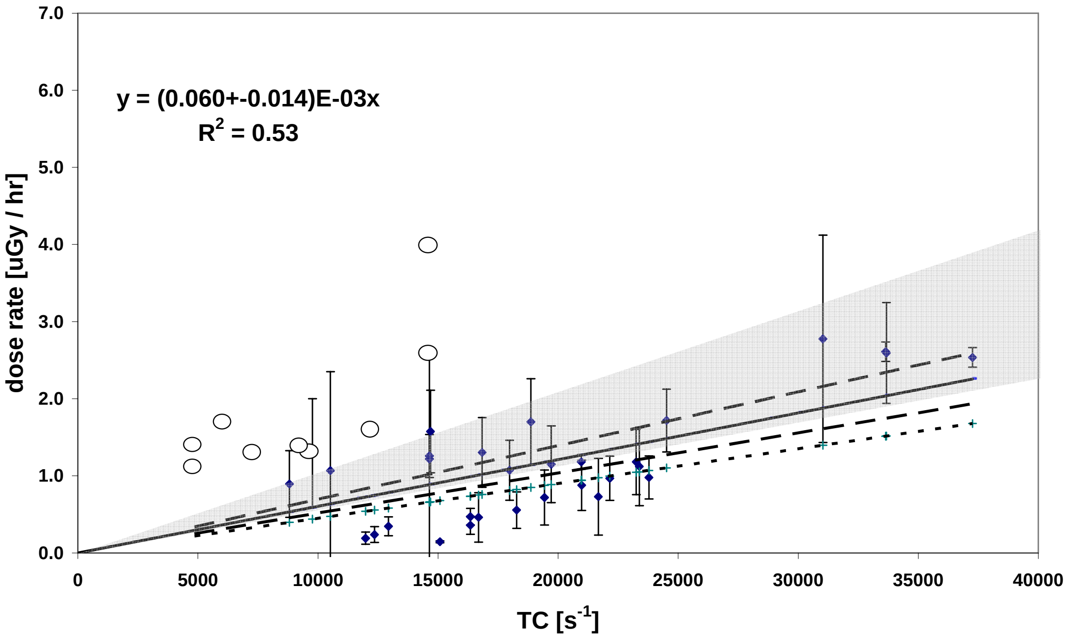


Figure 18 Airborne total gamma counts versus measured gamma dose rates on ground. Positive outliers (open circles, 3-sigma indicated by the shaded area) from the ground survey have been removed and the remaining data points used to derive the slope (solid) and 95% confidence interval (dashed). Error bars show one standard error of the mean of the groundbased measurements.

Similarly to dose rates, eU, eTh and K-40 soil activity concentrations can be determined from the airborne count rates in the respective channels. Figure 19 shows the near surface soil activity concentrations of eU, eTh and K-40, in Bq·kg^{-1} plotted versus airborne measurements in counts per second in the respective channel. Again, a 3-sigma test was used for eU and K-40 data to remove outliers that exhibited significantly higher activity concentrations due to the different footprints, and the line was re-fitted.

Using the conversion factors a, b and c, given in equation 1, and the slopes calculated from the regression lines to eU, eTh, and K-40 data, respectively (Figure 19), dose conversion factors [nGy·hr^{-1}·s] for the respective channels were calculated. Nuclide specific gamma dose rates were then added, and total dose rates compared with those inferred using the regression from Figure 18. Table 5 shows the results of this comparison, and average dose rates for the total area surveyed, environmental areas, and the Sleisbeck pit.

To estimate the average terrestrial background gamma dose rate a histogram (not shown) of airborne count rates [s^{-1}] was plotted. Assuming that the maximum of the distribution reflects the airborne counts detected at natural background areas, as most of the area surveyed is undisturbed, the resulting terrestrial background gamma dose rate amounts to 0.10–0.14 μGy·hr^{-1}. This is in agreement with terrestrial background gamma dose rates measured elsewhere in the region, such as Nabarlek (0.103 μGy·hr^{-1}, Martin 2000) or the South Alligator River Valley (0.06–0.14 μGy·hr^{-1}, Tims et al 2000).

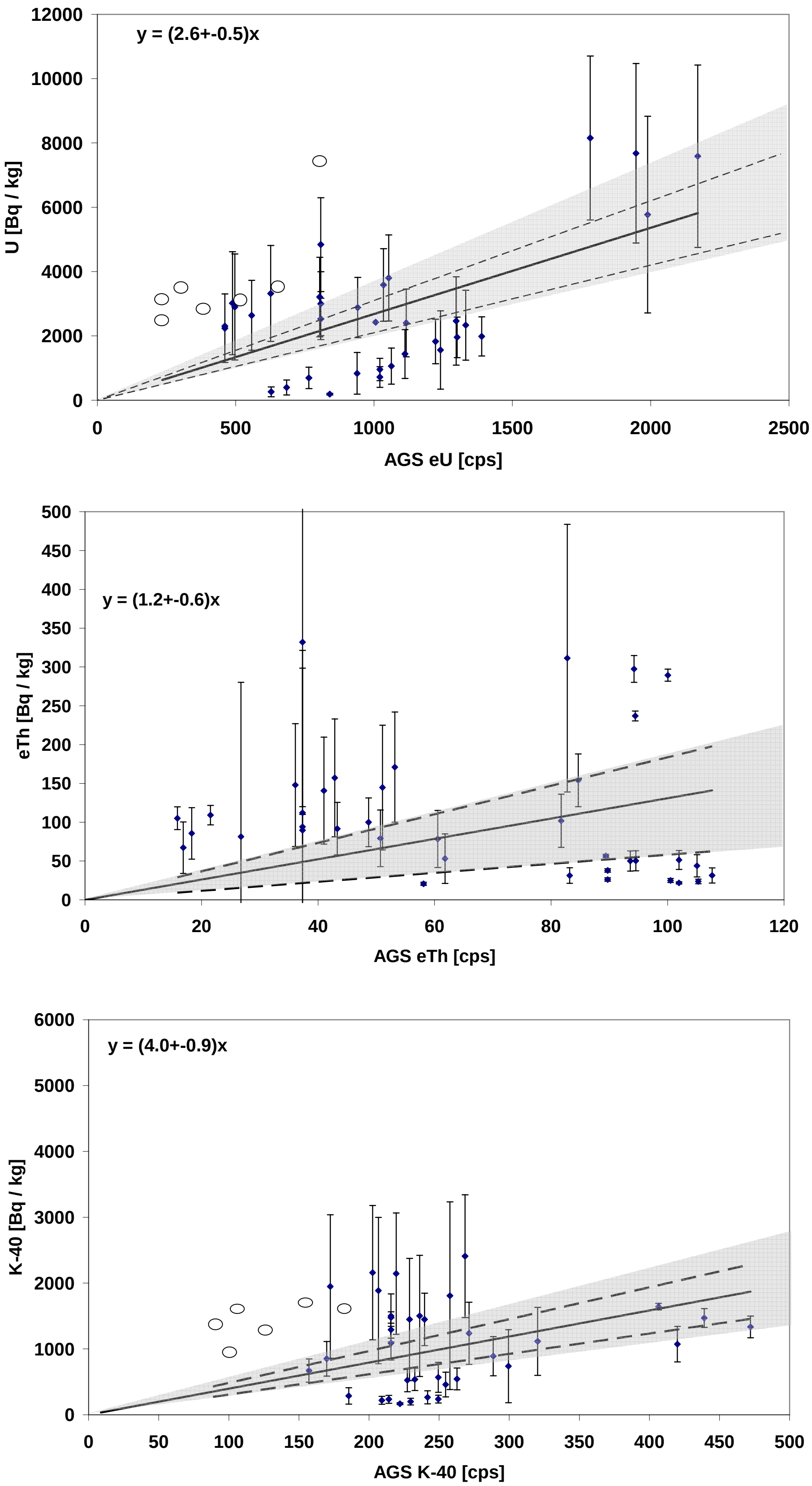


Figure 19 Airborne versus ground measurements for eU, eTh and ^{40}K. If positive outliers (3-sigma indicated by the shaded area) from the ground survey were rejected they are indicated by open circles and the remaining data points were used to derive the slope (solid) and 95% confidence interval (dashed). Error bars show one standard deviation of the mean of the groundbased measurements.

Table 5 Terrestrial gamma dose rates (total, and contribution from eU, eTh and K-40) in the Sleisbeck area calculated using the conversion factors determined from ground truthing the AGS data using the Mini Instruments, 6–80/MC-71 Environmental Radiation Meter, and the GS512 NaI(Tl) field gamma spectrometer. The Sleisbeck dump area annotates the area of the coloured pixels in Figure 10, and is much larger than the actual physical area of the truck dumps, which is only 1.2 ha.

Site	Area [ha]	γ dose rate [nGy/hr]	eU [nGy/hr]	eTh [nGy/hr]	K-40 [nGy/hr]	ΣeU,Th,K [nGy/hr]
Conversion factor [nGy·hr^{-1}·s]		*0.045–0.06*	*1.20±0.21*	*0.73±0.24*	*0.16±0.04*	
Total area surveyed	1558	123–165	101±18	67±22	11±2	179±28
Sleisbeck dump area	13	569–760	825±145	52±17	33±7	910±146
Environmental areas		104–142	82±14	57±19	7±2	146±24
Maximum		1697–2263	2610±459	195±64	87±19	2892±464

The removal of the dumped material in the vicinity of the Sleisbeck mine should result in an overall decrease of the terrestrial gamma dose rate from an average of approximately 0.6–0.8 μGy·hr^{-1} to levels of around 0.15 μGy·hr^{-1}. A groundbased gamma survey after the removal of the material is recommended to ensure that no residual material is left behind.

Given that the dumps have been weathering on the land surface for decades it is possible that radionuclides have been leached into the underlying soil profile and radionuclide activity concentrations may be enhanced below the original ground surface. If topsoils were significantly contaminated below the dump-soil interface, the volume of material needing to be excavated could be much larger than indicated by the surface extent. Hence, trenches were dug at the identified hot spots and samples taken down the wall of the trenches to determine the extent of leaching of radionuclides into the soil profile. This strategy is important from a remediation point of view to ensure that all of the contaminated material is removed and that any residual contamination of the underlying soil profile is also taken out.

3.5 Soil radionuclide activity concentration profiles

Figures 20 a–c show the activity concentrations of ^{238}U, ^{234}Th, ^{226}Ra and ^{210}Pb measured in trenches A, B and C, respectively. Table 6 shows the results including members of the thorium decay chain and ^{40}K. The results of the chemical analyses via ICPMS are shown in Table 7.

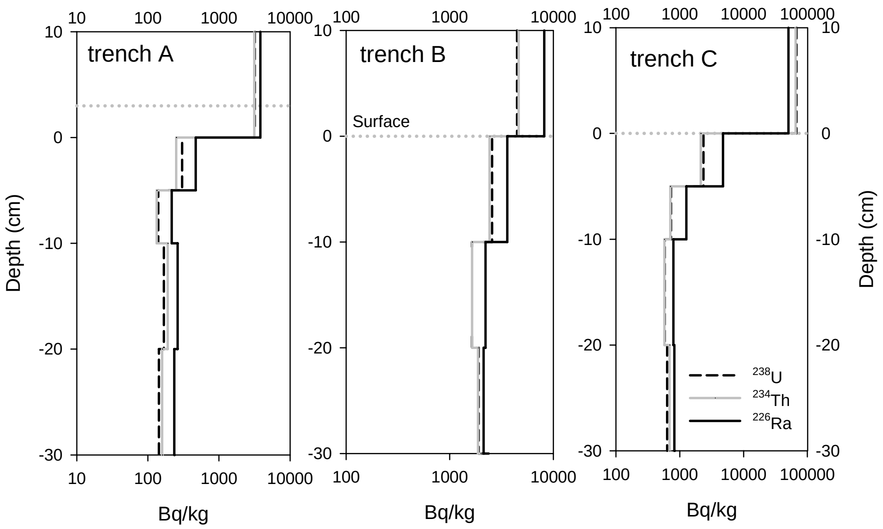


Figure 20 Radionuclide activity concentration profiles in trenches A, B and C

Table 6 Radionuclide activity concentrations [Bq·kg^{-1}] in samples from trenches A, B and C, respectively. Uncertainties given are 1 standard deviation from counting statistics only.

trench	**depth**	**sample**	**^{238}U [Bq·kg^{-1}]**	**^{234}Th [Bq·kg^{-1}]**	**^{226}Ra [Bq·kg^{-1}]**	**^{228}Ra [Bq·kg^{-1}]**	**^{228}Th [Bq·kg^{-1}]**	**^{210}Pb [Bq·kg^{-1}]**	**^{40}K [Bq·kg^{-1}]**
A	0 to 10	SL06005	3187±257	3136±135	3820±70	79±12	80±4	3378±152	1112±97
A	0 to -5	SL06006	303±48	250±18	470±10	12±5	29±2	428±23	155±29
A	-5 to -10	SL06007	140±33	133±13	216±5	26±4	30±2	380±20	90±23
A	-10 to -20	SL06008	168±37	191±15	263±6	23±5	32±2	373±21	130±26
A	-20 to -30	SL06009	143±32	159±13	236±5	37±5	29±2	238±16	129±25
B	0 to 10	SL06014	4467±434	4628±193	8156±148	145±15	108±5	4704±211	1064±100
B	0 to -10	SL06015	2560±231	2424±108	3594±66	52±13	50±5	2602±120	595±74
B	-10 to -20	SL06016	1637±149	1643±74	2217±41	12±9	45±4	1714±80	688±67
B	-20 to -30	SL06017	1900±159	1875±83	2124±40	43±10	64±4	1451±70	593±64
B	-30 to -40	SL06018	2226±176	2000±88	2378±44	47±10	39±4	1820±86	590±62
C	0 to 10	SL06024	67332±4361	65353±2557	50550±913	231±42	231±15	44183±1938	1486±204
C	0 to -5	SL06025	2355±256	2137±97	4760±87	16±12	21±5	3251±148	191±54
C	-5 to -10	SL06026	729±86	711±37	1272±24	23±7	17±3	1494±70	36±31
C	-10 to -20	SL06027	582±66	575±30	796±15	26±6	26±3	1363±63	79±27
C	-20 to -30	SL06028	634±68	689±36	823±16	25±6	19±3	907±48	126±28

Table 7 Metal concentrations [ppm] in samples from trenches A, B and C, respectively

trench	**depth**	**sample**	**Al ppm**	**As ppm**	**Ba ppm**	**Ca ppm**	**Zn ppm**	**Cu ppm**	**Fe ppm**	**K ppm**	**Mg ppm**	**Mn ppm**	**Mn ppm**	**Pb ppm**	**S ppm**	**Sr ppm**	**U ppm**
A	0 to 10	SL06005	53600	32	492	500	11.5	15.6	113000	22700	4090	13.9	14	132	540	192	228
A	0 to -5	SL06006	20700	26.5	74.5	100	8.5	10	120000	2450	810	106	98	9.4	40	8.4	19.2
A	-5 to -10	SL06007	19600	23	50.2	100	8	9.8	112000	2000	780	64.4	62	9.2	40	6.55	9.59
A	-10 to -20	SL06008	21000	23	66.8	130	7.5	9.8	106000	2000	950	62.5	59	8.8	40	7.25	12.3
B	0 to 10	SL06014	35300	12.5	163	16200	8.5	5.8	38200	16700	3110	29.9	29	68	40	99.8	367
B	0 to -10	SL06015	50500	18.5	423	820	35	11.8	48000	11800	5260	74.3	70	30	60	63.2	204
B	-10 to -20	SL06016	53600	11	296	570	80	8.8	52600	11600	11100	228	216	12.8	40	32.2	134
B	-20 to -30	SL06017	56500	8	358	580	93	8.4	67700	12400	11700	521	497	14.6	100	29.6	149
C	0 to 10	SL06024	70800	43.5	678	750	14	14.6	25100	28700	5250	23.1	23	177	60	370	5340
C	0 to -5	SL06025	17400	12.5	80	280	5	8.6	46700	3350	1020	63.3	60	11.4	40	22.9	177
C	-5 to -10	SL06026	15200	11.5	55.4	360	5	8.2	47600	1850	840	84.9	79	6.4	40	10.3	53.8
C	-10 to -20	SL06027	19400	15.5	54.8	190	5	9	62600	1950	940	48.4	46	7	40	8.15	44

Activity concentrations of uranium series radionuclides in trenches A and C drop by 1–2 orders of magnitude between +10 cm and -10 m depth of the profile, whereas profile B shows a less pronounced decrease. Metal profiles in the trenches behave similarly, with lead, copper, zinc, arsenic and strontium showing a marked decrease with increasing depth in trenches A and C, but a less pronounced decrease in trench B.

It should be noted here that trench B is not part of dumps 2 or 3. The trench was dug in a smaller soil heap that consisted of reworked material (possibly from the original truck dumps), with relatively loose soils exhibiting enhanced soil radionuclide activity concentration (060718-L2P23 in Table 3) close to the edge of the pit. There was strong evidence of some mixing in profile B, as well as some material from the top of the profile dropping into the underlying samples during sampling, which explains the less pronounced decline with depth in this profile.

Trenches A and C show, that the radionuclide activity concentration 0-5 cm below the soil surface are 10–30 times lower than activity concentrations of the mineralised material on top. The next slice in the profile (from -5 to -10 cm depth) is another factor of 2–3 lower in radionuclide activity concentration, however, there is no substantial decrease in samples further down the profile (-10 to -20 cm).

The current average terrestrial gamma dose rate across the footprint of the truck dumps amounts to 0.6–0.8 $\mu Gy \cdot hr^{-1}$ (see Table 5) but can be above 7 $\mu Gy \cdot hr^{-1}$ at localised areas. Assuming that 5 cm of the top soil profile is removed with the removal of truck dumps 1, 2 (trench A) and 3 (trench C) and assuming that the residual soil activity concentration of ^{238}U, ^{228}Th and ^{40}K is between 200–600 $Bq \cdot kg^{-1}$, 20–30 $Bq \cdot kg^{-1}$ and 40–130 $Bq \cdot kg^{-1}$, respectively, terrestrial gamma dose rate across the footprint of the truck dumps will be in the order of between 0.1–0.3 $\mu Gy \cdot hr^{-1}$ after rehabilitation of the truck dumps. This, however, is most likely an overestimate as the trenches were dug at identified hot spots in the area.

Recommendations

Although guideline values (35 000 $Bq \cdot kg^{-1}$ and 7.5 $\mu Gy \cdot hr^{-1}$) for the clean up of the radiological contaminated areas at the South Alligator River Valley are only exceeded at a few localised areas within the truck dumps at the Sleisbeck mine, it is recommended that all the mineralised material is removed and placed back in the pit. Material from areas with the highest measured soil activity concentrations in the vicinity of trenches A, B and C should be shifted first and placed in the bottom of the pit, progressively followed by material of lower radionuclide activity concentrations and capped by compacted clean fill.

The clean up will likely result in a low hill, closely resembling pre mining conditions. It is important to emphasise that the rehabilitation and backfill of the pit area is performed in a way such that the exposed hot spot in the mineralised pit wall (Tims & Ryan 1998) is covered by material with comparatively lower activity concentrations to reduce the risk of exposure to elevated gamma radiation. At the moment this hot spot can only be accessed by boat as the pit is filled with water. However, after rehabilitation the pit will be backfilled and areas of the mineralised pit wall may be exposed and accessible by foot. Consequently, the cover material needs to be sufficiently stable and batter slopes designed in a way such that significant erosion can be excluded. The risk could further be reduced if access to the hill is restricted.

A total dump area of approximately 1.2 ha needs to be rehabilitated, based on visual inspection and dose rate measurements. Taking into account the average pile heights at the truck dumps, this will result in a total volume of material to be removed of approximately

8000 m^3. Scraping off 5 cm of topsoil underlying the dumps, will result in an additional 600 m^3 of material to be removed. The anticipated total volume of material to be relocated is likely to be in the order of less than 10 000 m^3 at Sleisbeck.

The removal of the mineralised material immediately south of the pit will lead to a significant reduction of terrestrial gamma dose rates. Assuming that ^{238}U, ^{232}Th and ^{40}K activity concentrations of the residual soil will be <600 Bq·kg^{-1}, 30 Bq·kg^{-1} and 130 Bq·kg^{-1}, respectively this will result in an average terrestrial gamma dose rate of less than 0.3 μGy·hr^{-1}. This is 25 times below the recommended guideline value, approximately 3 times lower than the average terrestrial dose rate in the vicinity of the pit and truck dumps at present, and approximately 2–3 times above typical background dose rates in the region. A post rehabilitation groundbased gamma survey should be conducted to confirm that these predicted targets have been achieved.

Assuming a pre-mining background of 0.15 μGy·hr^{-1}, the maximum mining related terrestrial gamma dose rate in the area after clean up will in the worst case be ~ 0.15 μGy·hr^{-1}. An occupancy of 365 days a year would result in a total whole body effective dose of less than 2 mSv per year, which is only 20 per cent of the recommended guideline value of 10 mSv for intervention trigger threshold. Actual occupancy times will be one to two orders of magnitude lower, based on information provided by Traditional Owners, and the radiological risk to people accessing the area will thus be negligible.

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