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Australian Radiation Protection and Nuclear Safety Agency

A Survey of Naturally Occurring Radioactive Material Associated with Mining

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The authors would like to thank their colleagues Liesel Green, Jane Courtier, Emma Carey, David Urban and Robert Guilfoyle for assisting in the collection of samples. Shirley Hinton performed most of the radiochemical analysis on the samples and Ben Paritsky analysed the second set of radon monitors.

The assistance and cooperation provided by all of the mine operators that volunteered to participate in the study should also be acknowledged.

Summary

This study comprised a brief scoping program to identify if there may be issues involving naturally-occurring radioactive material (NORM) arising from a variety of mining activities (excluding uranium mining). This will enable any later efforts to be directed at only those mine types that may have NORM issues.

A total of 29 mining operations in New South Wales were surveyed for this study, comprising 7 collieries, 12 mines that processed ore for the metals it contains, 9 mines that quarried various minerals or rocks and 1 tourist mine.

The survey consisted of sampling all of the input, product and waste streams from the mining operations and analysing the samples for the activity concentration of those naturally occurring radionuclides which may give rise to significant radiation doses. The survey also included on-site measurement of radon in underground mines.

In most cases, the activity concentrations of the U-238 and Th-232 decay series radionuclides in the ore, tailings and solid waste from all of the mine types were found to be consistent with the range expected from soils (20 – 70 Bq/kg). Furthermore, in most cases, the radionuclides in each series were found to be in secular equilibrium, indicating that the processing of the ores does not significantly alter the elemental composition of the materials.

Almost all of the waters from the mines exhibited significant enhancement of U-234. They also exhibit significant variations in the activity concentrations of the other radionuclides in the series relative to U-238. Nonetheless, the actual activity concentrations in most of the water samples were low and most would meet the Australian Drinking Water Guidelines (NHMRC 2004) in terms of radioactivity.

These results indicate that most mining operations do not have issues related to elevated levels of naturally occurring radioactive materials.

The significant exceptions were three metalliferous mines which were found to have activity concentrations of U-238 and Th-232 decay series radionuclides in the ore, products, tailings and solid wastes approaching the reference level of 1000 Bq/kg (IAEA 2004). However, all three of these mines extract heavy metal products from the ores and are already covered by a specific code of practice (ARPANSA 2005).

It was noted that in many of the coal mines, the process waters were highly recycled, enabling U-234 to accumulate over time. It was also noted that these highly recycled process waters were relatively depleted in Ra-226. The large disequilibrium between uranium and radium in the process water and whether the radium precipitates out in the system should be further investigated to ensure that scale inside the water pipes does not present a radiation hazard.

The measurements of radon from the underground mines gave average radon concentrations which were below the action level for occupational exposure (1000 Bq/m^3). However, given the high variability observed, both within and between minesites, and the limited number of mines sampled in this study, it is likely that some underground mines may be above the action level.

Contents

1. Introduction

1.1 Naturally Occurring Radioactive Material

The naturally occurring radioactive elements uranium and thorium, like most chemical elements, are formed in stars and comprise a small amount of the material that formed the earth. The radioactive isotopes uranium-238 (U-238) and thorium-232 (Th-232) have decay times (half-lives) which are comparable with, or larger than, the age of the earth, so they have always been present in the earth's crust and within the tissues of all living species.

When the atoms of either of these two radionuclides undergo radioactive decay, they spontaneously emit a particle and form lighter atoms which are also radioactive. Furthermore, when these new radionuclides undergo radioactive decay, they create yet lighter atoms which are also radioactive. This process is repeated until the radioactive decay results in a stable nuclide. The decay chain of U-238 contains 14 radioactive isotopes, before ending with a stable isotope of lead (Pb-206), while the decay chain of Th-238 contains 11 radioactive isotopes, before ending in another stable isotope of lead (Pb-208). These decay chains are summarised in tables 1 and 2. In these tables, the radionuclides which, by themselves, produce negligible radiation doses (low dose coefficients) are shaded. In the analyses for this study, the radionuclides with low dose coefficients were assumed to be in secular equilibrium[1] with the long-lived, parent radionuclide above them.

Usually, these naturally occurring radionuclides are present at only trace levels (approximately 10 parts-per-million by mass). Nonetheless, their presence throughout the environment is responsible for approximately half of the radiation dose (approximately 1 mSv/year) to people. It is noteworthy that the medical use of radiation to diagnose and treat disease is responsible for nearly half of the dose received by the Australian public.

In the context of radiation protection, the term Naturally Occurring Radioactive Materials (NORM) is used when describing situations where human activities have increased the potential for exposure to these radionuclides in comparison to the naturally occurring situation. For example, mining may bring people into closer contact with ores containing higher concentrations of these radionuclides and the processing of ores may concentrate one or more of these radionuclides into a particular product or waste stream. NORM represents an existing exposure situation with the potential to lead to radiation protection concerns through the exposure of workers or the public, or the management of products and wastes.

[1] Secular equilibrium is the condition that the activity (or activity concentration) of a radioactive decay product with a short half-life is equal to the activity (or activity concentration) of its much longer-lived parent radionuclide. For example, the activity concentration of Po-214 is almost always equal to that of Bi-214 because of the exceedingly short half-life of Po-214 compared to that of Bi-214.

Table 1: The important properties of the radionuclides of the U-238 decay chain

Nuclide	Half-life	Radiations
U-238	4.5 Billion Years	α
Th-234	24 Days	β
Pa-234m	1 Minute	β
U-234	250,000 Years	α
Th-230	75,000 Years	α, γ
Ra-226	1,600 Years	α, γ
Rn-222	3.8 Days	α, γ
Po-218	3 Minutes	α, γ
Pb-214	27 Minutes	β, γ
Bi-214	20 Minutes	β, γ
Po-214	1.6×10^{-6} Seconds	α, γ
Pb-210	22 Years	β, γ
Bi-210	5 Days	β, γ
Po-210	138 Days	α, γ

Table 2: The important properties of the radionuclides of the Th-232 decay chain

Nuclide	Half-life	Radiations
Th-232	14 Billion Years	α, β, γ
Ra-228	6 Years	β
Ac-228	6 Hours	β, γ
Th-228	2 Years	α
Ra-224	4 Days	α, γ
Rn-220	1 Minute	α
Po-216	0.1 Seconds	α
Pb-212	10Hours	β, γ
Bi-212	1 Hour	α, β, γ
Po-212	3×10^{-7} Seconds	α, β, γ
Tl-208	3 Minutes	β, γ

1.2 Management of NORM

With the publication of 'Management of Naturally Occurring Radioactive Material' in August 2008 (ARPANSA 2008b), ARPANSA provided national guidance on the management of NORM and a methodology for assessment of the need for a radiation protection approach in specific situations involving NORM. The purpose of that document is to assist regulators and industries which produce NORM, in managing NORM and assessing the need for radiation protection measures, including regulation of exposure to workers and the control of materials. The approach is based on the framework for management of NORM arising from the National Directory for Radiation Protection (ARPANSA 2004), and the Mining Code (ARPANSA 2005).

An important consideration for regulatory bodies is whether there is a need to regulate activities involving NORM, and at what activity concentration a regulatory approach is necessary. In addition, for many NORM operations, the practices may be optimised to the point where regulation may not lead to an improvement in radiation protection. For normal exposure situations, it is usually unnecessary to regulate materials with radionuclides of natural origin with activity concentrations below 1000 Bq/kg. Under these conditions, it can be anticipated that doses to members of the public are unlikely to exceed about 1 mSv/year (IAEA 2004). Exposure to a mineral deposit or other natural material may be excluded from the scope of regulatory instruments even if its state has been altered by human activities, when such exposure is deemed to be unamenable to control. However, it is appropriate for the regulatory body to take such exposure into consideration if the individual radionuclide concentration in the material exceeds about 1000 Bq/kg (IAEA 2004).

1.3 Radon

Radon is a radioactive noble gas. There are two isotopes of radon present in natural materials which can be important from a radiological protection point of view: Rn-222 and Rn-220. Of these, Rn-222 is generally the more important of these; this is the isotope which was measured in this study and in the remainder of this report Rn-222 is referred to simply as 'radon'. Rn-220 (sometimes referred to as 'thoron') can be important in the case of thorium-rich NORM, particularly in the mineral sands industry, but was not a part of the present study.

Radon is part of the uranium decay chain (see Table 1). As it is a gas, on its formation it can escape from uranium-bearing materials into the atmosphere, where it decays to form a series of short-lived radionuclides: Po-218, Pb-214, Bi-214 and Po-214. If these radionuclides are breathed in, they can attach to the lungs and respiratory tract. The subsequent radiological dose is recognised as one cause of lung cancers (WHO 2009; ICRP 2010).

The National Standard for Limiting Occupational Exposure to Ionizing Radiation (ARPANSA 2002) recommends a radon concentration action level for workplaces of 1000 Bq/m^3. For radiological protection purposes, the important factor is the long-term average levels to which workers are exposed rather than short-term exposures to elevated levels. If measured long-term average

values in a workplace are found to exceed the action level, and are not reduced below this level by intervention (for example, by improved ventilation), the workplace should be subject to a system of radiation protection.

Radon concentrations have the potential to build up in enclosed spaces. In particular, underground mines are more likely to have elevated levels of radon than are above-ground mines due to emanation from the mine tunnel materials and the potential build-up of radon levels with time in the mine air. Radon concentrations can vary markedly in underground areas, depending upon radon emanation rates from the tunnel walls and workings, and the ventilation rate. As air passes through the mine, it increases in radon concentration, and so higher levels may be expected at the exhaust locations. Other areas where concentrations may be elevated are low-ventilation areas.

1.4 Scope of Study

While some effort has been made to assess the activity concentrations of NORM associated with uranium mining and the mining and milling of mineral sands, very little attention has been paid to the mining, milling and processing of other ores. Therefore, regulators and industries have very limited information on which to base decisions to exclude or exempt certain mining practices from regulation.

This limited study is an attempt to provide some information on the activity concentrations of NORM in a variety of mine types to regulators and operators. While this study was limited to 29 mines operating in New South Wales, the information should enable later efforts to be directed at only those mine types that may have NORM issues.

2. Sampling and Analysis

The NSW Trade and Investment arranged for ARPANSA staff to visit a range of mine types within NSW to collect samples. Two staff from ARPANSA travelled to a set of geographically close mines over a period of one week to collect samples. There were a total of six such trips, spread between March and May 2011. A total of 29 mines were visited, comprising 7 collieries, 12 mines that processed ore for the metals it contains, 9 mines that quarried various minerals or rocks and 1 tourist mine (radon measurement only).

At each mine, ARPANSA staff collected, where possible, samples from all of the input, product and waste streams. Approximately 500g each of solid materials or approximately 1 litre of liquid materials were collected from each stream from each mine. In some cases, the actual collection of the material was done by mine personnel, under instruction, in order to limit the health and safety risk to ARPANSA personnel. A total of 142 separate samples were collected over the course of the sampling program. The samples were returned to ARPANSA for radiochemical analysis.

A total of 40 passive radon monitors were left at 10 underground mines. The operators agreed to place the monitors in areas of worker occupancy in their mines for a minimum period of two weeks

before returning them to ARPANSA for analysis. The two week sampling period for these monitors ensures that radon levels above the public action level (200 Bq/m^3) are readily discernible. For two of the minesites, a follow-up survey was undertaken where a further set of monitors was provided to the mine operators; these were deployed at the same locations as the original set.

At the tourist mine, radon was actively sampled and measured by an ARPANSA staff member accompanying a tour group using an AlphaGuard™ electronic radon monitor. An integrated average reading over the duration of the tour was obtained.

2.1 Sample Designation and Categorisation

In order to preserve the anonymity of the mines involved in this study, each mine was assigned an alphabetic designation (a, b, c ..., α, β, γ) for use in this report. Each sample was assigned a numeric designation based on the order in which it arrived at the laboratory. In this report, these two designators are combined: x123 is a sample from mine x and is the 123rd sample to arrive in the laboratory. Radon monitors were designated in a similar manner but with a dash separating the numeric designation (which signified the monitor number left at that mine): p-3 is the third radon monitor left at mine p.

The samples were characterised into six separate categories: ore, product, tailings, solid waste, mine water or process water. For the purposes of this study, these categories are defined as:

Ore – the raw material extracted from the earth

Product – the material on-sold by the mine

Tailings – solids that have been mixed with water during the on-site processing of the ore

Solid Waste – solids that have been removed from the ore by processes other than simple mixing with water

Mine Water – either water that collects within the mine or input water that enters the mining operation from off-site

Process Water – water that has been used during the processing of the ore

2.2 Radiochemical Analyses

2.2.1 Sample Pre-Treatment

Liquid samples were acidified to a pH of less than two and allowed to stand for a minimum of 16 hours. The samples were then filtered (<0.45 µm) and the filtrate was used for sample analyses. The filter plus solids was retained for further analysis if required.

Solid samples were dried at 70^{o}C and ground to a fine powder.

2.2.2 Analysis for Pb-210, Ra-226 and Ra-228 in Liquid Samples

The lead and radium isotopes were separated from the sample matrix using a lead sulphate co-precipitation. The precipitate was dissolved and the radium was then precipitated from the solution using barium sulphate. The activity concentration of Ra-228 in the barium precipitate was determined by high resolution gamma-spectrometry following the ingrowth of Ac-228. The activity concentration of Ra-226 in the barium precipitate was determined by liquid scintillation counting following dissolution, the addition of an organic scintillant and the ingrowth of Rn-222. The lead remaining in solution after the addition of barium sulphate was further purified and precipitated as lead sulphate. The lead sulphate was slurried with water then mixed with a scintillation cocktail before its activity concentration was determined using liquid scintillation counting.

2.2.3 Analysis for U-238, U-234, Th-230, Th-232 and Po-210 in Liquid Samples

The radionuclides were separated from the matrix using a manganese dioxide co-precipitation. The radionuclides were then sequentially separated from the re-dissolved precipitate using UTEVA chromatographic resin. Following the separation, the uranium and thorium radionuclides were electrodeposited onto stainless steel disks. The polonium fractions were further purified prior to autodeposition of polonium onto silver disks.

The activity on the discs was determined by high resolution alpha spectrometry.

2.2.4 Analysis for Pb-210, Ra-226, Ra-228 and Th-228 in Solid Samples

Subsamples of the ground samples were weighed into a 50 x 5 mm petri dish, allowed to sit for 30 days to allow for the ingrowth of Rn-222. The activity concentration of the radionuclides in the petri dishes was determined by high resolution gamma-ray spectrometry.

2.2.5 Analysis for U-238, U-234, Th-230, Th-232, Po-210 in Solid Samples

Coal samples were digested with nitric acid and hydrogen peroxide, using a microwave digestion technique. Centrifugation was used to separate the extracted radionuclides from the non-dissolved material. The extracted radionuclides were then separated from the solution using a manganese dioxide co-precipitation. The radionuclides were sequentially separated from one another using UTEVA resin.

Samples other than coal were digested with nitric and hydrofluoric acid, using a microwave digestion technique. Several samples could not be adequately digested by this technique, precluding further analysis. Also, it was found that this technique may give rise to a chemical interference which precluded analysis for thorium in many samples.

Boric acid was added to the digested solutions and these were then evaporated to near dryness. The residue was taken up in an acid solution and centrifuged prior to the sequential separation process (as above) using UTEVA resin.

Following the separation, the uranium and thorium radionuclides were electrodeposited onto stainless steel disks. The polonium fractions were further purified prior to autodeposition of polonium onto silver disks.

The activity on the discs was determined by high resolution alpha spectrometry.

2.3 Analysis of Radon Monitors

Radon measurements were carried out using Solid State Nuclear Track (SSNT) detectors. SSNT detectors consist of a diffusion barrier, a diffusion chamber and a CR-39 plastic plaque. The radon isotope Rn-222 diffuses though the diffusion barrier into the chamber, while the shorter-lived isotope Rn-220 is essentially excluded. Hence the measurements reported here are for Rn-222, and in the remainder of this report this isotope is referred to as 'radon'.

Radon in the chamber undergoes decay with the formation of subsequent radioactive decay products. Radon and some of its decay products are alpha particle emitters. The emitted alpha particles produce damage tracks in the CR-39 plaque.

These damage tracks can be made visible under a conventional microscope by etching the CR-39 plaque with a 6.25 M KOH solution for 6 hours at 70 degrees Celsius. This process enlarges the damage tracks to an approximate diameter of 25 µm.

After the CR-39 plaques had been etched they were then scanned using a flatbed scanner at a resolution of 12800 DPI. These images were then enhanced and the number of damage tracks was counted across 80% of the plaque using customized macros in Image-Pro Plus™.

The sensitivity of the CR-39 plastic is determined from plaques exposed to known radon concentrations in ARPANSA's radon chamber. Typically, the sensitivity of the plaque is 4 Bq·d/m^3/track and the number of tracks produced over a two week period is approximately 4000 for a radon concentration of 750 Bq/m^3.

3. Results

3.1 Solids and Liquids from Quarries

The 9 mines included in this category sell products that are, to a large extent, the ore that is mined. That is, very little processing of the ore is performed. However, this processing usually involves washing the crushed ore, which can potentially dissolve some of the radionuclides from the ore into the process water.

3.1.1 Measured Activity Concentrations

The measured activity concentrations for the long-lived radionuclides are shown in figures 1 -4. In these figures, the measured value of the radionuclide is shown by the height of the shaded bar,

with each radionuclide having a different shading as indicated in the legend shown in the figure. For some samples, a bar may be absent, indicating that the activity concentration of that radionuclide in that sample was below measurable levels.

The error bars shown in the figures indicate the 95% confidence limits for the measurement. That is, there is a 95% probability that the real activity concentration of the radionuclide lies within these limits.

Most of the figures include a light grey background which indicates the range of activity concentrations found in normal soils. The United Nations Scientific Committee on the Effects of Atomic Radiation (2000) reports that the normal range of uranium and thorium series radionuclides in soils is 20 – 70 Bq/kg. UNSCEAR reports a very large range of uranium and thorium series radionuclides in drinking water. The large range of these radionuclides in drinking waters is due to the high diversity in water sources and chemistry.

Most of the figures show the activity concentration in Bq/kg on a linear scale. However, the activity concentrations of radionuclides in water are shown in mBq/litre (thousandths of a becquerel per litre) on a logarithmic scale. A logarithmic scale is used in this case because the activity concentrations vary over several orders of magnitude. A smaller unit is used in the case of waters because the activity concentrations are several orders of magnitude smaller than those in solids.

For most of the ores and products from the quarries, neither Th-230 nor Th-232 could be measured because, following digestion, the thorium was in a form that was not able to be separated using the resin. In these cases, an arrow in the figures indicates that a measurement of that radionuclide could not be made on the sample. The activity concentrations of Th-228 were derived from measurements of the samples by gamma-spectrometry, assuming that Pb-212 and Bi-212 were in secular equilibrium with Th-228 and that negligible Rn-220 escaped from the sample.

The thorium series radionuclides are not reported for the waters from quarries because, in almost all cases, the levels were too low to be measured.

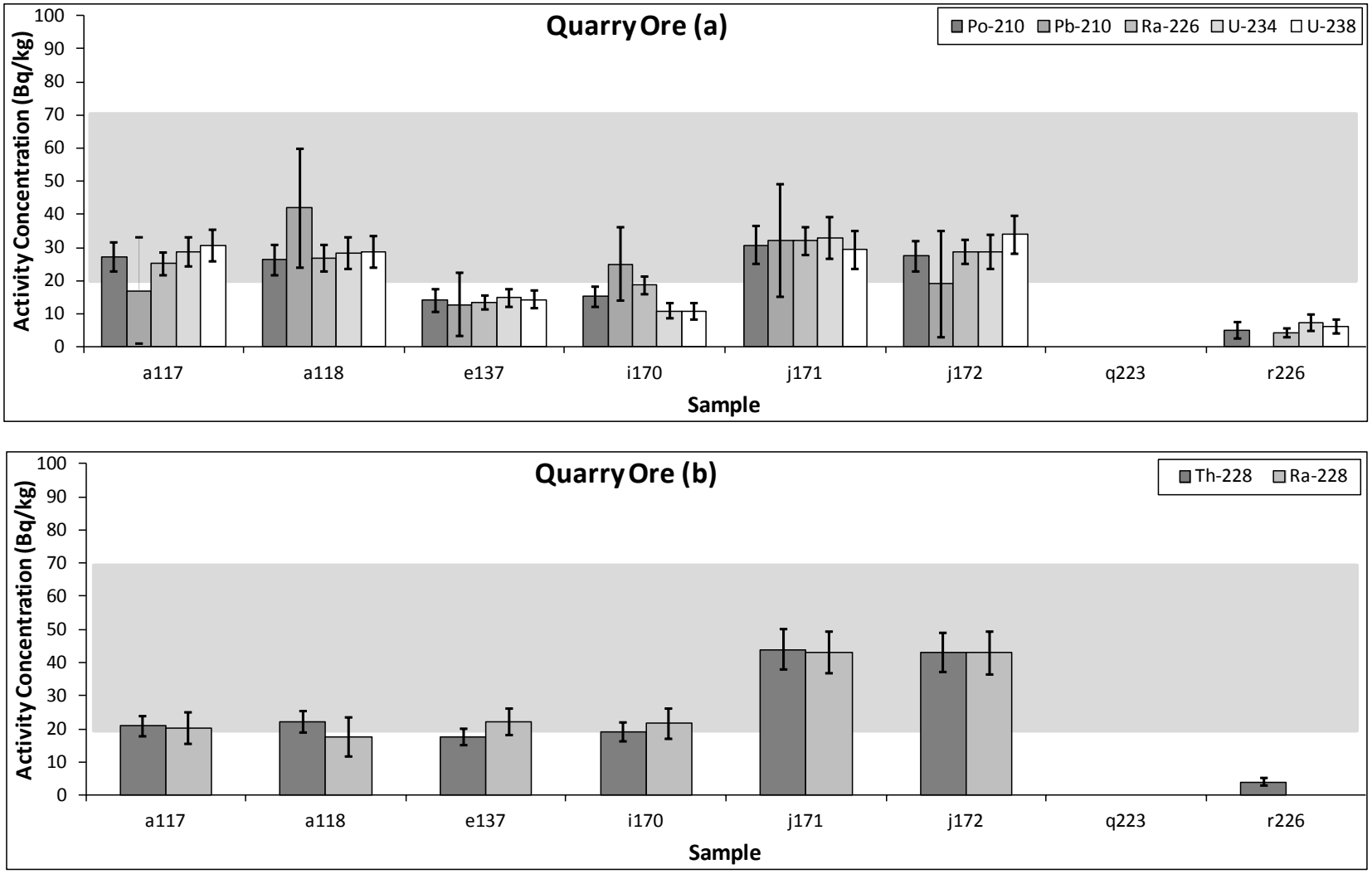

Figure 1: The measured activity concentration of uranium series (a) and thorium series (b) radionuclides in ore from quarries.
The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample.
The light grey background indicates the normal range of the radionuclides in soil.

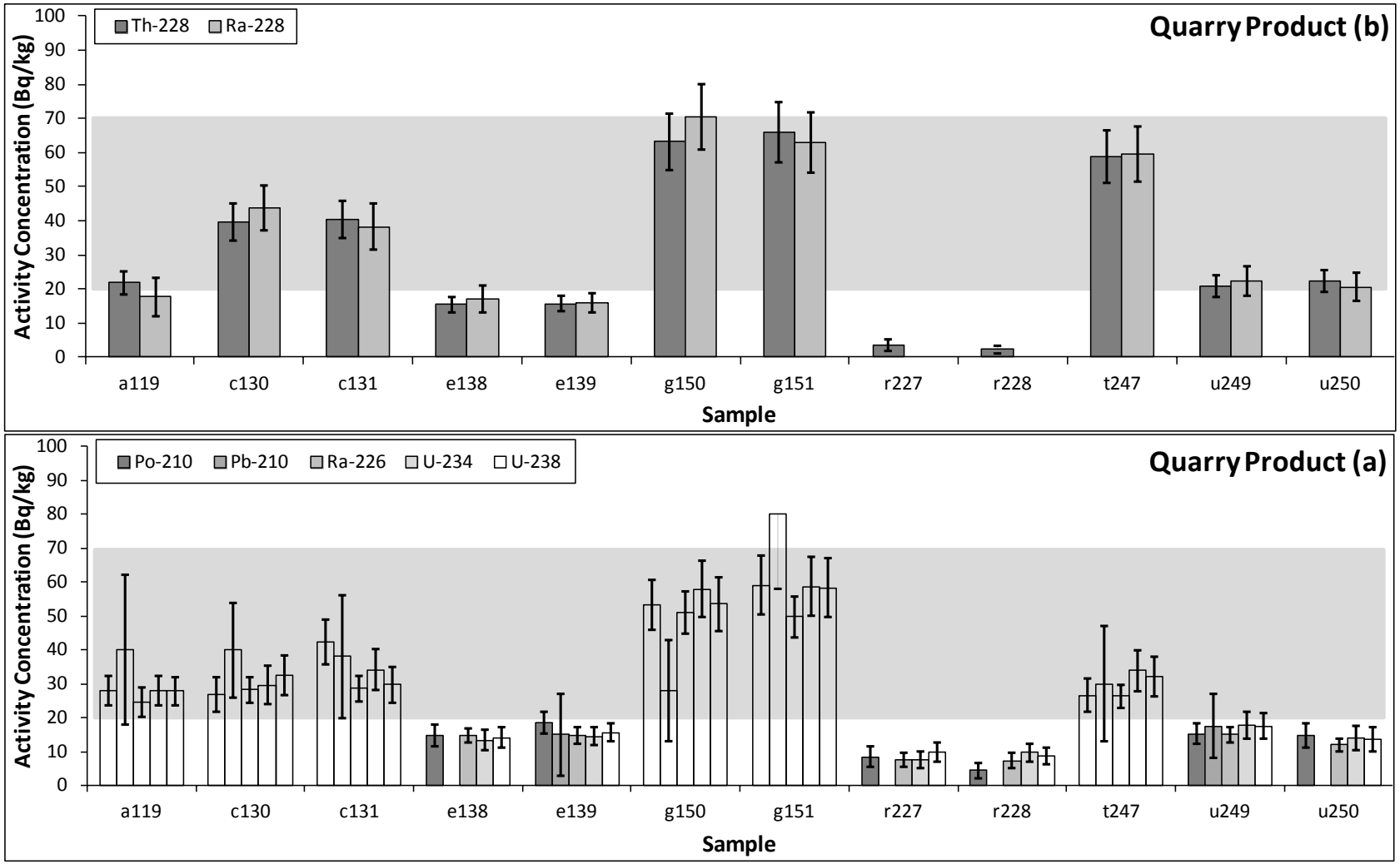

Figure 2: The measured activity concentration of uranium series (a) and thorium series (b) radionuclides in product from quarries. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample. The light grey background indicates the normal range of the radionuclides in soil.

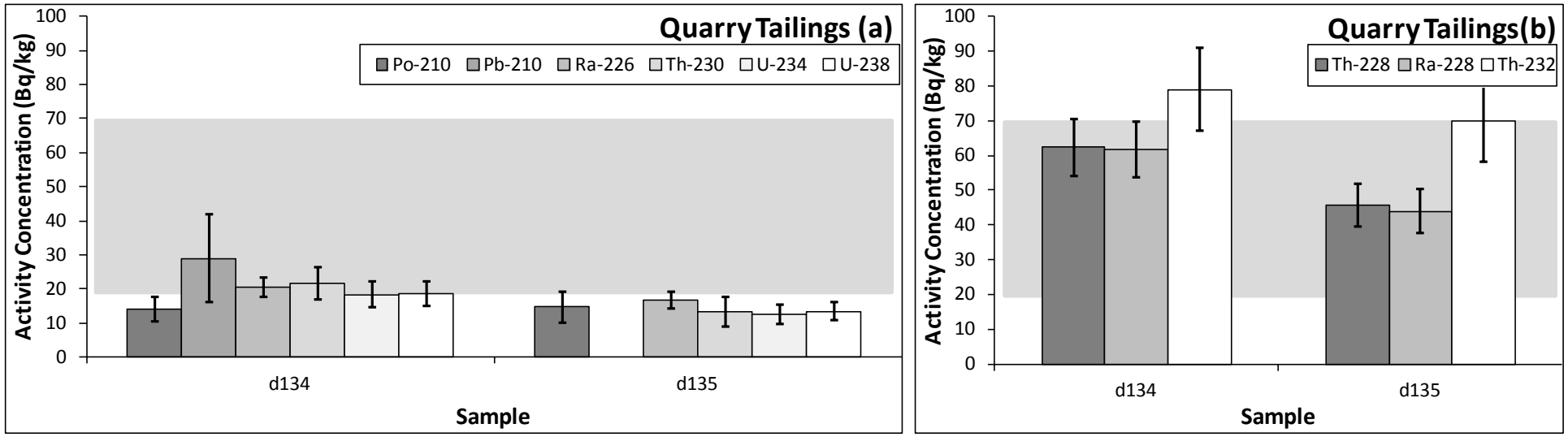

Figure 3: The measured activity concentration of uranium series (a) and thorium series (b) radionuclides in tailings from quarries.
The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample.
The light grey background indicates the normal range of the radionuclides in soil.

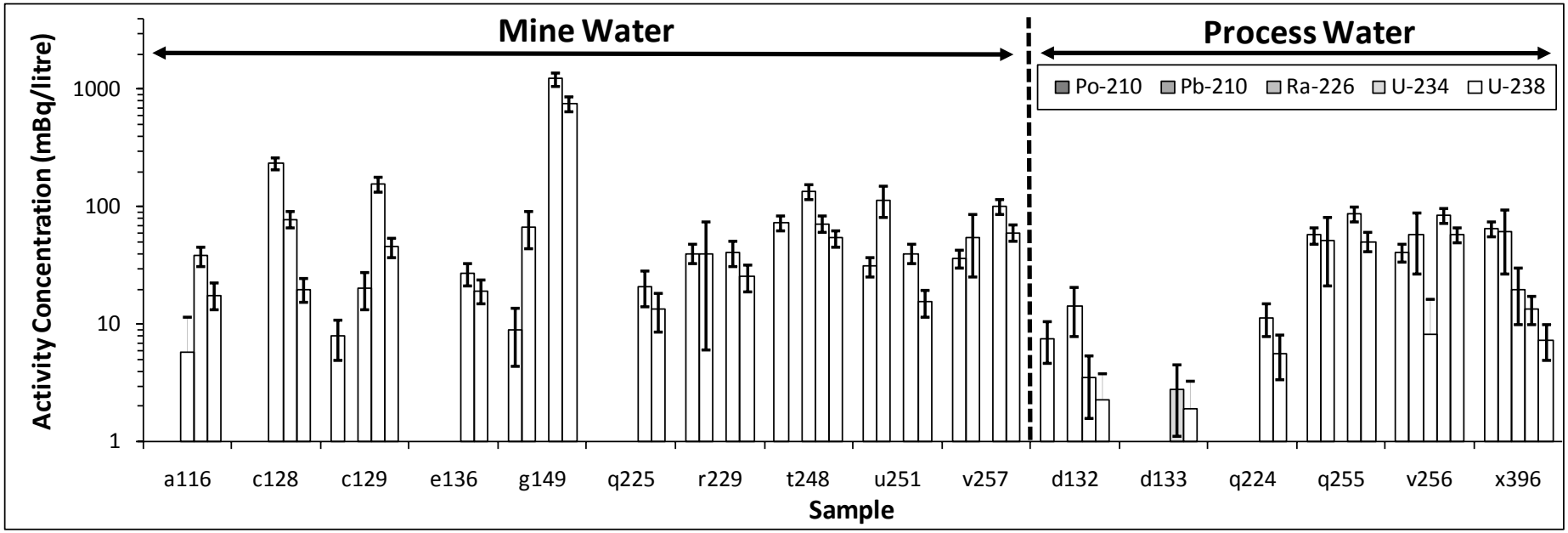

Figure 4: The measured activity concentration of uranium series radionuclides in mine and process water (as indicated) from quarries. Note that the activity concentrations of the thorium series radionuclides is not shown because the levels were, generally, not measurable. Note also that the vertical scale is logarithmic and in thousandths of a Bq per litre. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample.

3.1.2 Discussion

The activity concentrations of the measured radionuclides in the solids from the quarries were found to be consistent with the range expected from soils. In some cases, the activity concentrations were much lower than the levels found in soils due to the type of ore that was being quarried. However, all of the solid samples had measured activity concentrations at least an order of magnitude lower than the reference level of 1000 Bq/kg.

The activity concentrations of each of the radionuclides in the uranium series and thorium series should be equal to one-another if chemical or physical processes do not preferentially remove one (or more) of the elements. That is, the activity concentrations of U-238, U-234, Ra-226, Pb-210 and Po-210 will be equal to one-another and, similarly, the activity concentrations of Th-232, Ra-228 and Th-228 will be equal to one-another in samples that have not been chemically altered by the processing of the ore. Such a state is called secular equilibrium. It should be noted that ores may not, necessarily, be in secular equilibrium due to geochemical processes.

In all of the ore samples from quarries, the radionuclides in each of the uranium and thorium series were found to be in secular equilibrium, within the uncertainties of the measurements. This indicates that geochemical processes have not significantly affected the ores that are being quarried.

Similarly, the radionuclides in each series were found to be in secular equilibrium, within the uncertainties of the measurements, for both the product and tailings samples measured. This indicates that the processing of the ores at these quarries does not significantly alter the elemental composition of the materials.

A previous study (ARPANSA 2008a), found that uranium series radionuclides in Australian drinking waters ranged in activity concentration between 10 and several hundred mBq/litre. The activity concentrations found in waters associated with the quarries studied are consistent with this large range.

The previous study also found that many drinking waters exhibited enhancement of U-234 relative to U-238. This is because the Th-234 atoms, generated by the radioactive decay of U-238 are more loosely bound to the crystal structure of the rocks containing the uranium due to the restructuring of the chemical bonds subsequent to the decay. This enables the Th-234 atoms to more easily enter the water, where they rapidly decay (24 day half-life), via Pa-234m (1 minute half-life), to U-234. The relatively long half-life of U-234 (250 thousand years) means that this radionuclide can accumulate in the water. Once the U-234 atoms are in solution, the elements created by its radioactive decay (principally Ra-226, Pb-210 and Po-210) are more actively involved in geochemical processes, meaning that they are also unlikely to remain in secular equilibrium.

Almost all of the waters measured for this survey exhibit significant enhancement of U-234. They also exhibit significant variations in the activity concentrations of the other radionuclides in the series relative to U-238. Nonetheless, the actual activity concentrations in most of the water samples were low and most would meet the Australian Drinking Water Guidelines (NHMRC 2004)

in terms of radioactivity. The one exception was sample g149, which is water from the sump of an open-cut quarry. It is probable that the high activity concentration measured in this sample is due to the leached radionuclides being concentrated as the water evaporates.

3.2 Solids and Liquids from Metalliferous and Other Mines

Twelve mines were included in this category. In most cases, the categorisation is straightforward. However, this category also includes a mine that produces quicklime and another whose principal product is sand. Although these two mines are not metalliferous, they do process the ore to a greater extent than quarries.

3.2.1 Measured Activity Concentrations

The measured activity concentrations for the long-lived radionuclides are shown in figures 5-9. In these figures, the measured value of the radionuclide is shown by the height of the shaded bar, with each radionuclide having a different shading as indicated in the legend shown in the figure. For some samples, a bar may be absent, indicating that the activity concentration of that radionuclide in that sample was below measurable levels.

For some of the samples, some isotopes of thorium and uranium could not be measured because the sample could not be chemically treated in order to extract these elements. In these cases, an arrow in the figures indicates that a measurement of that radionuclide could not be made on the sample. The activity concentrations of thorium-228 were derived from measurements of the samples by gamma-spectrometry, assuming that Pb-212 and Bi-212 were in secular equilibrium with Th-228 and that negligible Rn-220 escaped from the sample.

The error bars shown in the figures indicate the 95% confidence limits for the measurement. That is, there is a 95% probability that the real activity concentration of the radionuclide lies within these limits.

The figures for activity concentration in solids include a light grey background which indicates the range of activity concentrations found in normal soils (20 – 70 Bq/kg). Due to the large number of samples of mine ores and products, the activity concentrations of the uranium series radionuclides have been broken into two figures for clarity: one showing the series from U-238 through to Ra-226 and the other showing the series from Ra-226 through to Po-210.

The figures showing the activity concentration in solids are in Bq/kg, while that showing the activity concentrations of radionuclides in water is shown in mBq/litre (thousandths of a becquerel per litre). The smaller unit is used in the case of waters because the activity concentrations are several orders of magnitude smaller than those in solids. Note that these figures use a logarithmic scale because the activity concentrations vary over several orders of magnitude.

The thorium series radionuclides are not reported for the waters from the metalliferous mines because, in almost all cases, the levels were too low to be measured.

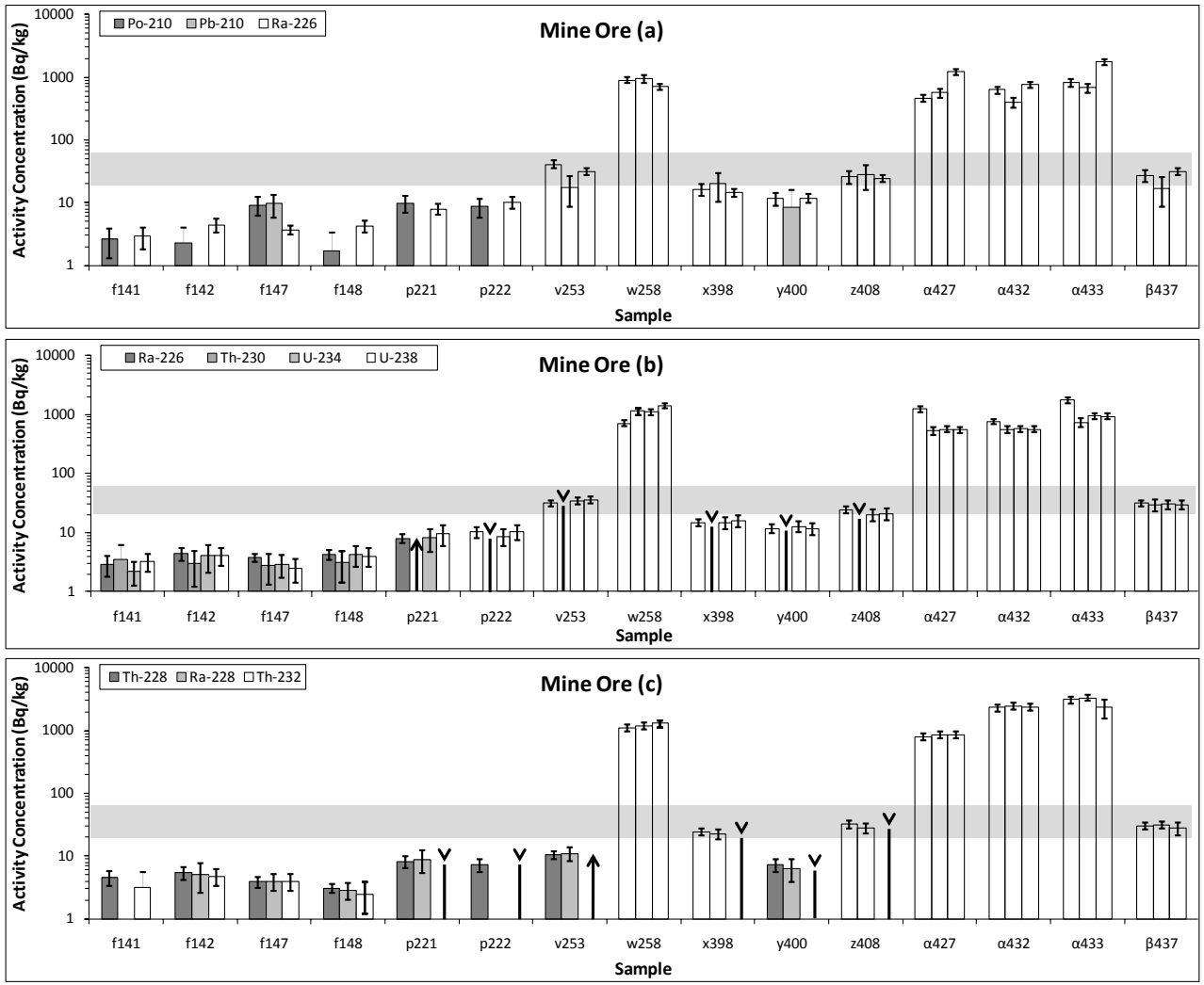

Figure 5: The measured activity concentration of the first part (a) and second part (b) of the uranium series and thorium series (c) radionuclides in ore from metalliferous mines. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample. An arrow indicates that a particular radionuclide could not be analysed in the sample. The light grey background indicates the normal range of the radionuclides in soil.

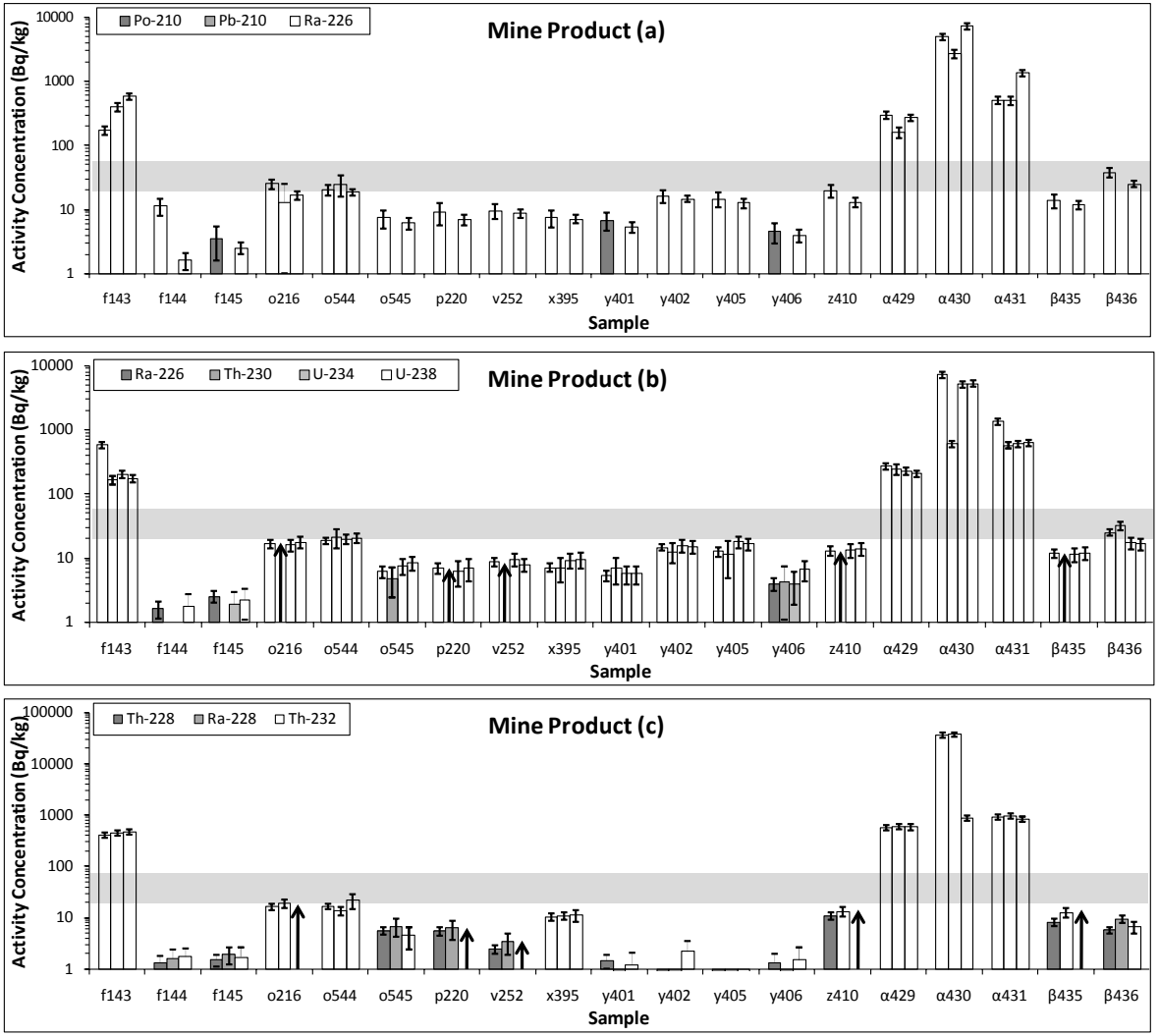

Figure 6: The measured activity concentration of the first part (a) and second part (b) of the uranium series and thorium series (c) radionuclides in products from metalliferous mines. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample. An arrow indicates that a particular radionuclide could not be analysed in the sample. The light grey background indicates the normal range of the radionuclides in soil.

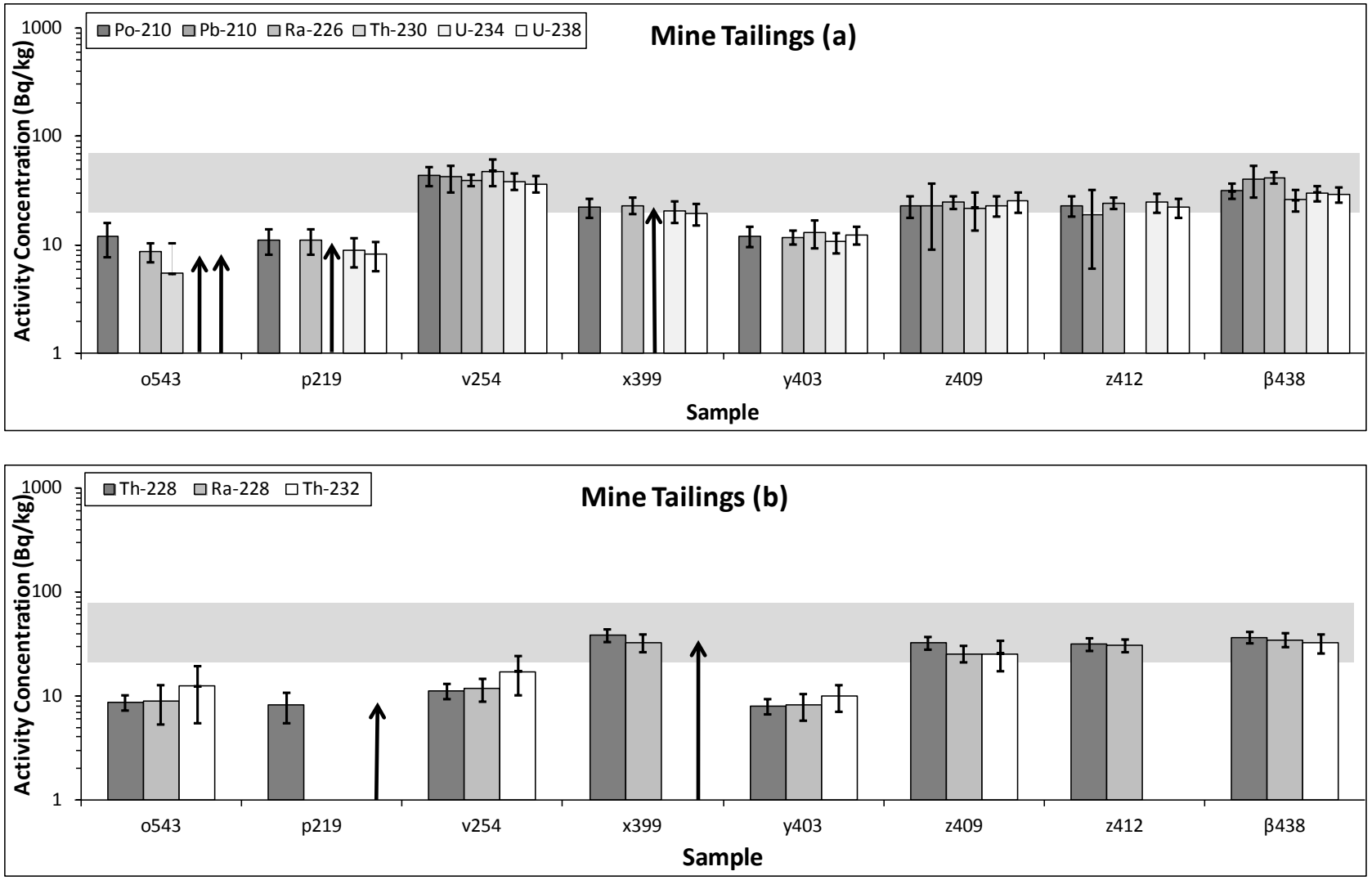

Figure 7: The measured activity concentration of the uranium series (a) and thorium series (b) radionuclides in tailings from metalliferous mines. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample. An arrow indicates that a particular radionuclide could not be analysed in the sample. The light grey background indicates the normal range of the radionuclides in soil.

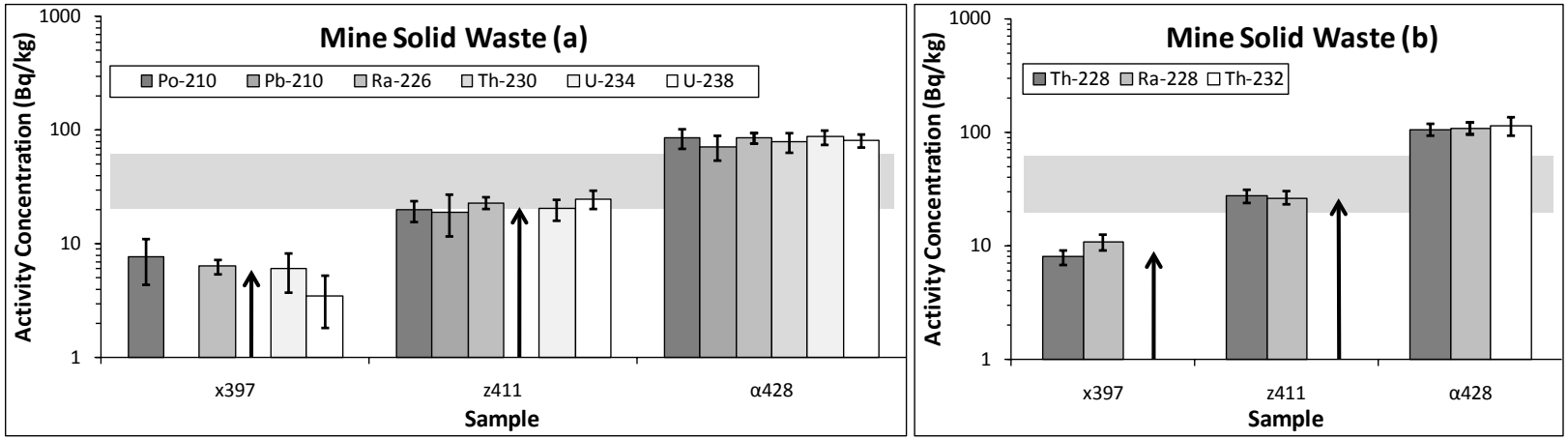

Figure 8: The measured activity concentration of the uranium series (a) and thorium series (b) radionuclides in solid waste from metalliferous mines. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample. An arrow indicates that a particular radionuclide could not be analysed in the sample. The light grey background indicates the normal range of the radionuclides in soil.

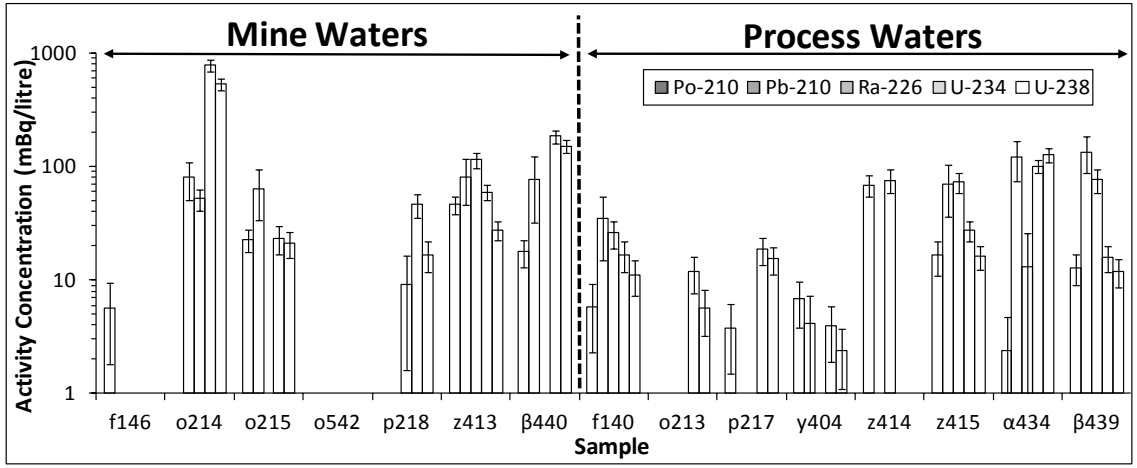

Figure 9: The measured activity concentration of the uranium series radionuclides in mine and process waters (as indicated) from metalliferous mines. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample.

3.2.2 Discussion

The activity concentrations of the measured radionuclides in the ores from most of the mines were found to be lower than the range expected from soils. However, the ores from mines w and α were found to be considerably higher. Mines w and α deal with heavy minerals and it is well known that such ores are enriched in NORM and are already covered by a specific code of practice (ARPANSA 2005). As expected, most of the ores were found to be in secular equilibrium (all radionuclides in each of the uranium and thorium series having equal activity concentrations to one-another). However, the ores from mine α were found to have significantly enhanced levels of Ra-226 while the ore from mine w was found to have significantly reduced levels of the same radionuclide. It is worth noting that mine f also deals with sand but its input is normal rather than mineral sand.

With the exception of mines f, w and α, the products from the metalliferous mines were below or within the range of activity concentrations in normal soils and indicated that secular equilibrium had not been disturbed by the processing of the ores. The products from mines f, w and α that exhibited activity concentrations approaching the reference level of 1000 Bq/kg were the heavy metal products extracted from the sands, which are known to have high NORM content. In each of the products from these sand mines, the radionuclides in the uranium series were significantly disturbed from secular equilibrium, indicating that the processing of the ores in these cases acted differently on the various elements.

The tailings from those metalliferous mines that provided samples were also below or within the range of activity concentrations in normal soils and indicated that secular equilibrium had not been disturbed by the processing of the ores.

Of the three mines which provided samples of solid waste, only that from mine α exhibited activity concentrations above the range found in normal soils. It is worth noting that the activity concentrations in the solid waste from mine α are an order of magnitude lower than the reference level of 1000 Bq/kg and are in secular equilibrium.

All of the waters from the metalliferous and other mines measured for this survey exhibit significant disequilibrium in the uranium series radionuclides. Again, the highest activity concentrations found in these water samples were those from the sump of an open-cut mine. Apart from this sample, the others would probably meet the Australian standard for drinking water in terms of radioactivity.

3.3 Solids and Liquids from Collieries

This study separated the 7 mines that excavated coal from the other mine types on the basis that the ore is an organic material and may, therefore, be subject to different chemical processes.

3.3.1 Measured Activity Concentrations

The measured activity concentrations for the long-lived radionuclides are shown in figures 10 - 14. In these figures, the measured value of the radionuclide is shown by the height of the shaded bar, with each radionuclide having a different shading as indicated in the legend shown in the figure. For some samples, a bar may be absent, indicating that the activity concentration of that radionuclide in that sample was below measurable levels.

For two of the samples, some isotopes of thorium and uranium could not be measured because the samples could not be chemically treated in order to extract these elements. In these cases, an arrow in the figures indicates that a measurement of that radionuclide could not be made on the sample. The activity concentrations of thorium-228 were derived from measurements of the samples by gamma-spectrometry, assuming that Pb-212 and Bi-212 were in secular equilibrium with Th-228 and that negligible Rn-220 escaped from the sample.

The error bars shown in the figures indicate the 95% confidence limits for the measurement. That is, there is a 95% probability that the real activity concentration of the radionuclide lies within these limits.

The figures for activity concentration in solid wastes and tailings include a light grey background which indicates the range of activity concentrations found in normal soils (20 – 70 Bq/kg).

The figures showing the activity concentration in solids are in Bq/kg, while that showing the activity concentrations of radionuclides in water is shown in mBq/litre (thousandths of a becquerel per litre). The smaller unit is used in the case of waters because the activity concentrations are several orders of magnitude smaller than those in solids. Note that figure 14 uses a logarithmic scale because the activity concentrations vary over several orders of magnitude.

The thorium series radionuclides are not reported for the waters from these mines because, in almost all cases, the levels were too low to be measured. Neither Po-210 nor Pb-210 activity concentrations are reported in the water samples for the same reason.

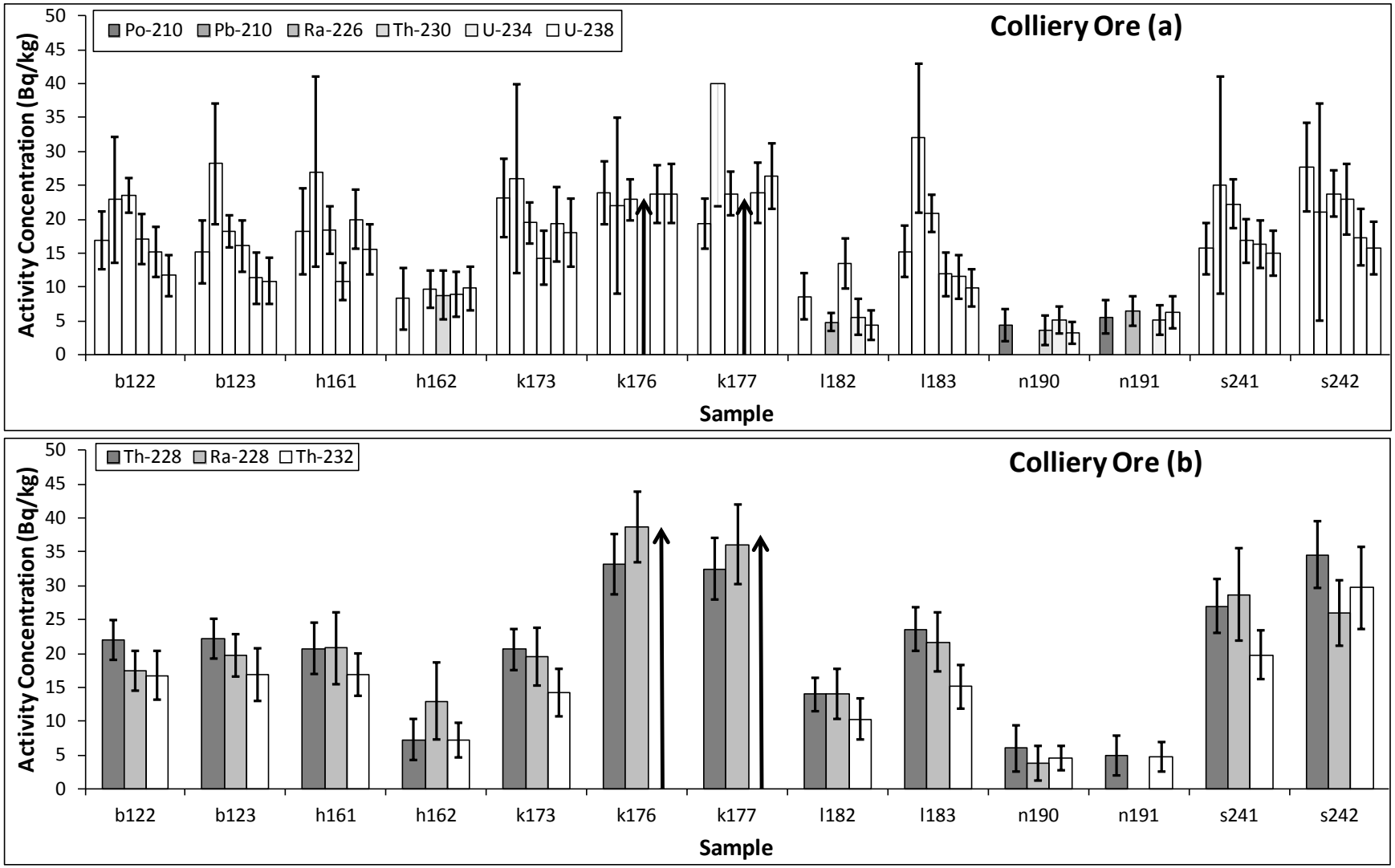

Figure 10: The measured activity concentration of the uranium series (a) and thorium series (b) radionuclides in ore from coal mines. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample. An arrow indicates that a particular radionuclide could not be analysed in the sample.

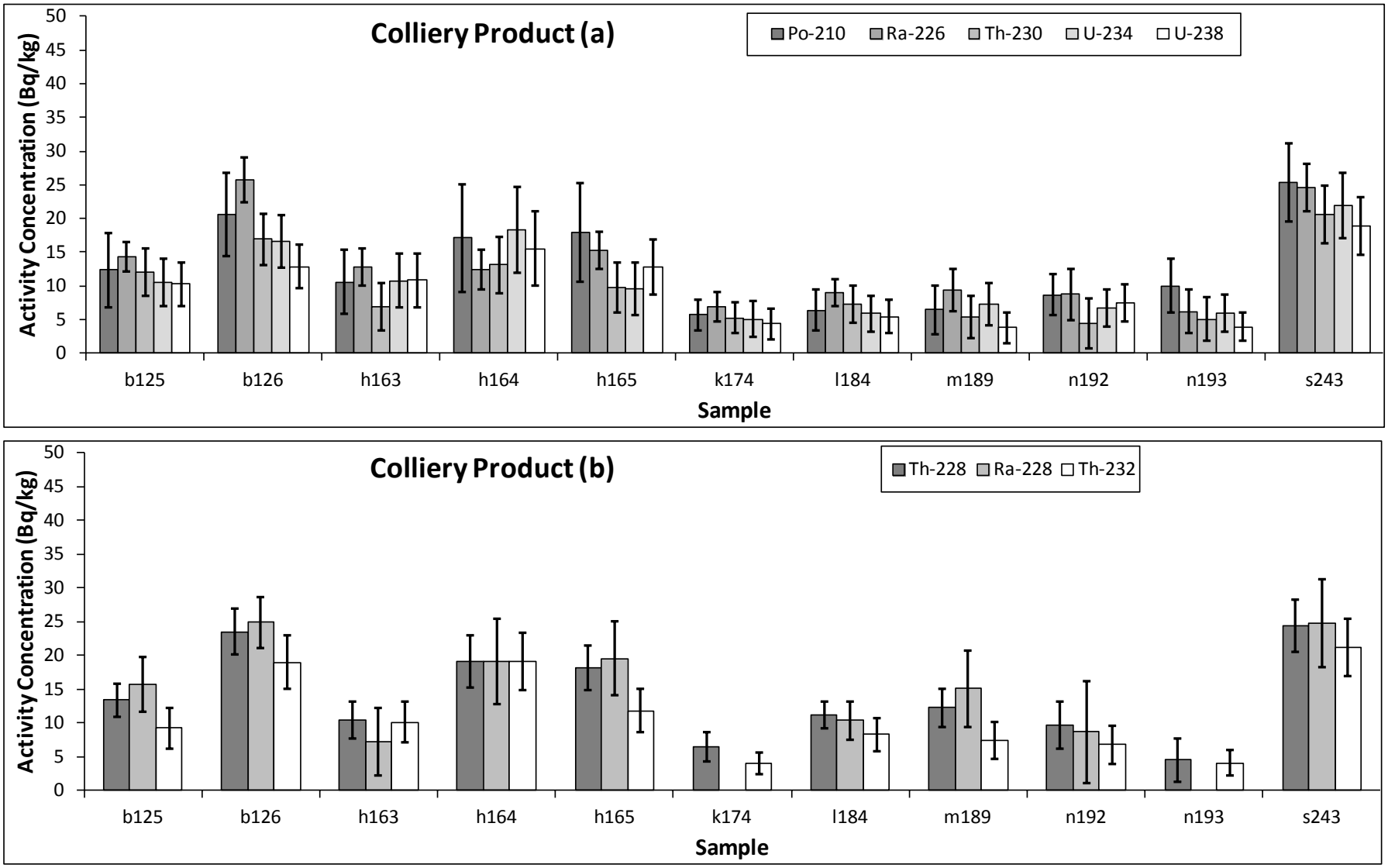

Figure 11: The measured activity concentration of the uranium series (a) and thorium series (b) radionuclides in products from coal mines. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample.

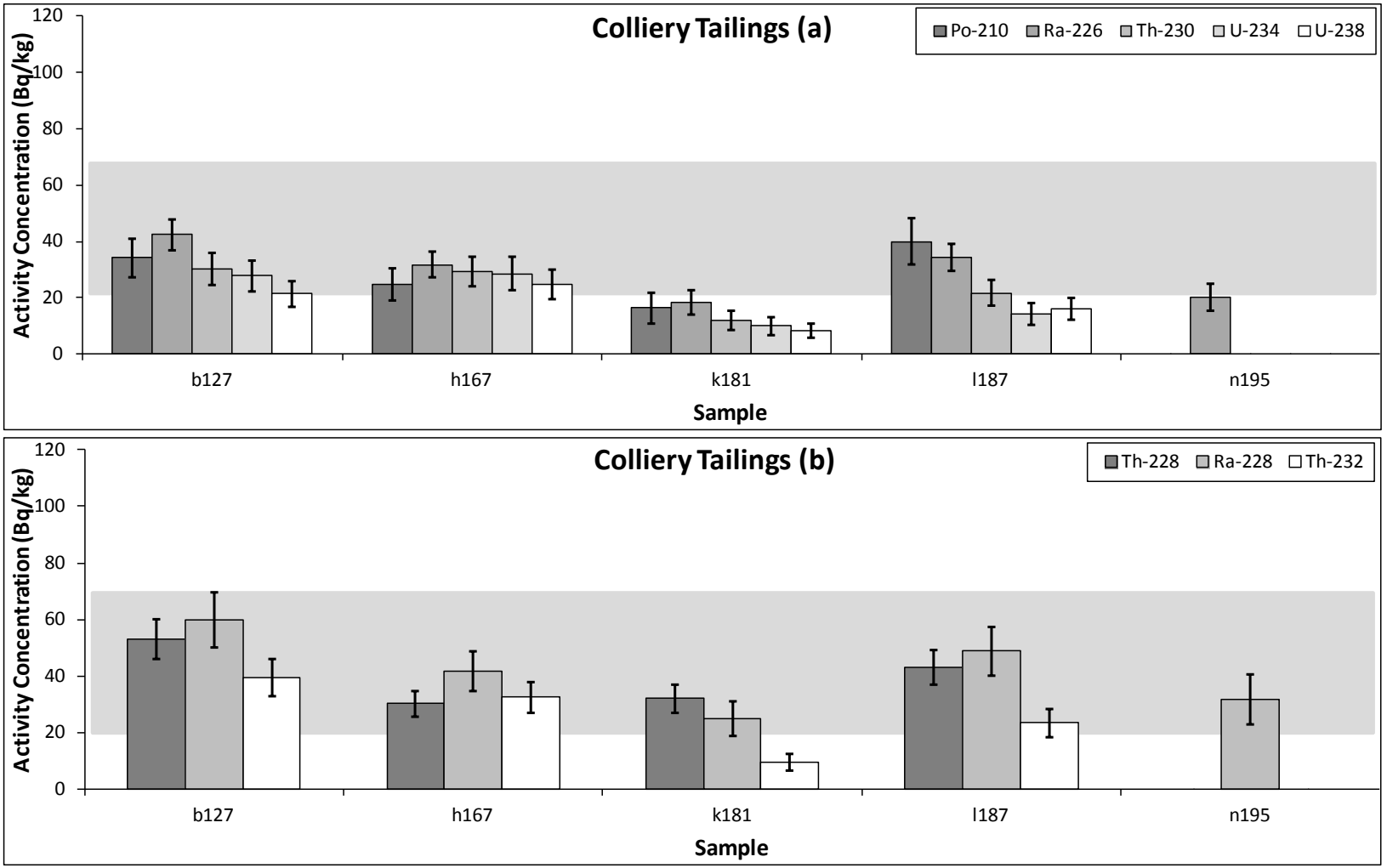

Figure 12: The measured activity concentration of the uranium series (a) and thorium series (b) radionuclides in tailings from coal mines. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample. The light grey background indicates the normal range of the radionuclides in soil. Note that, in most of these samples, Pb-210 activity concentrations were too low to be accurately measured and, hence, are not shown.

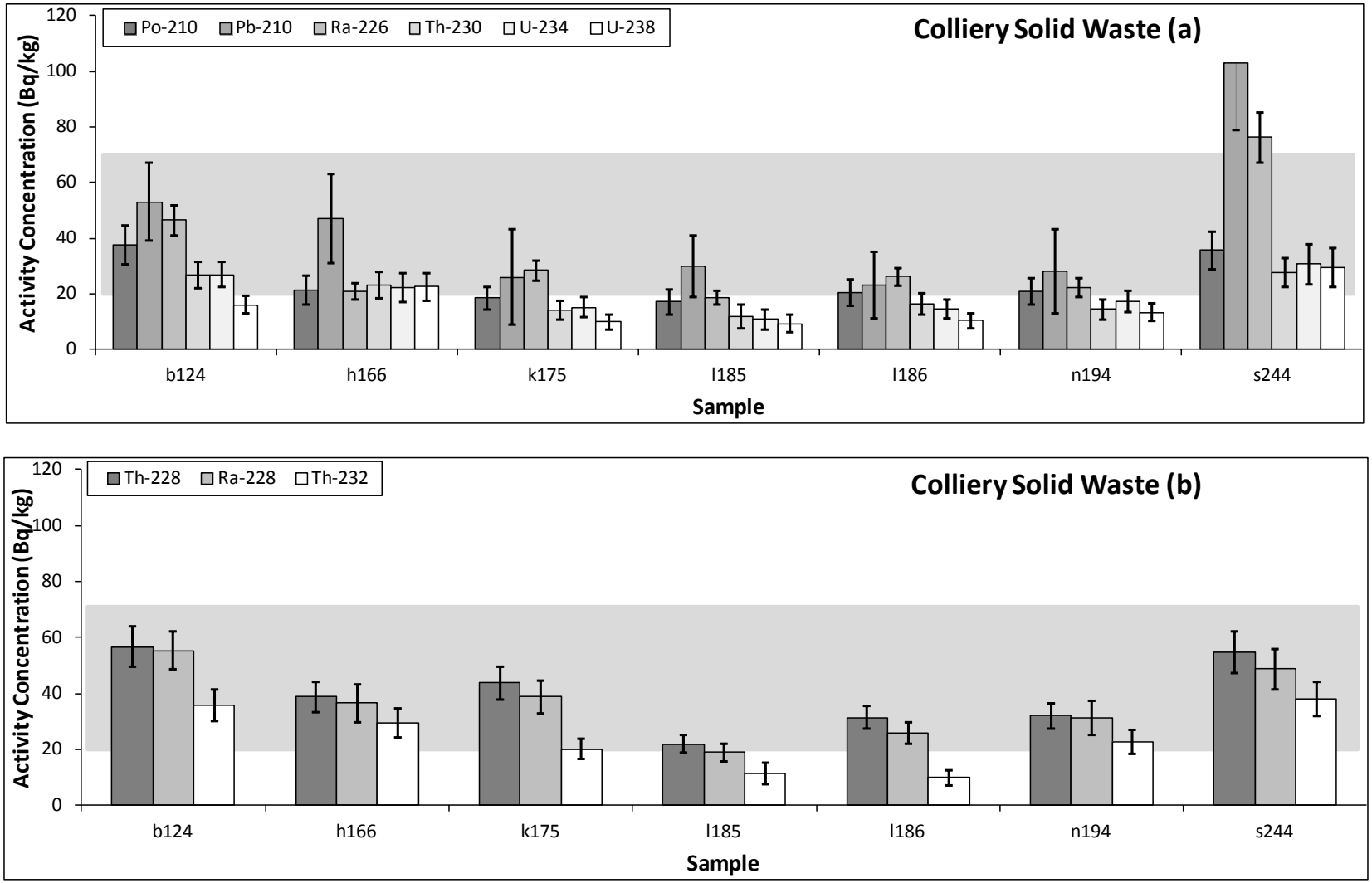

Figure 13: The measured activity concentration of the uranium series (a) and thorium series (b) radionuclides in solid waste from coals mines. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample. The light grey background indicates the normal range of the radionuclides in soil.

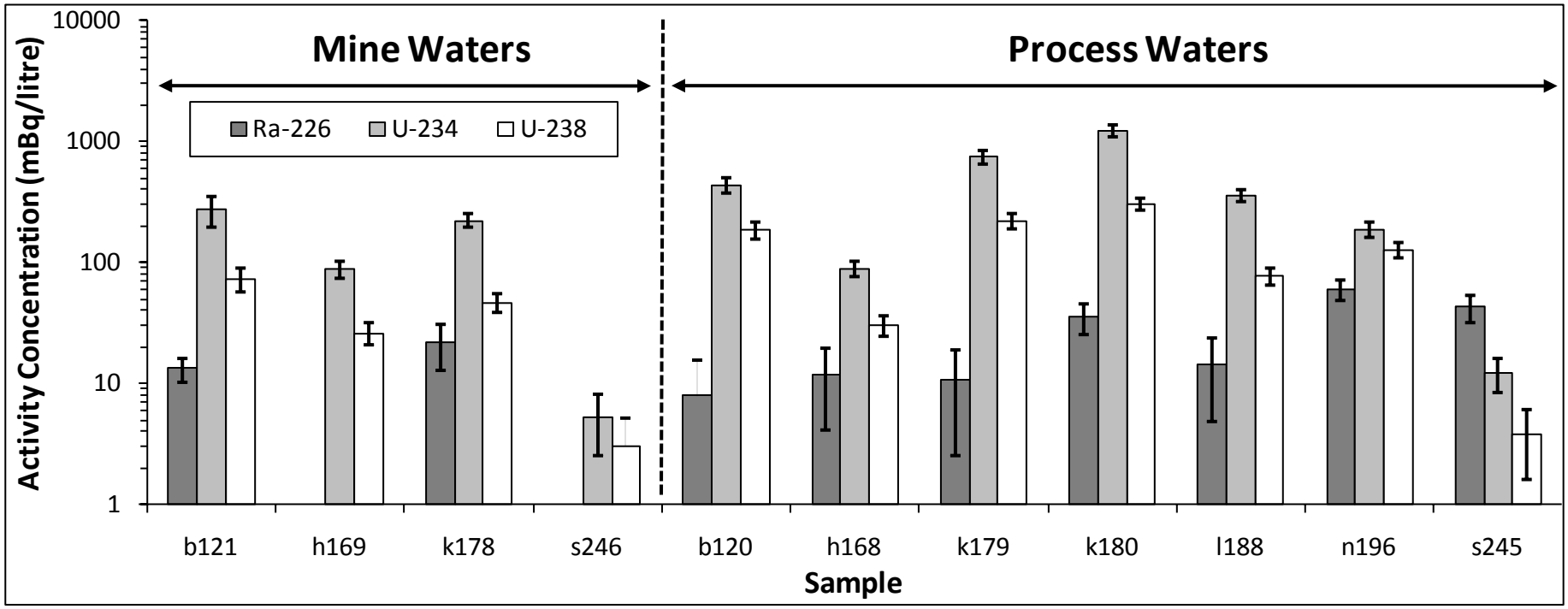

Figure 14: The measured activity concentration of the uranium series radionuclides in mine and process waters (as indicated) from coal mines. The error bars indicate the 95% confidence interval of the measurement and the absence of a bar indicates that that radionuclide was not present in measurable levels in the sample. Note that, in most of these samples Po-210 and Pb-210 activity concentrations were too low to be accurately measured and, hence, are not shown.

3.3.2 Discussion

The activity concentrations of the measured radionuclides in the ores from the coal mines were found to be lower than, or consistent with, the range expected from soils and were well below the reference activity concentration of 1000 Bq/kg. Unfortunately, at these low levels, the uncertainties associated with the measurements make it difficult to determine whether the ores were in secular equilibrium (all radionuclides in each of the uranium and thorium series having equal activity concentrations to one-another). The data do suggest that many of the ores may have elevated levels of both radium isotopes, but this cannot be confirmed by these measurements.

The activity concentrations of the measured radionuclides in the products from the coal mines were also found to be lower than, or consistent with, the range expected from soils and were well below the reference activity concentration of 1000 Bq/kg. Indeed, the activity concentrations for Pb-210 were so low that it was not measurable in most cases and, so, is not shown in figure 11. Again, the measurements suggest that both radium isotopes may have elevated levels, but the uncertainty in the measurements preclude confirmation of this.

The activity concentration of the measured radionuclides in both the tailings and solid wastes from the coal mines were generally consistent with the range expected from normal soils and were well below the reference level of 1000 Bq/kg. For these samples, the uncertainties were relatively smaller and the data do indicate that both the tailings and solid wastes have elevated levels of both radium isotopes relative to the head of each series. The coarse reject material from mine s (sample s244) was found to have Ra-226 and Pb-210 activity concentrations slightly greater than that expected in normal soils. However, the measured levels in this sample were still an order of magnitude lower than the reference level.

The mine waters from the coal mines participating in this study were consistent with the activity concentrations of the measured radionuclides in normal waters. However, the activity levels of U-234 were found to be relatively high in most of the process waters. These process waters are highly recycled and, hence, have the opportunity to leach this element from a very large amount of material. That is, each litre of water may have passed over many tonnes of crushed ore and, even if only a tiny fraction of the U-234 is leached from each tonne, a relatively large amount of this radionuclide could be dissolved in the water.

Also of interest is the observation that in most cases the activity concentration of Ra-226 is an order of magnitude lower than that of uranium. It could be that Ra-226 is not as easily leached as uranium from coal. However, it could also be that Ra-226 precipitates out in the recirculation system. This could well be the case if the process water contains sulphates or carbonates and is basic (high pH). Unfortunately, this survey did not investigate whether these mines had issues with scale formation. The large disequilibrium between uranium and radium in the process water and whether the radium precipitates out in the system should be further investigated.

3.4 Radon in Underground Mines

The results from the initial survey are shown in figure 15. The measured radon concentrations are indicated by the height of the individual bars, while the error bars indicate the 95% confidence limits for each measurement. The bars are shaded to more easily differentiate data from different mines. The dark grey horizontal line shows the action level for occupational exposure (1000 Bq/m^3; ARPANSA, 2002).

For most of the minesites, the averages of the measured radon concentrations were below the action level for occupational exposure.

For operator o, the average of the measured concentrations exceeded the action level. The two measurements were carried out at mine extraction exhaust locations, and so it is possible that concentrations in other parts of the mine are lower than at these locations.

A further set of monitors were sent to operators o and y to be placed in the working areas of the mine as a follow-up survey. Monitors were in place in the period February-April 2012 (Figure 16). In the case of operator o, there were two underground mines being worked in the same region, and sufficient monitors were supplied to make measurements in both mines on this occasion. The repeat results for the first mine are designated o31-o36 and those from the second (new) mine are designated o21-o26. The repeat results for the other operator are designated y21-y26. For all three minesites, the averages of the radon concentrations measured were below the action level.

Overall, variability in radon concentrations between minesites was quite large with averages at each mine ranging from less than 100 Bq/m^3 to above 800 Bq/m^3. There was also high variability between samples at each individual mine. This was to be expected considering the different types of location for detectors chosen at each of the mines. A number of detectors were placed in mine exhausts, but some detectors were also placed in well ventilated areas where radon concentrations could be expected to be low. The results are presented in Table 3.

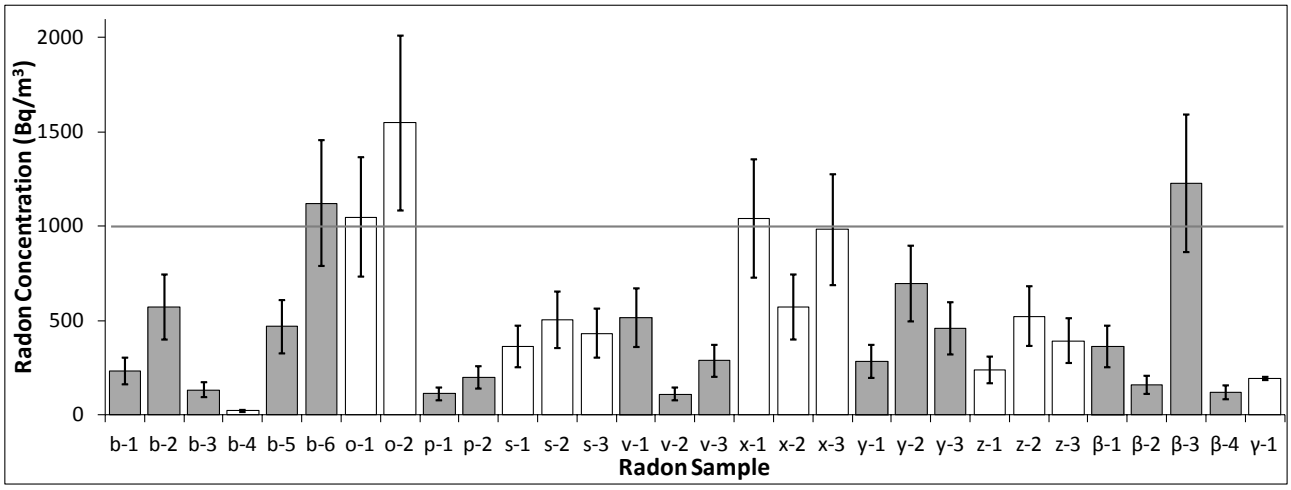

Figure 15: Measured radon concentration in underground mines, March-May 2011.
The error bars indicate the 95% confidence interval of the measurements.
The horizontal line indicates the action level for occupational exposure to radon.

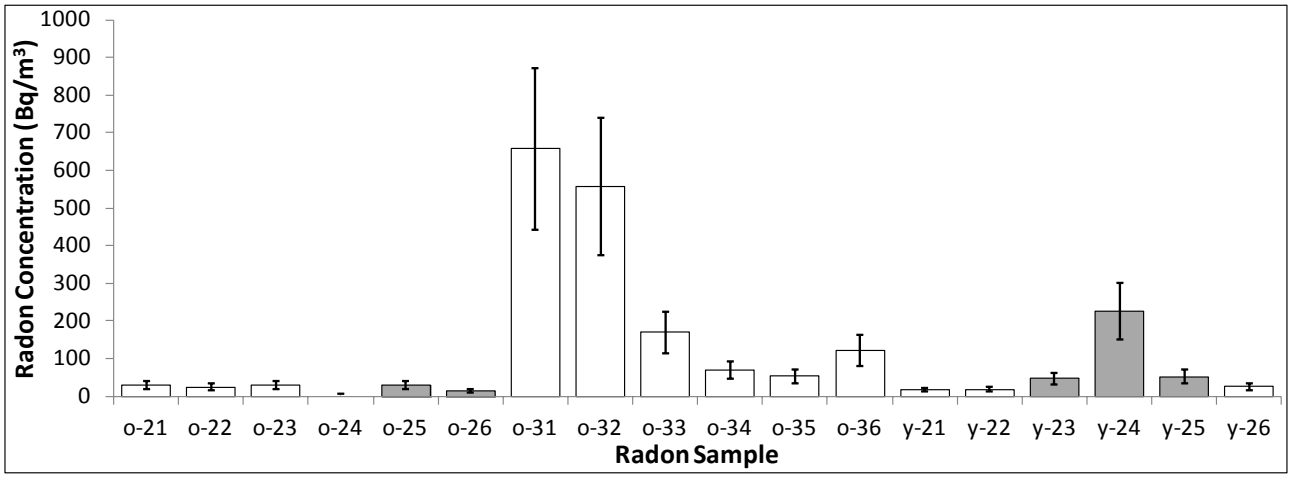

Figure 16: Measured radon concentration at work areas in mines, February-April 2012. The error bars indicate the 95% confidence interval of the measurements.

Table 3: Placement of radon monitors at mines, and average and range of measured radon concentrations

Mine	Number of Monitors	Date Placed	Days in Place	Average Rn (Bq/m^3)	Range (Bq/m^3)
b-1-6	6	March 2011	54	420	20-1120
o-1,2 o-31-36	2 6	April 2011 February 2012	14 31	1300 270	1050-1550 50-660
p-1,2	2	April 2011	83	160	110-200
s-1,2,3	3	April 2011	21	430	360-500
v-1,2,3	3	April 2011	34	300	110-520
x-1,2,3	3	May 2011	14	860	570-1040
y-1,2,3 y-21-26	3 6	May 2011 February 2012	15 30	480 70	280-700 20-230
z-1,2,3	3	May 2011	36	380	240-520
β-1,2/3,4	2	May-June 2011	37,48	470	120-1230
o-21-26	6	February 2012	41	20	0-30

4. Conclusion

In most cases, the activity concentrations of the U-238 and Th-232 decay series radionuclides in the ore, tailings and solid waste from all of the mine types were found to be consistent with the range expected from soils (20 – 70 Bq/kg). Furthermore, in most cases, the radionuclides in each series were found to be in secular equilibrium, indicating that the processing of the ores does not significantly alter the elemental composition of the materials.

Almost all of the waters from the mines exhibited significant enhancement of U-234. They also exhibit significant variations in the activity concentrations of the other radionuclides in the series relative to U-238. Nonetheless, the actual activity concentrations in most of the water samples were low and most would meet the Australian Drinking Water Guidelines (NHMRC 2004) in terms of radioactivity.

These results indicate that most mining operations do not have issues relating to elevated levels of naturally occurring radioactive materials.

The significant exceptions were three metalliferous mines which were found to have activity concentrations of U-238 and Th-232 decay series radionuclides in the ore, products, tailings and solid wastes approaching the regulatory reference level of 1000 Bq/kg. However, all three of these mines extract heavy metal products from the ores and are already covered by a specific code of practice (ARPANSA 2005).

While the mine waters from the coal mines were consistent with the activity concentrations found in normal waters, the activity levels of U-234 were found to be relatively high in most of the process waters. It was noted that these process waters were highly recycled, enabling this radionuclide to accumulate over time. It was also noted that the highly recycled process waters were relatively depleted in Ra-226. The large disequilibrium between uranium and radium in the process water and whether the radium precipitates out in the system should be further investigated.

The measurements of radon from the underground mines gave average radon concentrations which were below the action level for occupational exposure (1000 Bq/m^3), for the period and locations measured. However, variability in concentrations was quite high, both within and between minesites. The high variability between sampling locations within some minesites is most probably due to the effects of varying ventilation rates in different areas and accumulation of radon in the air stream as it passes through the mine workings. Average mine concentrations ranged from less than 100 Bq/m^3 to above 800 Bq/m^3. Given the high variability observed, and the limited number of mines sampled, this study indicates that it is likely some underground mines may be above the action level.

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Appendix A: Tabulated Results for Quarries

In the following tables:

The quoted uncertainties indicate the 95% confidence interval.
The term 'Not Available' means that sample could not be chemically treated in order to extract these radionuclides.
The term 'MDC' refers to estimate of the smallest activity concentration of the radionuclide that can be quantified with 95% confidence.
The term '<MDC' means that the activity concentration of the radionuclide could not be quantified in the sample.

Table A1: Activity Concentration (Bq/kg) of Radionuclides in Ore

Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238	Thorium-228	Radium-228	Thorium-232
a117	27.3 ± 4.4	17 ± 16	25.1 ± 3.5	Not Available	28.6 ± 4.4	30.6 ± 4.6	20.8 ± 3.1	20.1 ± 4.8	Not Available
a118	26.3 ± 4.6	42 ± 18	26.7 ± 4.1	Not Available	28.3 ± 4.6	28.7 ± 4.6	22.2 ± 3.3	17.5 ± 5.8	Not Available
e137	14.1 ± 3.4	13 ± 9	13.6 ± 2.1	13.5 ± 5.3	14.8 ± 2.8	14.3 ± 2.7	17.6 ± 2.5	22.0 ± 4.0	14.9 ± 5.5
i170	15.2 ± 3.1	25 ± 11	18.6 ± 2.8	Not Available	10.9 ± 2.4	10.7 ± 2.4	19.0 ± 2.8	21.6 ± 4.5	Not Available
j171	30.7 ± 5.7	32 ± 17	32.0 ± 4.2	Not Available	32.9 ± 6.2	29.3 ± 5.8	43.9 ± 6.0	43.0 ± 6.3	Not Available
j172	27.4 ± 4.6	19 ± 16	28.6 ± 3.7	Not Available	28.7 ± 5.1	33.9 ± 5.8	43.2 ± 5.9	42.9 ± 6.5	Not Available
q223	<MDC	<MDC	<MDC	Not Available	<MDC	<MDC	<MDC	<MDC	Not Available
r226	5.0 ± 2.5		4.3 ± 1.2	Not Available	7.2 ± 2.5	6.0 ± 2.1	4.0 ± 1.1	<MDC	Not Available
MDC	*4.0*	*20*	*10*	*4.0*	*4.0*	*4.0*	*10*	*10*	*4.0*

Table A2: Activity Concentration (Bq/kg) of Radionuclides in Product

Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238	Thorium-228	Radium-228	Thorium-232
a119	28.0 ± 4.5	40 ± 22	24.6 ± 4.2	Not Available	27.9 ± 4.4	27.8 ± 4.3	21.9 ± 3.4	17.7 ± 5.6	Not Available
c130	27.0 ± 5.1	40 ± 14	28.2 ± 3.8	Not Available	29.6 ± 5.6	32.4 ± 5.9	39.5 ± 5.4	43.7 ± 6.7	Not Available
c131	42.5 ± 6.6	38 ± 18	28.7 ± 3.8	27.2 ± 7.6	34.2 ± 6.0	29.7 ± 5.4	40.4 ± 5.6	38.3 ± 6.7	40.3 ± 9.4
e138	14.6 ± 3.2	<MDC	14.8 ± 2.1	Not Available	13.4 ± 3.0	14.1 ± 3.1	15.5 ± 2.3	17.1 ± 3.8	Not Available
e139	18.6 ± 3.3	15 ± 12	14.8 ± 2.3	Not Available	14.5 ± 2.6	15.7 ± 2.7	15.7 ± 2.3	15.9 ± 2.9	Not Available
g150	53.2 ± 7.3	28 ± 15	51.0 ± 6.2	Not Available	58.0 ± 8.3	53.5 ± 7.8	63.1 ± 8.3	70.4 ± 9.5	Not Available
g151	59.1 ± 8.7	80 ± 22	49.7 ± 6.1	Not Available	58.7 ± 8.7	58.3 ± 8.6	65.8 ± 8.8	63.0 ± 8.9	Not Available
r227	8.4 ± 3.0	<MDC	7.5 ± 2.0	Not Available	7.5 ± 2.4	9.9 ± 2.7	3.5 ± 1.7	<MDC	Not Available
r228	4.4 ± 2.3	<MDC	7.4 ± 2.2	Not Available	9.7 ± 2.6	8.7 ± 2.4	2.3 ± 1.2	<MDC	Not Available
t247	26.6 ± 5.0	30 ± 17	26.3 ± 3.4	Not Available	33.9 ± 6.1	32.2 ± 5.9	58.7 ± 7.7	59.5 ± 8.1	Not Available
u249	15.3 ± 3.0	18 ± 9	15.0 ± 2.2	19.0 ± 8.6	17.7 ± 4.0	17.6 ± 3.9	20.8 ± 3.1	22.4 ± 4.2	31 ± 11
u250	14.9 ± 3.6	<MDC	12.0 ± 2.0	11.9 ± 5.7	14.0 ± 3.6	13.7 ± 3.5	22.3 ± 3.2	20.6 ± 4.1	25.7 ± 8.2
MDC	*4.0*	*20*	*10*	*4.0*	*4.0*	*4.0*	*10*	*10*	*4.0*

Table A3: Activity Concentration (Bq/kg) of Radionuclides in Tailings

Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238	Thorium-228	Radium-228	Thorium-232
d134	14.0 ± 3.7	29 ± 13	20.5 ± 2.8	21.7 ± 4.6	18.4 ± 3.7	18.6 ± 3.6	62.3 ± 8.1	61.7 ± 8.1	79 ± 12
d135	14.7 ± 4.5	<MDC	16.8 ± 2.4	13.3 ± 4.4	12.6 ± 2.8	13.5 ± 2.8	45.6 ± 6.1	44.0 ± 6.2	70 ± 12
MDC	*4.0*	*20*	*10*	*4.0*	*4.0*	*4.0*	*10*	*10*	*4.0*

Table A4: Activity Concentration (mBq/kg) of Radionuclides in Mine and Process Water

	Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238
Mine	a116	<MDC	<MDC	5.8 ± 5.8	<MDC	38.5 ± 7.4	17.8 ± 4.4
	c128	<MDC	<MDC	234 ± 28	<MDC	78.5 ± 12.0	19.9 ± 4.5
	c129	7.9 ± 3.0	<MDC	20.5 ± 7.2	<MDC	157 ± 23	45.3 ± 8.1
	e136	<MDC	<MDC	<MDC	<MDC	27.0 ± 5.5	19.2 ± 4.4
	g149	9.1 ± 4.7	67 ± 23	<MDC	<MDC	1230 ± 160	750 ± 100
	q225	<MDC	<MDC	<MDC	<MDC	21.2 ± 7.0	13.5 ± 4.8
	r229	39.9 ± 7.5	40 ± 34	<MDC	<MDC	40.8 ± 9.8	25.6 ± 6.6
	t248	73 ± 11	<MDC	136 ± 20	<MDC	72 ± 11	54.1 ± 8.7
	u251	31.3 ± 6.0	114 ± 34	<MDC	<MDC	40.1 ± 7.3	15.5 ± 4.0
	v257	36.6 ± 6.7	55 ± 30	<MDC	<MDC	100 ± 15	60.2 ± 9.8
Process	d132	7.6 ± 3.0	<MDC	14.3 ± 6.5	<MDC	3.5 ± 1.9	2.3 ± 1.5
	d133	<MDC	<MDC	<MDC	<MDC	2.8 ± 1.7	1.9 ± 1.4
	q224	<MDC	<MDC	<MDC	<MDC	11.4 ± 3.5	5.7 ± 2.3
	q255	57.7 ± 9.4	51 ± 30	<MDC	<MDC	87 ± 13	50.8 ± 9.0
	v256	40.6 ± 7.2	58 ± 31	8.2 ± 8.2	<MDC	85 ± 12	57.9 ± 9.1
	x396	65 ± 10	61 ± 34	20 ± 10	2.9 ± 2.4	13.5 ± 3.7	7.4 ± 2.5
	MDC	*4.0*	*40*	*10*	*4.0*	*4.0*	*4.0*

Appendix B: Tabulated Results for Metalliferous and Other Mines

In the following tables:
The quoted uncertainties indicate the 95% confidence interval.
The term 'Not Available' means that sample could not be chemically treated in order to extract these radionuclides.
The term 'MDC' refers to estimate of the smallest activity concentration of the radionuclide that can be quantified with 95% confidence.
The term '<MDC' means that the activity concentration of the radionuclide could not be quantified in the sample.

Table B1: Activity Concentration (Bq/kg) of Radionuclides in Ore

Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238	Thorium-228	Radium-228	Thorium-232
f141	2.6 ± 1.3	<MDC	2.9 ± 1.1	3.5 ± 2.7	2.2 ± 1.0	3.3 ± 1.1	4.5 ± 1.2	<MDC	3.2 ± 2.3
f142	2.3 ± 1.7	<MDC	4.4 ± 1.1	3.0 ± 1.8	4.1 ± 2.0	4.1 ± 1.4	5.4 ± 1.3	5.1 ± 2.5	4.8 ± 1.5
f147	9.2 ± 3.0	9.6 ± 3.9	3.7 ± 0.6	2.8 ± 1.5	2.9 ± 1.2	2.5 ± 1.1	3.9 ± 0.8	4.0 ± 1.2	4.0 ± 1.2
f148	1.7 ± 1.6	<MDC	4.3 ± 0.9	3.1 ± 1.7	4.2 ± 1.6	4.0 ± 1.4	3.1 ± 0.5	2.9 ± 0.9	2.5 ± 1.3
p221	9.9 ± 3.1	<MDC	8.0 ± 1.5	Not Available	8.1 ± 3.4	9.5 ± 3.6	8.1 ± 1.7	8.8 ± 3.5	Not Available
p222	8.7 ± 3.0	<MDC	10.2 ± 2.2	Not Available	8.6 ± 2.7	10.3 ± 2.9	7.2 ± 1.7	<MDC	Not Available
v253	41.0 ± 6.1	17.4 ± 8.9	31.1 ± 3.8	Not Available	34.6 ± 5.1	36.1 ± 5.3	10.5 ± 1.6	11.0 ± 2.7	Not Available
w258	895 ± 100	940 ± 140	706 ± 78	1130 ± 150	1100 ± 130	1400 ± 130	1110 ± 140	1200 ± 140	1300 ± 170
x398	16.5 ± 3.6	20.3 ± 9.8	14.7 ± 2.1	Not Available	14.7 ± 3.5	15.8 ± 3.6	24.6 ± 3.4	22.3 ± 4.1	Not Available
y400	11.6 ± 2.7	8.3 ± 7.5	11.7 ± 1.9	Not Available	12.7 ± 2.7	11.5 ± 2.6	7.2 ± 1.6	6.4 ± 2.6	Not Available
z408	25.8 ± 5.6	27.9 ± 12.2	24.4 ± 3.3	Not Available	20.0 ± 4.7	21.0 ± 4.6	31.9 ± 4.5	27.7 ± 4.8	Not Available
α427	460 ± 59	563 ± 88	1220 ± 130	523 ± 74	560 ± 66	551 ± 65	789 ± 97	855 ± 99	860 ± 110
α432	628 ± 77	392 ± 69	758 ± 83	560 ± 81	572 ± 66	559 ± 65	2330 ± 290	2460 ± 280	2380 ± 300
α433	810 ± 110	680 ± 110	1750 ± 190	725 ± 126	935 ± 110	920 ± 106	3100 ± 380	3330 ± 380	2345 ± 780
β437	27.1 ± 5.6	17.1 ± 8.5	31.6 ± 3.7	29.6 ± 6.5	29.9 ± 5.5	29.7 ± 5.4	30.6 ± 4.0	31.3 ± 4.2	27.6 ± 6.1
MDC	*4.0*	*20*	*10*	*4.0*	*4.0*	*4.0*	*10*	*10*	*4.0*

Table B2: Activity Concentration (Bq/kg) of Radionuclides in Product

Sample	Polonium-210		Lead-210		Radium-226		Thorium-230		Uranium-234		Uranium-238		Thorium-228		Radium-228		Thorium-232	
f143	170	± 24	393	± 60	579	± 64	165	± 26	204	± 27	175	± 24	408	± 51	446.0	± 52.0	472	± 62
f144	11.3	± 3.2		<MDC	1.6	± 0.5		<MDC		<MDC	1.7	± 1.0	1.3	± 0.5	1.6	± 0.8	1.7	± 0.8
f145	3.5	± 1.9		<MDC	2.5	± 0.5		<MDC	1.9	± 1.1	2.2	± 1.1	1.5	± 0.4	2.0	± 0.7	1.7	± 0.9
o216	25.2	± 4.5	13	± 12	16.5	± 2.6	Not Available		16.0	± 3.4	17.6	± 3.6	16.5	± 2.5	19.1	± 3.8	Not Available	
o544	20.1	± 3.9	24.7	± 9.0	18.5	± 2.2	21.4	± 7.0	19.9	± 3.7	20.6	± 3.7	16.7	± 2.3	13.5	± 2.4	21.6	± 6.9
o545	7.4	± 2.4		<MDC	6.1	± 1.3	4.8	± 2.4	7.5	± 2.0	8.4	± 2.1	5.6	± 1.0	6.8	± 2.6	4.5	± 2.1
p220	9.0	± 3.4		<MDC	7.0	± 1.4	Not Available		6.2	± 2.6	7.0	± 2.6	5.5	± 1.0	6.3	± 2.6	Not Available	
v252	9.5	± 2.5		<MDC	8.7	± 1.4	Not Available		9.6	± 2.2	7.9	± 1.9	2.4	± 0.5	3.4	± 1.5	Not Available	
x395	7.5	± 2.2		<MDC	7.1	± 1.1	7.0	± 2.9	9.2	± 2.3	9.5	± 2.6	10.4	± 1.5	10.9	± 1.9	11.2	± 2.8
y401	6.8	± 2.1		<MDC	5.3	± 1.0	6.9	± 3.0	5.7	± 1.8	5.7	± 1.8	1.4	± 0.4		<MDC	1.2	± 0.9
y402	16.2	± 3.6		<MDC	14.6	± 1.7	12.6	± 4.4	15.6	± 3.5	14.9	± 3.3		<MDC		<MDC	2.2	± 1.4
y405	14.6	± 3.8		<MDC	12.7	± 2.1	11.6	± 6.8	17.9	± 4.0	16.5	± 3.6		<MDC		<MDC	0.0	0.0
y406	4.6	± 1.6		<MDC	3.9	± 0.9	4.2	± 3.1	4.0	± 2.1	6.6	± 2.2	1.4	± 0.6		<MDC	1.5	± 1.2
z410	19.8	± 4.4		<MDC	13.0	± 2.1	Not Available		13.4	± 3.3	14.0	± 3.2	11.0	± 2.0	13.2	± 2.7	Not Available	
α429	293	± 40	161	± 31	273	± 30	244	± 44	227	± 28	205	± 25	566	± 70	604	± 70	593	± 88
α430	4880	± 550	2650	± 400	7270	± 790	601	± 73	5130	± 580	5230	± 590	36000	± 4400	37400	± 4300	890	± 110
α431	505	± 71	500	± 76	1340	± 150	573	± 68	609	± 70	622	± 71	910	± 110	970	± 110	826	± 96
β435	13.9	± 3.3		<MDC	11.9	± 1.8	Not Available		11.3	± 2.6	11.9	± 2.6	8.2	± 1.3	12.5	± 2.6	Not Available	
β436	37.7	± 6.6		<MDC	24.8	± 2.8	32.0	± 5.1	17.4	± 3.7	16.8	± 3.5	5.8	± 0.8	9.4	± 1.4	6.6	± 1.8
MDC	*4.0*		*20*		*10*		*4.0*		*4.0*		*4.0*		*10*		*10*		*4.0*	

Table B3: Activity Concentration (Bq/kg) of Radionuclides in Solid Waste

Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238	Thorium-228	Radium-228	Thorium-232
x397	7.7 ± 3.3	<MDC	6.4 ± 0.9	Not Available	6.0 ± 2.3	3.5 ± 1.7	8.0 ± 1.2	10.8 ± 1.7	Not Available
z411	19.8 ± 4.2	19.2 ± 7.6	22.7 ± 2.7	Not Available	20.3 ± 4.2	25.0 ± 4.6	27.3 ± 3.6	26.5 ± 3.6	Not Available
α428	85 ± 17	72 ± 18	84.9 ± 9.7	79 ± 16	87 ± 12	81 ± 11	106 ± 13	108 ± 13	114 ± 21
MDC	*4.0*	*20*	*10*	*4.0*	*4.0*	*4.0*	*10*	*10*	*4.0*

Table B4: Activity Concentration (Bq/kg) of Radionuclides in Tailings

Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238	Thorium-228	Radium-228	Thorium-232
o543	11.9 ± 4.1	<MDC	8.7 ± 1.7	5.5 ± 4.8	Not Available	Not Available	8.7 ± 1.4	9.0 ± 3.7	12.3 ± 6.8
p219	11.0 ± 2.9	<MDC	11.0 ± 2.8	Not Available	8.9 ± 2.7	8.2 ± 2.5	8.1 ± 2.6	<MDC	Not Available
v254	43.2 ± 8.2	42 ± 12	39.4 ± 4.8	48 ± 13	38.6 ± 6.4	36.6 ± 6.1	11.2 ± 1.8	11.7 ± 2.9	17.2 ± 7.0
x399	22.2 ± 4.6	<MDC	23.1 ± 4.0	Not Available	20.5 ± 4.6	19.6 ± 4.5	38.5 ± 5.6	32.7 ± 6.3	Not Available
y403	12.1 ± 2.5	<MDC	11.8 ± 1.8	13.1 ± 3.8	10.7 ± 2.3	12.4 ± 2.4	7.9 ± 1.3	8.1 ± 2.4	9.9 ± 2.9
z409	22.9 ± 5.0	23 ± 14	24.7 ± 3.3	21.8 ± 8.2	23.2 ± 5.1	25.2 ± 5.2	32.2 ± 4.5	25.5 ± 4.4	25.3 ± 8.1
z412	23.2 ± 4.8	19 ± 13	24.5 ± 3.0	Not Available	24.8 ± 4.9	22.3 ± 4.4	31.2 ± 4.2	30.5 ± 4.4	Not Available
β438	31.6 ± 5.3	40 ± 13	41.8 ± 5.1	26.1 ± 6.0	30.0 ± 4.9	29.5 ± 4.8	36.5 ± 4.9	34.4 ± 5.3	32.3 ± 6.7
MDC	*4.0*	*20*	*10*	*4.0*	*4.0*	*4.0*	*10*	*10*	*4.0*

Table B5: Activity Concentration (mBq/litre) of Radionuclides in Mine and Process Water

	Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238
Mine	f146	5.6 ± 3.8	<MDC	<MDC	<MDC	<MDC	<MDC
	o214	<MDC	80 ± 29	52 ± 11	<MDC	778 ± 91	536 ± 64
	o215	22.7 ± 5.0	64 ± 30	<MDC	<MDC	23.3 ± 6.3	21.1 ± 5.6
	o542	<MDC	<MDC	<MDC	<MDC	<MDC	<MDC
	p218	<MDC	<MDC	9.1 ± 7.5	<MDC	46 ± 11	16.8 ± 5.0
	z413	46.1 ± 8.1	81 ± 35	115 ± 18	2.2 ± 2.5	59.8 ± 9.4	27.6 ± 5.3
	β440	17.7 ± 4.7	77 ± 45	<MDC	65.1 ± 9.9	185 ± 24	151 ± 20
Process	f140	5.8 ± 3.5	35 ± 20	26.1 ± 7.1	<MDC	16.7 ± 5.0	11.1 ± 3.9
	o213	<MDC	<MDC	<MDC	<MDC	11.9 ± 4.2	5.7 ± 2.5
	p217	3.8 ± 2.3	<MDC	<MDC	<MDC	18.6 ± 5.0	15.4 ± 4.2
	y404	6.8 ± 3.0	4.1 ± 3.2	<MDC	<MDC	3.9 ± 2.0	2.4 ± 1.3
	z414	69 ± 15	<MDC	76 ± 18	<MDC	<MDC	<MDC
	z415	16.5 ± 5.6	70 ± 34	73 ± 15	<MDC	27.6 ± 5.6	16.1 ± 3.9
	α434	2.4 ± 2.3	122 ± 47	13 ± 13	25.5 ± 5.3	101 ± 14	127 ± 17
	β439	12.9 ± 3.9	135 ± 48	77 ± 18	<MDC	15.9 ± 4.1	11.8 ± 3.3
	MDC	*4.0*	*40*	*10*	*4.0*	*4.0*	*4.0*

Appendix C: Tabulated Results for Collieries

In the following tables:
The quoted uncertainties indicate the 95% confidence interval.
The term 'Not Available' means that sample could not be chemically treated in order to extract these radionuclides.
The term 'MDC' refers to estimate of the smallest activity concentration of the radionuclide that can be quantified with 95% confidence.
The term '<MDC' means that the activity concentration of the radionuclide could not be quantified in the sample.

Table C1: Activity Concentration (Bq/kg) of Radionuclides in Ore

Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238	Thorium-228	Radium-228	Thorium-232
b122	16.9 ± 4.3	22.9 ± 9.3	23.5 ± 2.5	17.1 ± 3.7	15.1 ± 3.7	11.7 ± 3.1	22.0 ± 3.0	17.5 ± 2.9	16.7 ± 3.6
b123	15.2 ± 4.6	28.2 ± 8.9	18.2 ± 2.3	16.1 ± 3.8	11.3 ± 3.7	10.9 ± 3.4	22.2 ± 3.0	19.7 ± 3.1	16.9 ± 3.9
h161	18.2 ± 6.3	27 ± 14	18.4 ± 3.5	10.8 ± 2.8	20.0 ± 4.3	15.6 ± 3.7	20.7 ± 3.8	20.8 ± 5.3	16.9 ± 3.2
h162	8.3 ± 4.5	<MDC	9.7 ± 2.7	8.8 ± 3.6	8.9 ± 3.3	9.8 ± 3.2	7.3 ± 3.0	13.0 ± 5.7	7.2 ± 2.5
k173	23.1 ± 5.8	26 ± 14	19.5 ± 3.0	14.3 ± 4.0	19.3 ± 5.5	18.0 ± 5.0	20.6 ± 3.1	19.5 ± 4.3	14.3 ± 3.5
k176	23.9 ± 4.6	22 ± 13	22.9 ± 3.0	Not Available	23.7 ± 4.3	23.8 ± 4.3	33.2 ± 4.5	38.6 ± 5.2	Not Available
k177	19.4 ± 3.7	40 ± 18	23.8 ± 3.3	Not Available	23.9 ± 4.5	26.4 ± 4.8	32.5 ± 4.6	36.1 ± 5.9	Not Available
l182	8.6 ± 3.4	<MDC	4.8 ± 1.3	13.4 ± 3.7	5.6 ± 2.7	4.4 ± 2.2	14.0 ± 2.5	14.1 ± 3.7	10.3 ± 3.0
l183	15.2 ± 3.8	32 ± 11	20.9 ± 2.8	11.9 ± 3.2	11.5 ± 3.2	9.9 ± 2.8	23.6 ± 3.3	21.7 ± 4.4	15.1 ± 3.2
n190	4.4 ± 2.4	<MDC	<MDC	3.6 ± 2.2	5.2 ± 2.0	3.3 ± 1.6	6.0 ± 3.4	3.8 ± 2.6	4.6 ± 1.8
n191	5.6 ± 2.4	<MDC	6.4 ± 2.2	<MDC	5.2 ± 2.2	6.3 ± 2.3	5.0 ± 2.9	<MDC	4.8 ± 2.2
s241	15.7 ± 3.8	25 ± 16	22.2 ± 3.6	16.8 ± 3.3	16.4 ± 3.5	15.0 ± 3.3	27.0 ± 4.0	28.7 ± 6.8	19.8 ± 3.6
s242	27.7 ± 6.5	21 ± 16	23.8 ± 3.5	23.0 ± 5.2	17.3 ± 4.2	15.8 ± 3.9	34.6 ± 4.9	26.0 ± 4.9	29.7 ± 6.0
MDC	*4.0*	*20*	*10*	*4.0*	*4.0*	*4.0*	*10*	*10*	*4.0*

Table C2: Activity Concentration (Bq/kg) of Radionuclides in Product

Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238	Thorium-228	Radium-228	Thorium-232
b125	12.4 ± 5.5	<MDC	14.3 ± 2.2	12.0 ± 3.5	10.6 ± 3.5	10.3 ± 3.2	13.4 ± 2.5	15.7 ± 4.0	9.3 ± 3.0
b126	20.6 ± 6.2	30 ± 16	25.7 ± 3.3	16.9 ± 3.8	16.6 ± 3.9	12.9 ± 3.2	23.5 ± 3.4	24.9 ± 3.8	19.0 ± 4.0
h163	10.6 ± 4.7	<MDC	12.8 ± 2.8	7.0 ± 3.5	10.8 ± 4.0	10.9 ± 4.0	10.4 ± 2.7	7.3 ± 5.0	10.1 ± 3.0
h164	17.1 ± 8.0	29 ± 22	12.4 ± 3.0	13.1 ± 4.2	18.3 ± 6.4	15.5 ± 5.5	19.1 ± 3.9	19.2 ± 6.3	19.1 ± 4.3
h165	17.9 ± 7.3	26 ± 16	15.3 ± 2.7	9.8 ± 3.7	9.6 ± 3.9	12.8 ± 4.1	18.2 ± 3.3	19.6 ± 5.4	11.8 ± 3.2
k174	5.7 ± 2.3	<MDC	7.0 ± 2.2	5.3 ± 2.2	5.1 ± 2.7	4.4 ± 2.3	6.5 ± 2.1	<MDC	4.0 ± 1.6
l184	6.4 ± 3.0	<MDC	9.1 ± 2.0	7.3 ± 2.7	5.9 ± 2.7	5.5 ± 2.4	11.2 ± 1.9	10.4 ± 2.8	8.3 ± 2.4
m189	6.5 ± 3.6	<MDC	9.4 ± 3.2	5.4 ± 3.1	7.3 ± 3.2	3.8 ± 2.2	12.3 ± 2.8	15.1 ± 5.7	7.4 ± 2.7
n192	8.7 ± 3.0	<MDC	8.8 ± 3.8	4.4 ± 3.7	6.7 ± 2.8	7.5 ± 2.7	9.7 ± 3.4	8.7 ± 7.6	6.8 ± 2.9
n193	10.0 ± 4.0	<MDC	6.2 ± 3.2	5.1 ± 3.2	6.0 ± 2.8	3.9 ± 2.1	4.6 ± 3.2	<MDC	4.1 ± 1.9
s243	25.3 ± 5.8	<MDC	24.6 ± 3.6	20.6 ± 4.3	21.9 ± 4.8	18.9 ± 4.3	24.4 ± 3.8	24.8 ± 6.5	21.2 ± 4.3
MDC	*4.0*	*30*	*10*	*4.0*	*4.0*	*4.0*	*10*	*10*	*4.0*

Table C3: Activity Concentration (Bq/kg) of Radionuclides in Solid Waste

Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238	Thorium-228	Radium-228	Thorium-232
b124	37.4 ± 7.0	53 ± 14	46.5 ± 5.4	26.7 ± 4.7	26.9 ± 4.6	16.0 ± 3.2	56.5 ± 7.2	55.3 ± 6.9	35.7 ± 5.5
h166	21.2 ± 5.1	47 ± 16	20.8 ± 3.1	23.1 ± 4.9	22.2 ± 5.3	22.4 ± 5.1	38.7 ± 5.4	36.4 ± 6.8	29.4 ± 5.2
k175	18.4 ± 4.2	26 ± 17	28.4 ± 3.7	14.1 ± 3.3	15.1 ± 3.6	9.8 ± 2.7	43.8 ± 5.9	38.7 ± 5.7	20.1 ± 3.7
l185	17.0 ± 4.5	30 ± 11	18.7 ± 2.5	12.0 ± 4.3	10.8 ± 3.6	9.2 ± 3.1	21.9 ± 3.1	18.8 ± 3.3	11.3 ± 3.8
l186	20.4 ± 4.7	23 ± 12	26.1 ± 3.2	16.4 ± 3.8	14.5 ± 3.5	10.3 ± 2.8	31.4 ± 4.2	25.9 ± 3.9	9.8 ± 2.8
n194	20.7 ± 4.8	28 ± 15	22.2 ± 3.3	14.4 ± 3.6	17.3 ± 3.8	13.2 ± 3.2	32.0 ± 4.6	31.2 ± 5.9	22.5 ± 4.2
s244	35.6 ± 6.8	103 ± 24	76.2 ± 9.0	27.7 ± 5.1	30.6 ± 7.1	29.4 ± 6.8	54.8 ± 7.4	48.6 ± 7.3	38.0 ± 6.0
MDC	*4.0*	*20*	*10*	*4.0*	*4.0*	*4.0*	*10*	*10*	*4.0*

Table C4: Activity Concentration (Bq/kg) of Radionuclides in Tailings

Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238	Thorium-228	Radium-228	Thorium-232
b127	34.1 ± 6.8	45.0 ± 21.0	42.4 ± 5.4	30.1 ± 5.7	27.7 ± 5.5	21.4 ± 4.6	53.1 ± 7.2	59.8 ± 9.6	39.5 ± 6.5
h167	24.8 ± 5.7	34.0 ± 22.0	31.7 ± 4.5	29.3 ± 5.3	28.4 ± 5.9	24.6 ± 5.2	30.2 ± 4.5	41.6 ± 7.0	32.5 ± 5.4
k181	16.4 ± 5.4	24.0 ± 25.0	18.3 ± 4.4	12.0 ± 3.5	10.0 ± 3.2	8.3 ± 2.7	32.0 ± 5.0	25.0 ± 6.2	9.7 ± 3.0
l187	39.9 ± 8.2	43.0 ± 19.0	34.3 ± 4.7	21.7 ± 4.6	14.2 ± 3.8	15.9 ± 3.8	43.2 ± 6.0	48.8 ± 8.7	23.4 ± 4.8
n195	Not Available	Not Available	20.3 ± 4.8	Not Available	Not Available	Not Available	Not Available	31.9 ± 8.9	Not Available
MDC	*4.0*	*30*	*10*	*4.0*	*4.0*	*4.0*	*10*	*10*	*4.0*

Table C5: Activity Concentration (mBq/litre) of Radionuclides in Mine and Process Water

	Sample	Polonium-210	Lead-210	Radium-226	Thorium-230	Uranium-234	Uranium-238
Mine	b121	<MDC	<MDC	13.3 ± 3.0	<MDC	274.0 ± 75.0	74.0 ± 16.0
	h169	<MDC	<MDC	<MDC	<MDC	88.0 ± 13.0	26.2 ± 5.5
	k178	<MDC	<MDC	21.7 ± 8.7	4.6 ± 3.9	223.0 ± 28.0	46.8 ± 8.0
	s246	41.4 ± 7.4	46.0 ± 29.0	<MDC	<MDC	5.3 ± 2.8	3.0 ± 2.1
Process	b120	<MDC	52.0 ± 27.0	7.9 ± 7.8	<MDC	433.0 ± 63.0	185.0 ± 29.0
	h168	4.8 ± 3.0	21.0 ± 26.0	12.0 ± 7.9	<MDC	89.0 ± 13.0	30.6 ± 6.0
	k179	<MDC	<MDC	10.7 ± 8.2	<MDC	751.0 ± 94.0	221.0 ± 31.0
	k180	<MDC	<MDC	35.3 ± 9.7	1.8 ± 1.2	1240.0 ± 140.0	305.0 ± 38.0
	l188	<MDC	<MDC	14.3 ± 9.5	<MDC	359.0 ± 44.0	78.0 ± 12.0
	n196	<MDC	<MDC	60.0 ± 12.0	<MDC	188.0 ± 25.0	128.0 ± 18.0
	s245	31.2 ± 6.0	54.0 ± 31.0	43.0 ± 11.0	<MDC	12.3 ± 3.8	3.8 ± 2.2
	MDC	*4.0*	*40*	*10*	*4.0*	*4.0*	*4.0*