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Dalgety Bay Headland Investigation

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ENVIRONMENTAL
RADIOACTIVITY LABORATORY

UNIVERSITY OF STIRLING

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Executive Summary

The aim of this investigation was to establish the presence of ^{226}Ra within the made ground that today forms the headland at Dalgety Bay. Following a preliminary site survey with ground penetrating radar and in the presence of an unexploded ordinance engineer, the site was carefully penetrated by auguring and manual excavation. A NaI(Tl) detector coupled with spectral analysis was used to confirm the presence of ^{226}Ra at depth. The spectra were used to estimate ^{226}Ra activity concentrations and to identify the possible presence of ^{226}Ra particles and their likely activity. The results indicated the presence of ^{226}Ra particles of the order of a few 10s kBq at a number of locations. Whilst the radius of investigation of each in-situ measurement within an augured hole is limited to around 300 mm, areas where ^{226}Ra contamination was consistently detected were delineated and mapped. Part of the site (to the eastern corner) is also heavily modified with rock armour, which may act as a conduit for ^{226}Ra particle or artefact movement.

1. Introduction

Since the first discovery of ^{226}Ra sources[1] (particles) at Dalgety Bay (Dale *et al.,* 2009; 2011), the continuing re-occurrence of ^{226}Ra contaminated particles and artefacts on the foreshore areas of the sailing club at Dalgety Bay has led to several hypotheses relating to the origin and pathways of these particles entering the environment that may then result in potential exposures to members of the public. The headland area (Figure 1) is an area of made ground, following the deposition of waste during and following the decommissioning of RNAS Donibristle and HMS Merlin after 1945. There appears to be very little information recorded that documents the waste materials used to make the new ground at the headland site. Today, the made ground underlies the sailing club house and grassed area immediately to the south and west of the club house.

The aim of this investigation was to determine whether radium contamination was present in the headland with the minimal disturbance to the current use of the site. If radium contamination was detected estimates of the potential ^{226}Ra concentrations would be made.

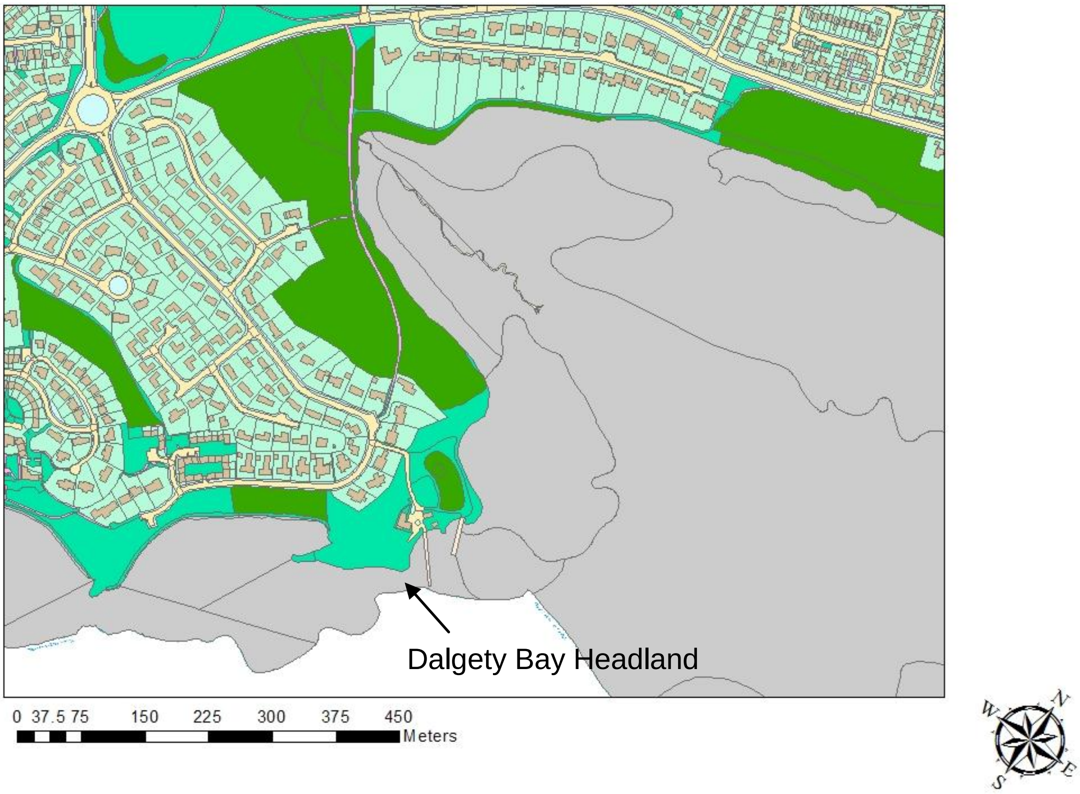


Figure 1. Map showing the location of the made ground forming the headland at Dalgety Bay

[1] The radioactive sources recovered from Dalgety Bay range in physical size from 'dust' to large pebbles and include artefacts from instrumentation of aircraft such as dials. Together with these sources, radioactive artefacts have been detected and recovered from Dalgety Bay. Many of these sources may pose a significant hazard to members of the public if they were to encounter these either inadvertently or from preferential selection of artefacts.

2. Methodology

2.1 Overview

Very little is known of the history of the site other than it is an area of made ground, following the deposition of waste material from MoD activities to the end of the war. In addition to radioactive substances, prior to investigation of this area a risk assessment had to take into account a range of waste materials including asbestos, heavy metals, acid and alkaline substances, contaminated ash, and unexploded ordinance (UXO). Added to this was the requirement of minimising site disturbance, as the attractiveness of the site has made it a very popular location for wedding photographs as well as for walkers.

A staged approach to the site investigation was therefore adopted to gather intelligence on the site prior to any intrusive investigation.

i) Use ground penetrating radar (GPR) to delineate areas of interest. In detail, the GPR established the depth of the made ground to bed rock, identified any morphological features that may provide information on the construction and infill structure of waste materials, and identified any artefacts that may indicate the presence of UXO, which needed to be avoided.

ii) Use surface gamma survey to identify possible areas of contamination.

iii) Using the information from above, areas to investigate were delineated, a magnetometer was used to identify areas of increased ferrous material concentration, which were marked as areas to be cautious of.

iv) In-situ gamma spectrometry of surface locations and cores excavated into the headland. Gamma spectrometry down profile was used to identify any areas of elevated ^{226}Ra contamination and the spectral information interpreted to establish the possible presence of particulate or relatively uniformly contaminated ^{226}Ra material.

The field sampling campaign was undertaken over a five day period from the 12th to the 16th September, 2011.

2.2 Ground Penetrating Radar (GPR)

A Mala Geoscience GPR system was deployed. This system comprises a tablet-type computer viewer (XV11), connected to a backpack control unit (CU11), via parallel-port printer cable. All antennae used connect to the CU via fibre optic ports. Four antennae were deployed: unshielded 50MHz rough terrain, 100MHz and 200MHz unshielded, and 500MHz shielded. The thin (2-3m) nature of unconsolidated material on bedrock precluded use of the 50MHz unit, as it did not achieve successful penetration. Thus the majority of transects (9 lines) were shot using 100 and 200 MHz antennae. Figure 2 illustrates the deployment of the instrumentation. Appendix A provides some background information to GPR survey work.

Figure 2. Deployment of GPR: 50MHz (image left) and 200 MHz (image right)

2.3 In-Situ Gross Gamma Survey

A gross counts gamma survey was undertaken with a Scintrex GIS-5 Integrating Spectrometer, with a 50mm x 50mm NaI(Tl) crystal. Counts were integrated across the U, Th and K windows and acquired for 30 s. Gross counts were recorded along with the GPS location (± 2 m positional accuracy).

2.4 In-situ Magnetometer Survey

Figure 3. Magnetometer deployment

Prior to the commencement of any excavation or coring work, the site and coring location was surveyed with a 48mm diameter magnetometer, which was also deployed down a auger hole with a nominal 60 mm diameter. The magnetometer was deployed by an RPS Explosives Safety Engineer who surveyed the site for the presence of ferro-metallic objects. Once the engineer was satisfied that the site was clear of anomalies, the excavation of coring commenced. The engineer surveyed the excavation or auger holes every 30 cm or so, and the instrument was able to provide a 1m "look ahead" capability. The engineer also inspected the material being investigated for evidence of ferro-metallic material or objects. Anomalies were frequently encountered and progress on a number of sites was only achieved with the help of the engineer (Figure 3).

2.5 Excavation

To minimise site disturbance, the preferred method of excavation was by auguring holes of 70 mm diameter into the site. However, at about 150 mm into the soil cover, a number of locations have been armoured by clay/rock hard-core and or slabs of concrete (Figure 4). Where auguring was not possible, excavation was achieved by a combination of digging and use of pickaxes. All soil and waste from auguring and digging was monitored using the RT30 portable gamma detector, bagged or piled onto plastic sheets to protect the surface of the site (Figure 4). The excavated surface was also routinely monitored following every few centimeters of excavation to identify areas or points of contamination and establish whether the count rate was increasing with increasing penetration into the site.

Where surface radioactive contamination was detected, turf was lifted and checked for contamination. The excavation proceeded carefully until any contaminated particles or artefacts were removed (Figure 4).

Figure 4. Site Excavation: Combined, digging and auguring (image top left); surface excavation (image top right); buried slabs of concrete (lower image).

2.6 In-situ gamma spectrometry

2.6.1 In-situ HPGe detector

A high purity germanium (HPGe) in-situ gamma spectrometer, 35% relative efficiency n-type detector was deployed on two sites of surface contamination to provide an indication of surface activity.

2.6.2 In-situ and auger-hole gamma spectrometry with NaI(Tl) technology

A 50 mm x 50 mm NaI(Tl) detector coupled to a Digibase system was cased within a 60 mm diameter white plastic pipe, that could be lowered to over 2 m depth. The detector and laptop were connected to and powered by a laptop, and spectra acquired and processed with Oterc's Scintivision software.

Prior to deployment, an experiment was performed at Stirling University to:

(i) calibrate the detector for ^{226}Ra activity estimation, primarily from the ^{214}Bi daughter (assuming ^{214}Bi is equilibrium with the parent).

(ii) evaluate whether there was potential for differentiating between a uniformly contaminated waste (or numerous particles) or the presence of a discrete particle at some distance from the detector.

The in-situ calibration site at Stirling University was augured in the same way as undertaken at Dalgety Bay. The detector was lowered within its plastic tube to about 800 mm depth. At 100 mm intervals a 600s spectrum was recorded. The augured hole was then cored by a 105 mm diameter golf hole corer. The core was section to 100 mm intervals and analysed in accordance with Stirling's ISO 17025 accredited procedures. The wet weight specific activity concentrations for ^{214}Bi were then used to calibrate the in situ measurements.

Net area counts were extracted from the NaI(Tl) detector for ^{214}Bi peaks at 609 keV and 1764 keV and a calibration derived from direct comparison with the laboratory derived specific activities.

A simple experiment was set up to establish the efficacy of identifying the presence of point sources of ^{226}Ra, through the differential attenuation of the two full energy peaks at 609 keV and 1764 keV (Tyler, 2007). The detector was set up beneath a bucket and a 68 kBq ^{226}Ra particle was sealed into a floating geometry above the detector and raised to fixed distances from the detector by carefully adding water to the bucket. This effectively increased the distance between the particle and the detector and adding water increased the differential attenuation between the detector and the particle in a similar way to increasing soil or waste depth (Figure 5).

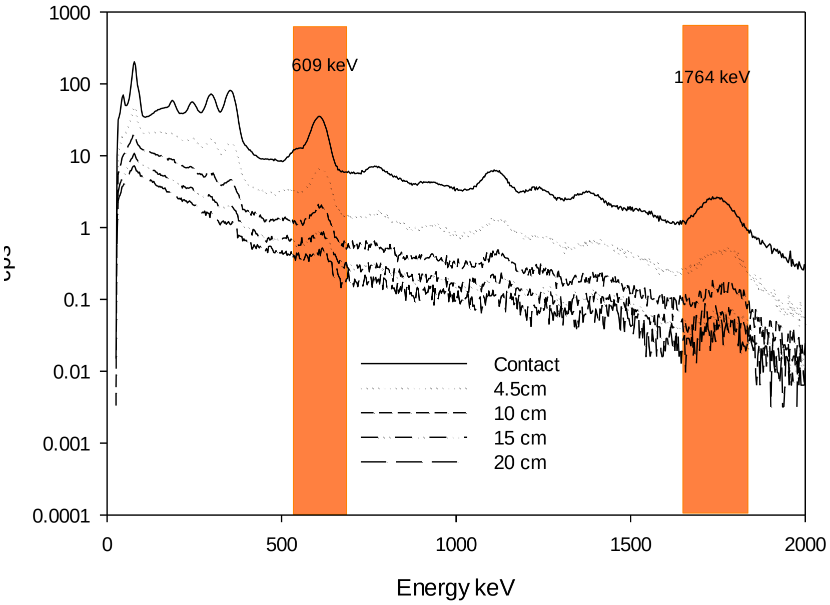


Figure 5. Change in spectral shape with increasing attenuation by water

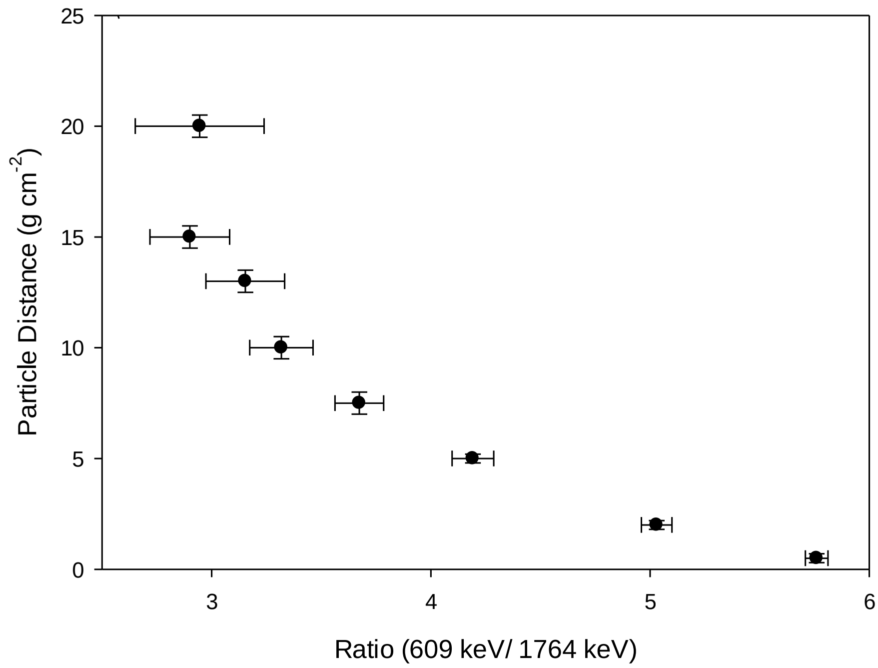


Figure 6. Showing the relationship between 609 keV / 1764 keV ratio and particle distance (r^2=0.94)

Figure 6 illustrates that a systematic increase in particle distance (or mass per unit area) can be estimated from the 609 keV / 1764 keV ratio. Similarly the calibration coefficient to convert spectral full energy peak area to a particle activity (Bq) can also be estimated (Figure 7).

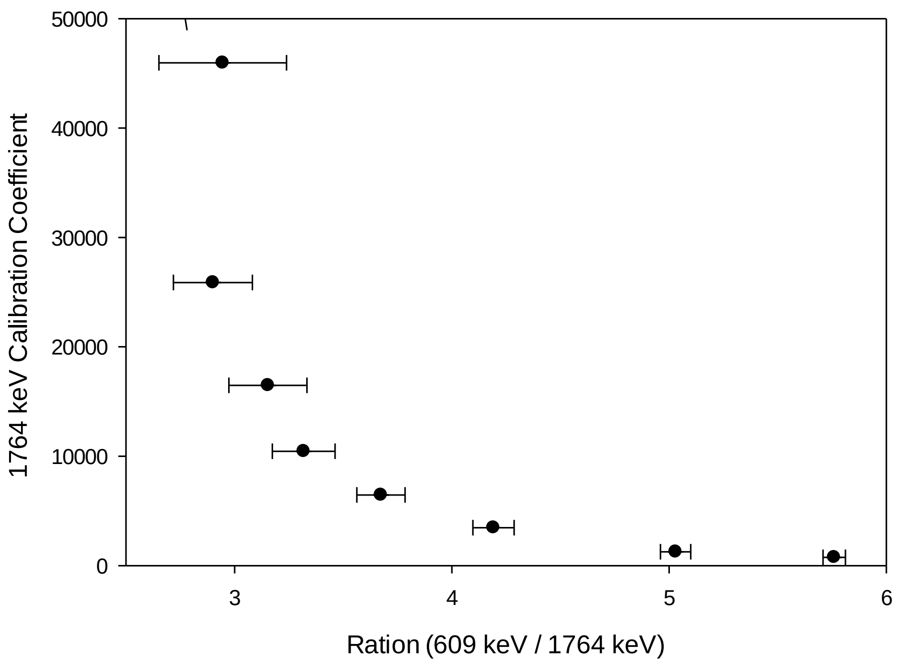


Figure 7. Showing the relationship between 609 keV / 1764 keV ratio and particle activity calibration at 1764 keV (r^2=0.90)

Figure 8. Deployment of the 50 mm x 50 mm NaI(Tl) detector at 1.5 m depth.

The NaI(Tl) detector was deployed to the required depth by pushing the detector into the augured hole (Figure 8). The detector was pushed in at intervals (100-200 mm) and spectra were acquired over a 600 s live time, or less when counting uncertainties of less than 5% were more quickly achieved.

3. Results and Discussion

3.1 Ground penetrating radar survey and magnetometer deployment

Figure 9 shows the GPR transects across the headland site and the broad interpretation of the data (shown in completeness in Appendix B).

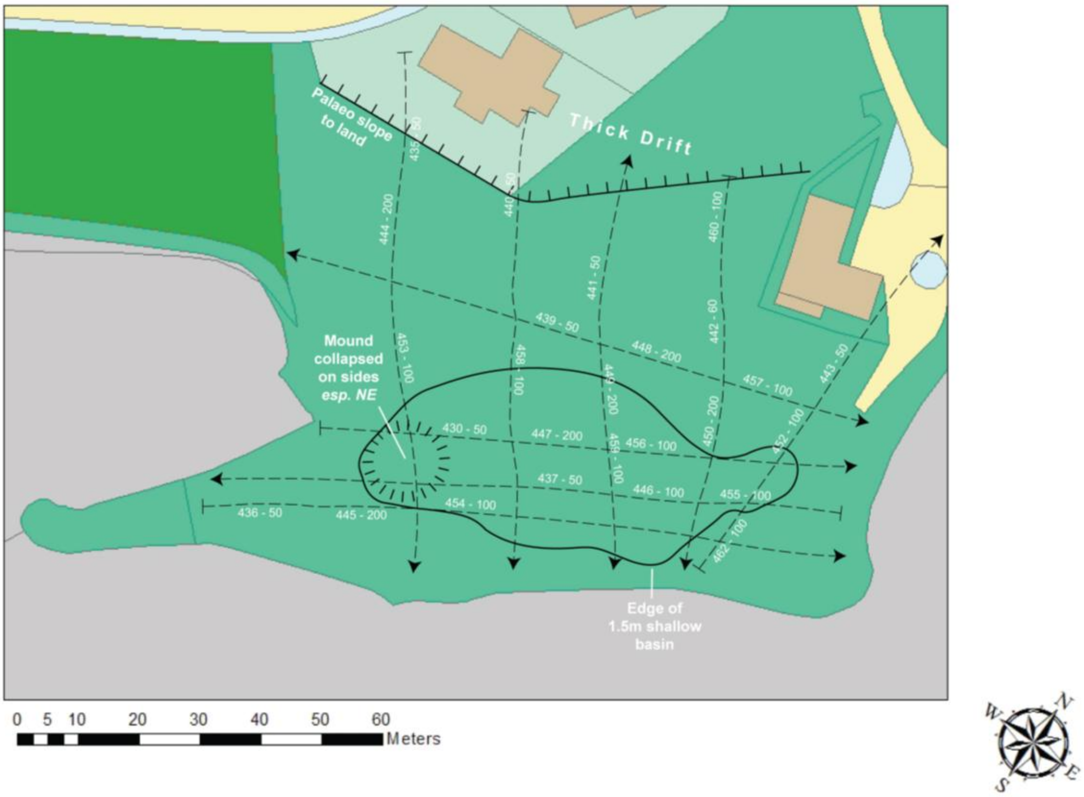


Figure 9. GPR transects and brief interpretation of the data

Figure 9 shows an outline of the main basin of the made ground. The basin infill was estimated to be about 2m deep from the surface of the site. The surficial infill material continues to the North under the club house and to the North West, which may indicate separate minor basins of infill (around 1.5 - 2 m deep). Figure 10 shows in detail the 100 MHz data, from which individual episodes of infill can be seen as material was “deposited” into the made ground.

The magnetometer survey identified numerous targets of elevated ferro-metallic materials, both across the area of interest and down the excavated holes. At times, the UXO engineer would assist with the excavation and surveyed materials being recovered. Often waste recovered would quickly oxidise, changing from a blackened to a reddish colour.

3.2 Surface contamination

The surface contamination was quickly mapped using gross counts and the results are mapped in Figure 11. The gross gamma background shows an elevated area to a little further north than the mapped basin (Figure 10) and which extends to the South West of the clubhouse (site 3). Particles were recovered from the highest activity area and to the area immediately South West of the Club House (Site 1; immediately East of the bushes).

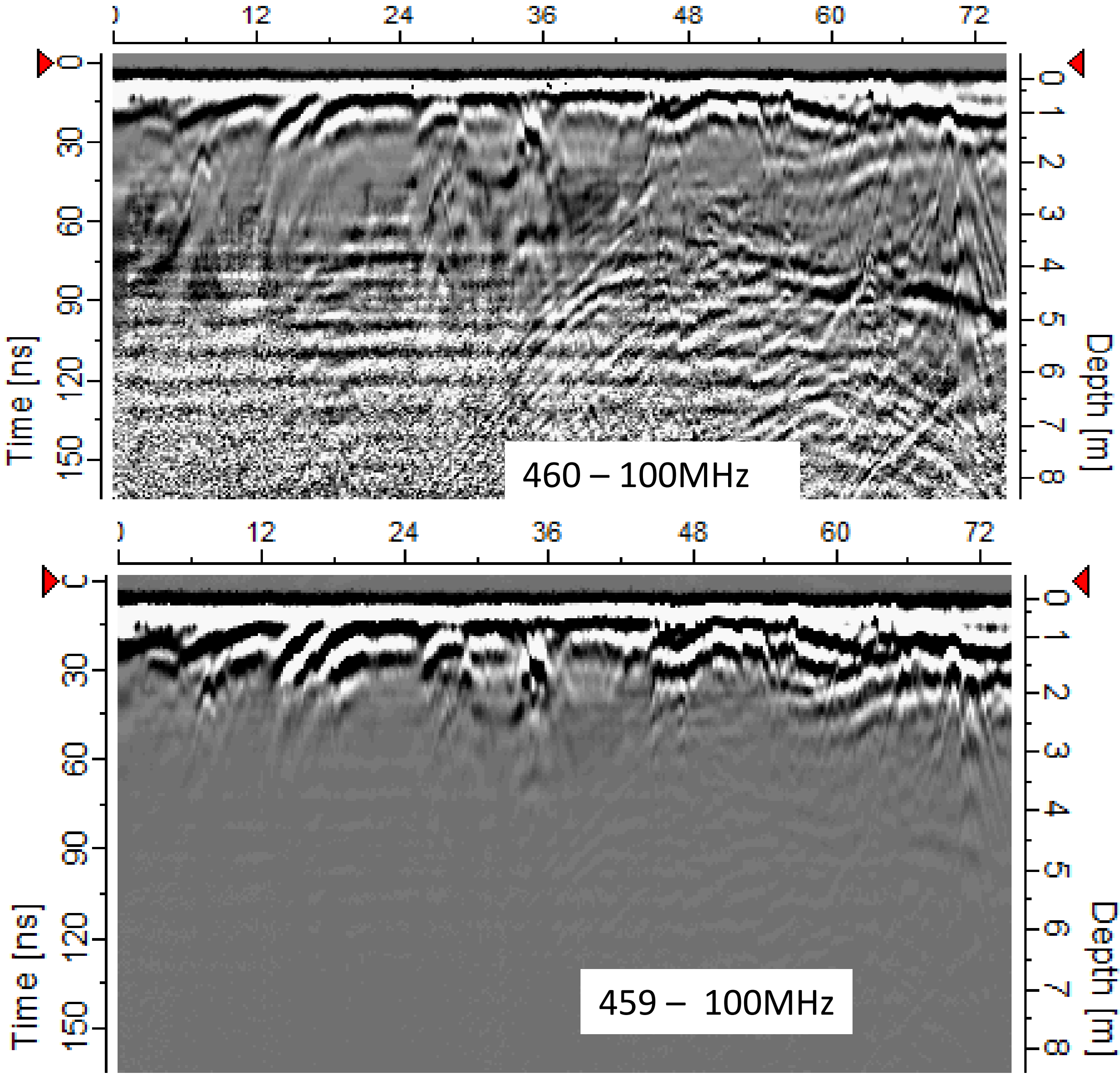


Figure 10. GPR (100 MHz) data along transect 459 and 460 (see Figure 9)

3.3 Contamination at depth

Appendix C summaries all the excavations undertaken. A total of 30 sites were investigated (Figure 12), 29 of which yielded useful data that either confirms the presence or absence of ^{226}Ra contaminated at the surface or at depth. Reconstructing the presence of particles was complicated by the presence of either multiple particles or relatively uniformly contaminated horizons, which exhibit evidence of stratification. Appendix C highlights possible locations where particles are present, usually, where the 609 keV / 1764 keV ratio is less than about 3.5 (Figures 5 & 6), indicating a high activity at some distance. This was observed at sites, 5, 6 and 30.

Figure 12 shows the area that can be delineated with elevated ^{226}Ra activity at depth. Detailed counting information for each site is given in Appendix C. At locations 5, 6 and 30, there is a suggestion of the presence of particles in the ^{226}Ra contaminated ground, perhaps of the order of a few tens of kBq. At this stage it is not possible to establish how far north the lens of contaminated material stretches.

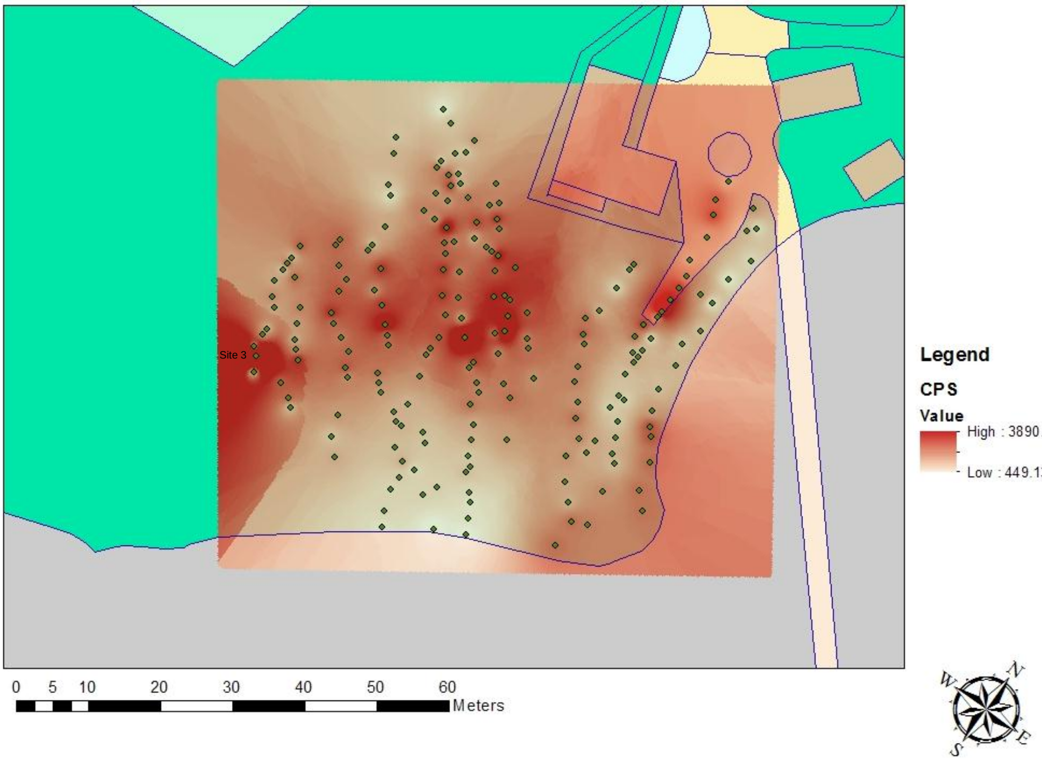


Figure 11. Gross gamma counts over the Dalgety Bay headland (red areas indicated elevated gamma background) showing areas of surface ^{226}Ra contamination

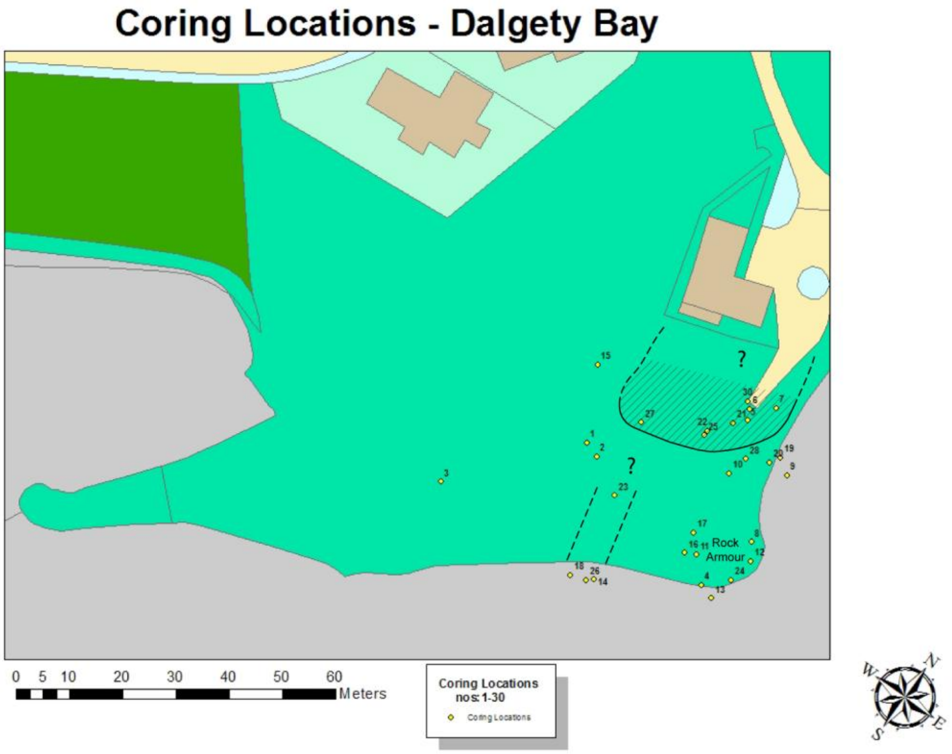


Figure 12. Sampling sites on Dalgety Bay headland and showing areas at depth where elevated ^{226}Ra activity and possible ^{226}Ra point sources were detected

Areas 11, 16 and 17, within the eastern corner of the made ground, were particularly difficult to excavate due to the presence of rock armour and broken concrete slabs (Figure 4). It was noted (and photographed) that there were substantial pore spaces between the slabs and rocks, 500-1000 mm in size. An aircraft dial (with no ^{226}Ra present) was also extracted from this area. It is conceivable that this area might act as a conduit for particle movement.

4. Conclusions

The site investigation has highlighted main areas of waste infill that was deposited forming the current headland area. The data indicate the presence of both surface contamination and contamination at depth that do not necessarily overlap spatially, suggesting a separate phase of contamination during the capping of the site. ^{226}Ra particles were recovered from the surface of the site, from within the elevated areas identified from the total gamma survey.

Penetration into the made ground was hindered at a number of locations by the presence of rocks and broken slabs of concrete, especially in the south eastern corner of the site. This area contained many cavities and an aircraft dial was recovered from the south-eastern corner. Progress was also slowed by the presence of ferro-metallic objects at many of the sites investigated. Nevertheless, by combining information from GPR and gamma surveys of the surface and depth, the main area of contamination appears to extend from the area in front of the sailing clubhouse and possibly underneath the building itself. The extent to which the contamination continues north is difficult to establish from the data collected and access restrictions under the main clubhouse and tarmac areas. Nevertheless, the data shows a lens of ^{226}Ra contaminated waste, which appears to be stratified. There is also the suggestion of the presence of ^{226}Ra particles, although it is difficult to be conclusive due to the potential complexity of the radiation environment from distributed and point sources of ^{226}Ra. Contamination was also detected, and a particle recovered, on the southern edge of the site and this appears to extend north into the headland.

References

Dale, P., Hunter, G., Milne, J. (2009). Dalgety Bay Radium Contamintation. Publication by SEPA RS Policy Unit. 86pp.
www.sepa.org.uk/radioactive_substances/publications/dalgety_bay_reports.aspx

Dale, P., Gemmill, J., Milne, J. (2011). Dalgery Bay Radium Contamination. . Publication by SEPA RS Policy Unit. 44pp.
www.sepa.org.uk/radioactive_substances/publications/dalgety_bay_reports.aspx

Tyler, A.N. (2007) *In Situ* and airborne gamma-ray spectrometry. In: *Analysis of Environmental Radionuclides*, Edited by P. P. Povinec. Elsevier: Radioactivity in the Environment, Volume 11. 532pp.

Appendix A

GPR – How the method Works

GPR uses the transmission and reflection of radio waves (typically 25 to 2GHz) in imaging the subsurface. Radar waves, introduced in the ground, may reflect back to surface when they intersect objects or surfaces of varying dielectric permittivity. Thus a GPR system requires a source antenna and receiving antenna (built to measure the same frequency). The transmitting antenna generates a pulse of radiowaves that the receiver detects at a set time interval: the longer the time interval, (potentially) the deeper the waves will have travelled into the ground and back again. When the ground has a slow radarwave velocity, so a buried object may appear deeper than in ground with a fast transmissive velocity. As the antennae pass over discrete objects with different dielectric properties to the surrounding medium (boulders, pipes, coffins), they may generate hyperbolae, or arc-like reflections.

Radar waves also travel horizontally from the transmitting antenna, which in open ground simply dissipate with distance. However, in areas with upstanding structures, especially those that have a significant dielectric contrast to their surroundings, interference from such surface objects can create artifacts on the radargram. When such isolated objects (powerlines, telegraph wires, metal poles, trees) are passed during a traverse, a series of hyperbolae may be generated that appear like a subsurface object but are simply out-of-plane reflections. Radar antennae are commonly elongate, generating radar waves in a widening arc from their long axis. Thus when moved in parallel to the antennae axis, the radar waves may reflect from a larger subsurface area in front and beyond the antenna, (the so-called footprint) than when moved with the antennae at right angles to survey direction. Antennae may be shielded with radio-wave attenuating materials that reduce such out-of-plane interference.

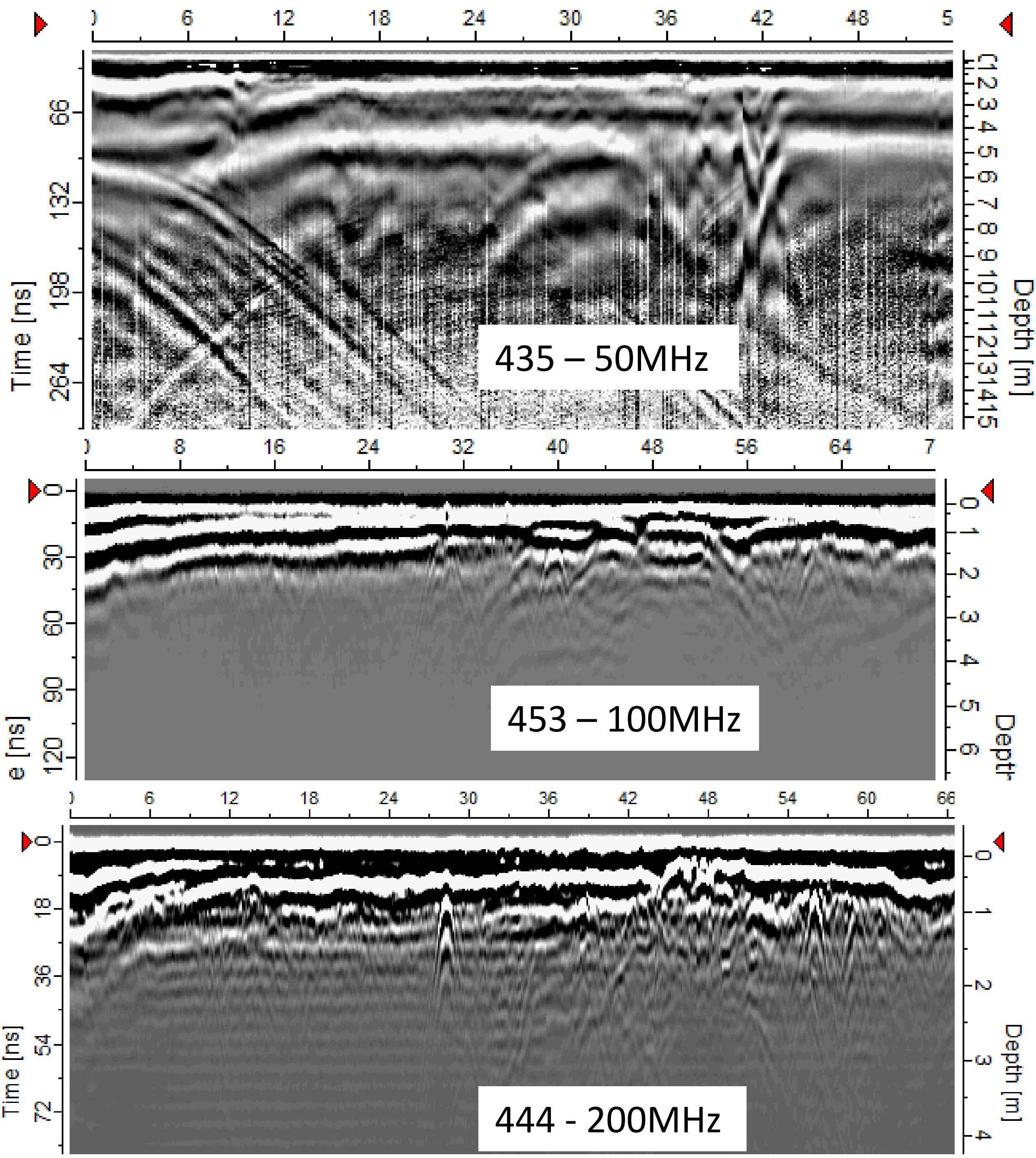
Unlike other forms of electromagnetic radiation used in geophysics, radio waves have far higher rates of attenuation, and thus penetration and reflection depths are typically low, but horizontal accuracy is high, coupled with rapid, real-time results, unlike all other geophysical techniques bar metal detectors and magnetometer raw data. The receiving antenna has either electronic or fibre-optic link to a recorder that converts incoming radiowaves to digital format and displays these graphically as wavelets. As the transmitter-receiver array is moved, so these wavelets are stacked horizontally to produce a radargram, a kind of x-ray slice into the Earth, but recorded in the time taken for radar waves to penetrate and reflect, as opposed to real depth. The speed of radiowave propagation is determined by the makeup of the transmitting medium: in this case the speed of light and dielectric permittivity. Magnetic properties can also influence radar wave speed. Changes in dielectric permittivity can cause radar wave reflection, without which GPR profiling would be impossible. Radarwave attenuation, or signal loss is extreme in conductive media such as seawater, clays (especially hydrous) and some leachate. GPR has good depth penetration (tens to hundreds of metres) in ice (with minor fracturing/interstitial water), hard rocks like limestone and granite and clay-poor quartz silts or sands. Vertical resolution *vs.* depth penetration is of major concern when choosing antenna frequency. Low frequencies (15-50MHz) achieve deep penetration with poor vertical resolution in the received signal, due to the long wavelength. High frequencies (500-1000MHz) show high resolution with weak penetration (centimetres to metres). Low-frequency antennae are large (a few metres long), high frequency antennae are small (tens of centimetres). Again, this can influence the use of the method, as deeply-buried targets in enclosed spaces are virtually impossible to survey.

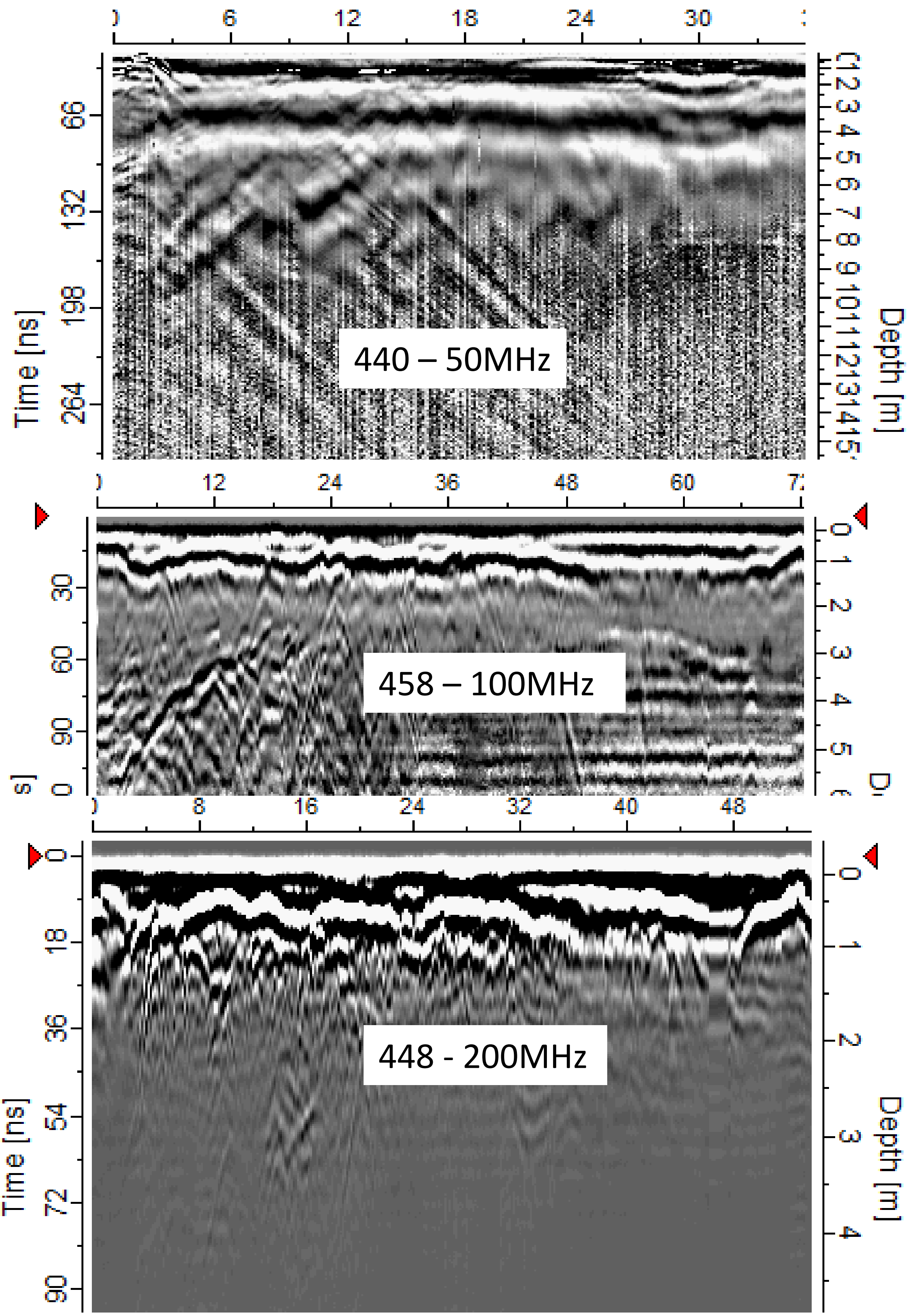
As with all geophysical methods, some intelligence concerning the likely size and makeup of the target is useful: where unknown or questioned, then a range of antennae should be used, and in very poorly understood locations, with other geophysical and invasive techniques (Blunderbuss Approach). Moisture contents influence radar wave velocity because in homogenous media porosity has a direct relationship to dielectric permittivity. Thus dry sand will allow increased wave propagation: sand with high freshwater content will give improved vertical resolution.

A major problem with early antennae was the effect of 'out-of-plane' reflections. It is easy to think of the radar wave as a focused beam (the ray-path at right-angles to the wave) when in fact the radar wave as it travels into the subsurface is more like a bubble, hemispherical at first, expanding and becoming distorted as it travels at different speeds into the ground. Thus lateral to the antennae, on or in the ground surface may be structures (buildings, posts, drains) that cause reflections at ground level. The effect of these surface features can be diminished by altering the orientation of the antennae, or by shielding the above-ground portion of the antennae, such that the radio wave is only allowed to penetrate the ground. GPR has found it's best uses in imaging glaciers, frozen ground, sand deposits (river deposits, non-saline coastal sands), aquifers (porous nature), archaeological features (moats, buried buildings) and concrete/pavements.

Alastair Ruffel, Queens University Belfast

Appendix B GPR profile results

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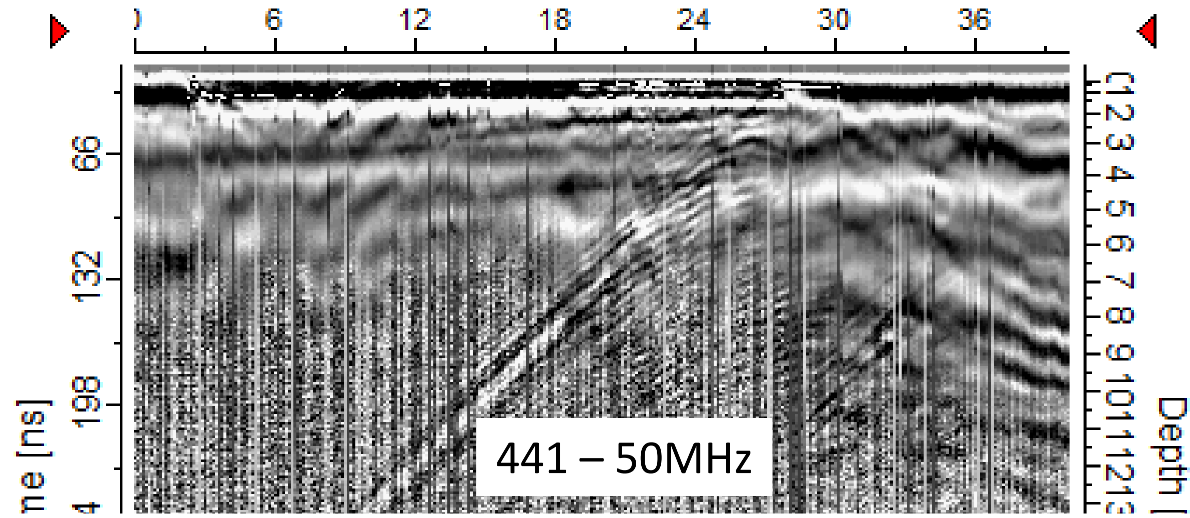
Time [ns]
Depth [m]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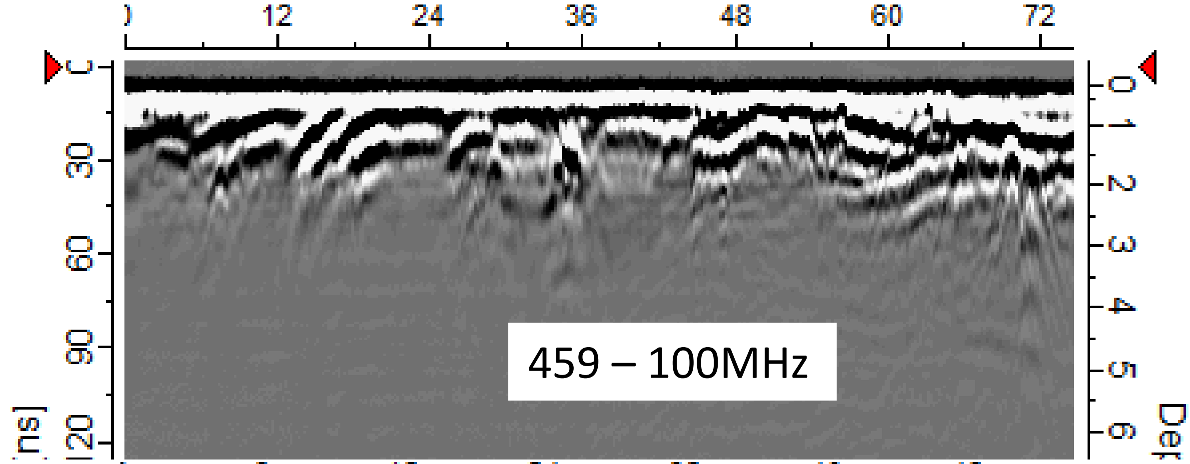
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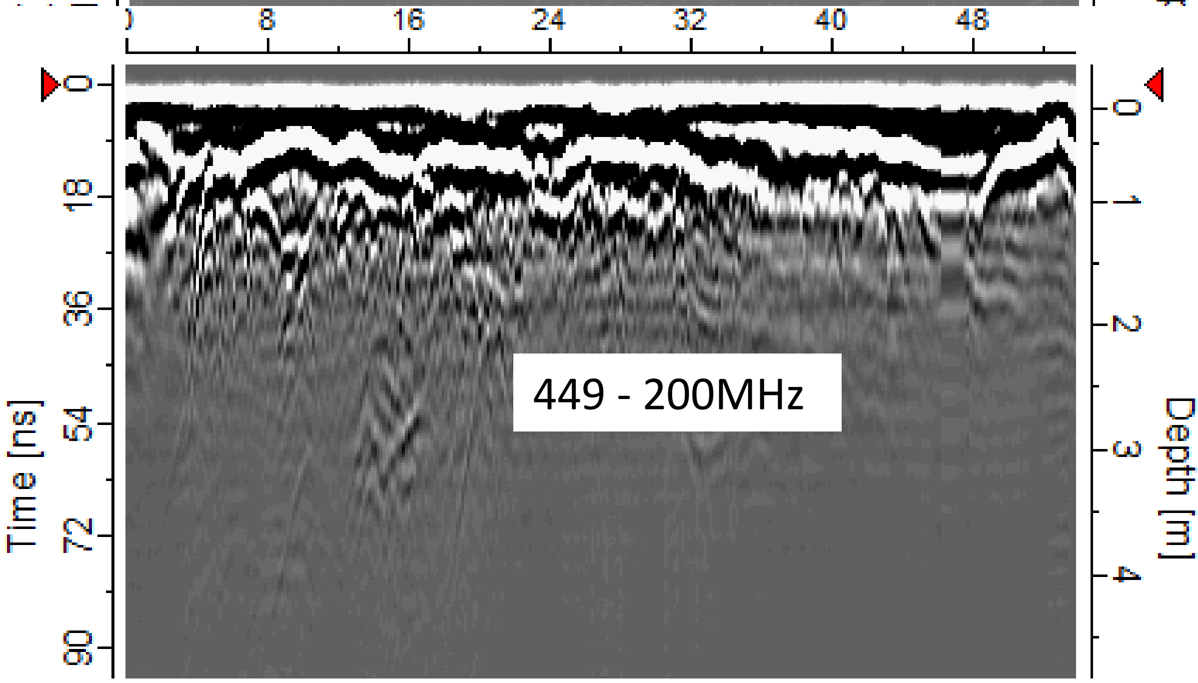
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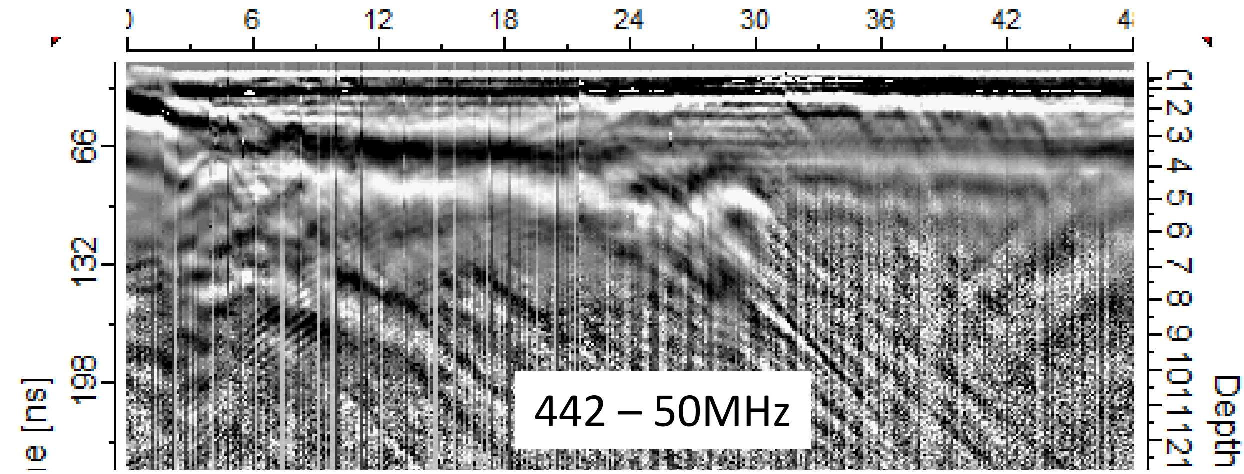
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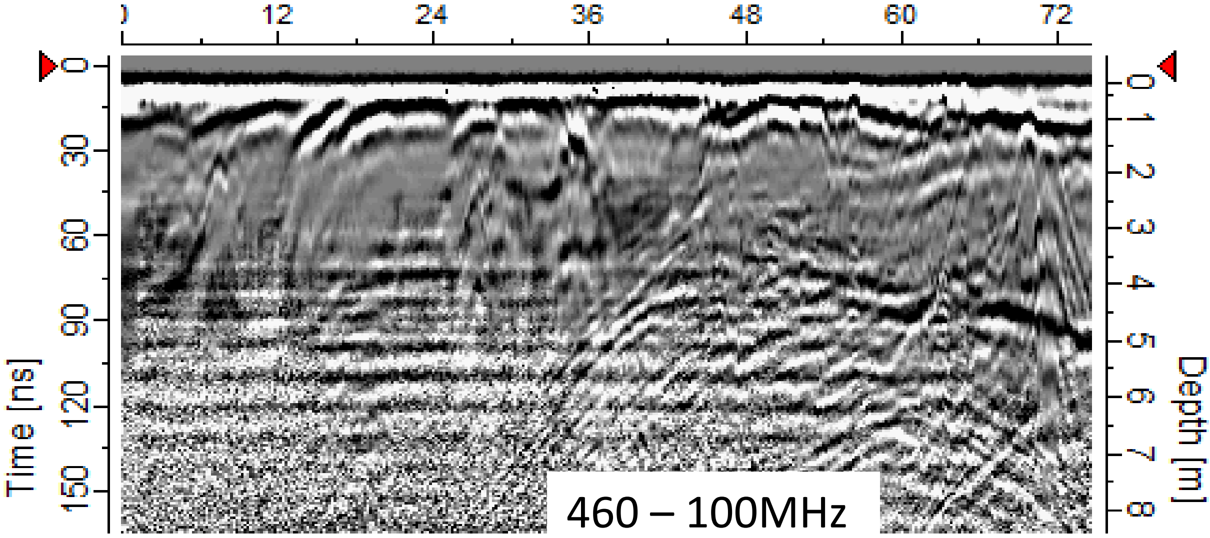
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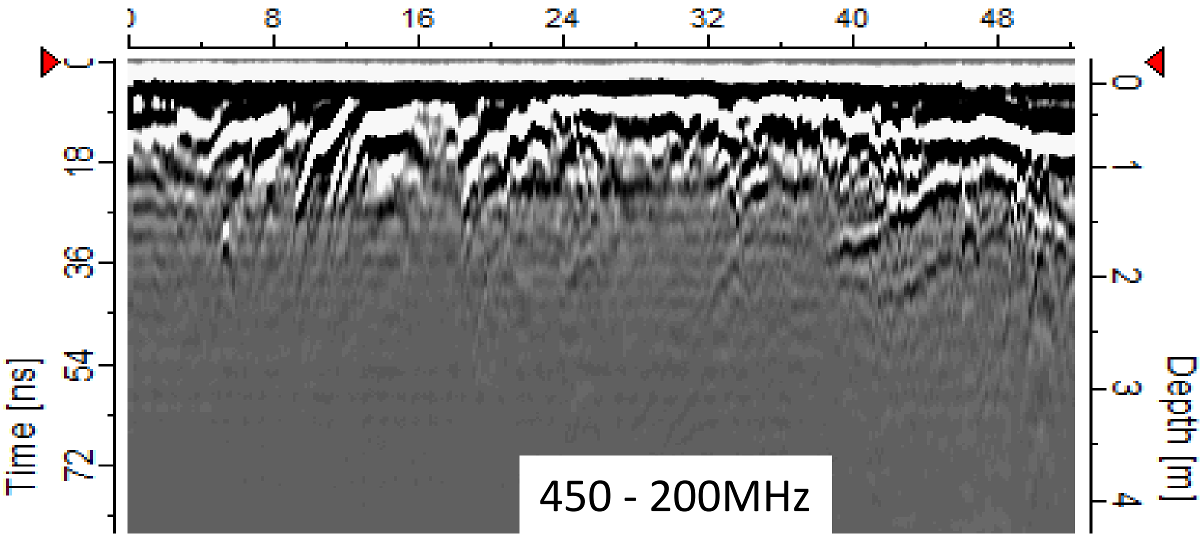
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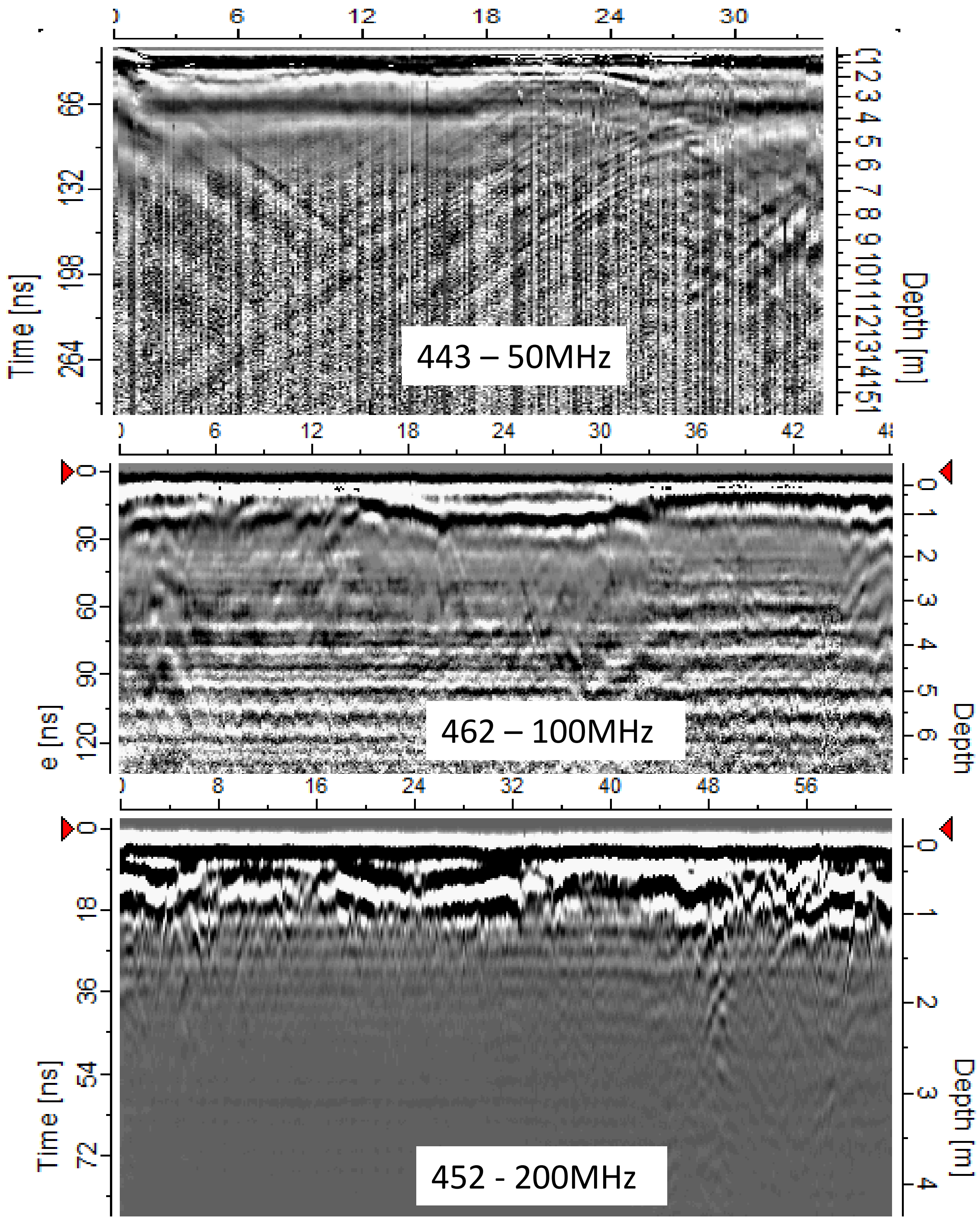
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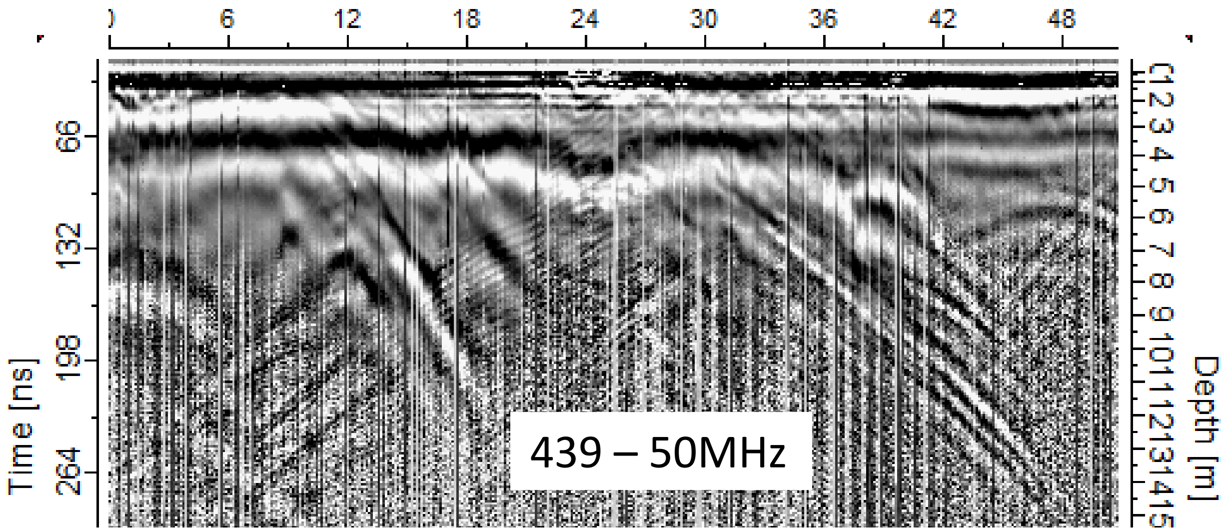
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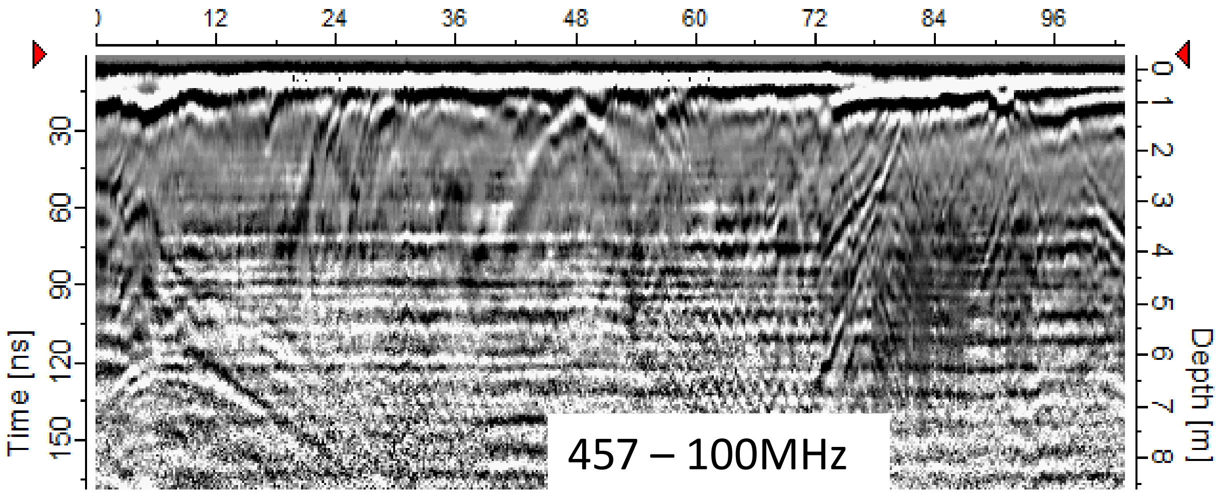
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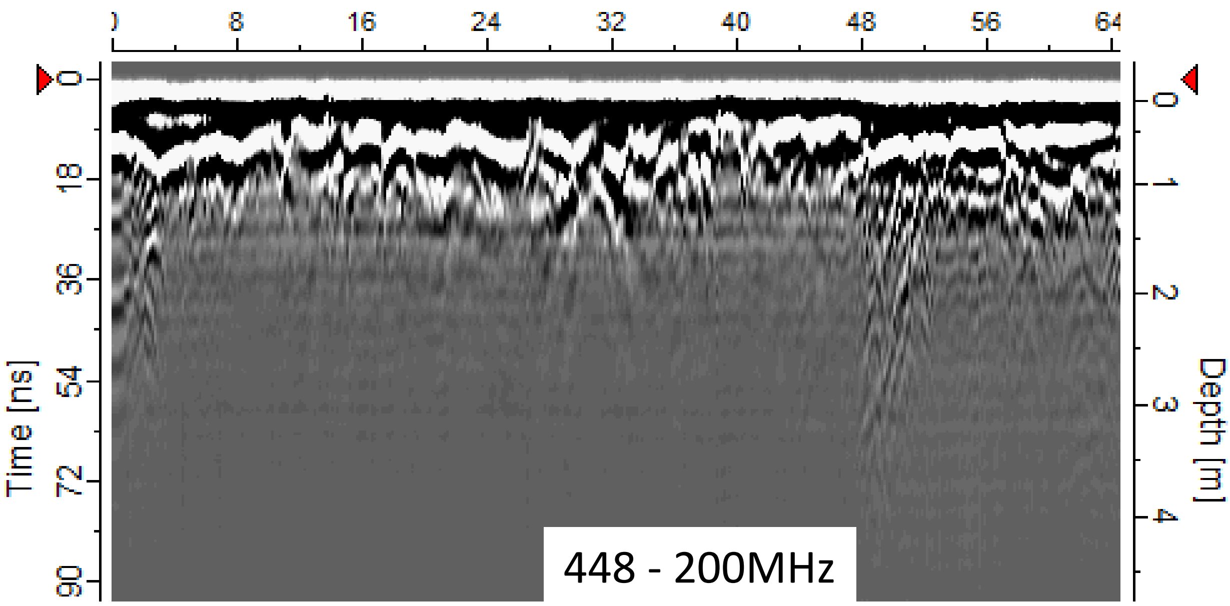
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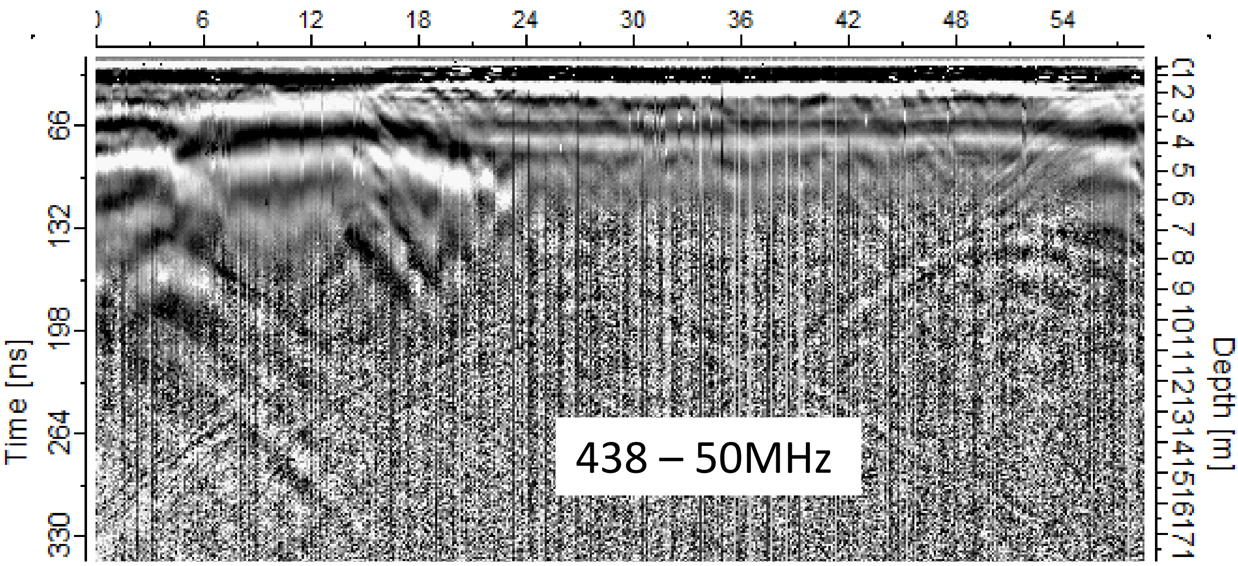
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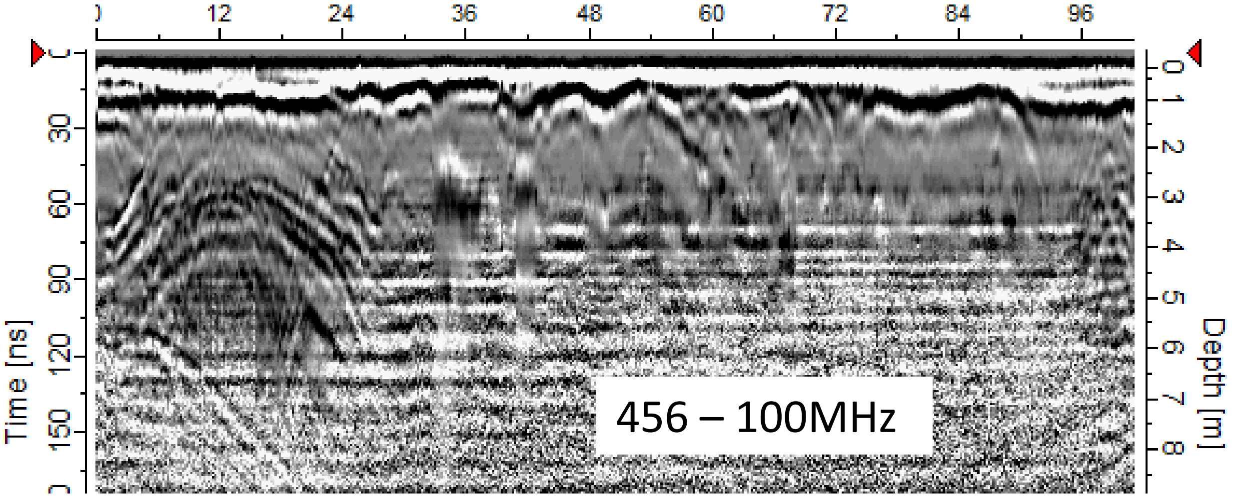
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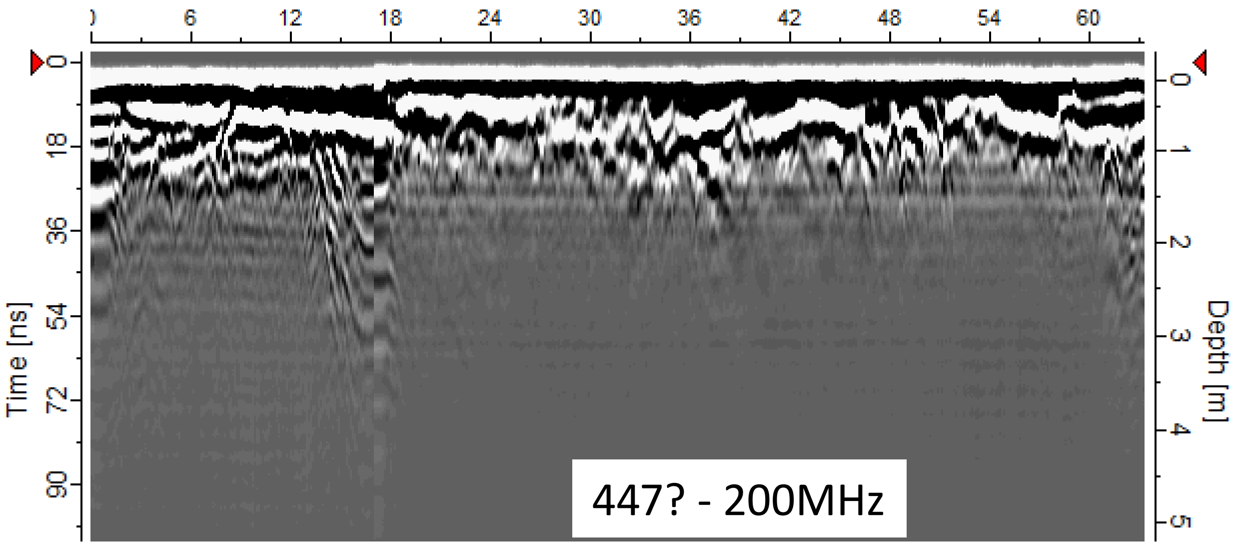
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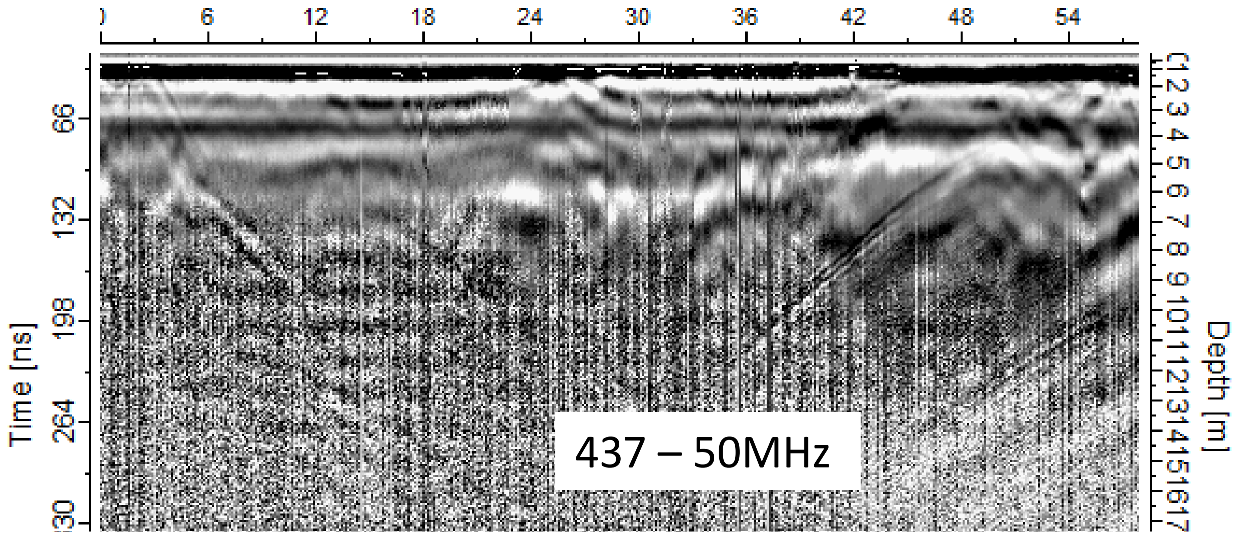
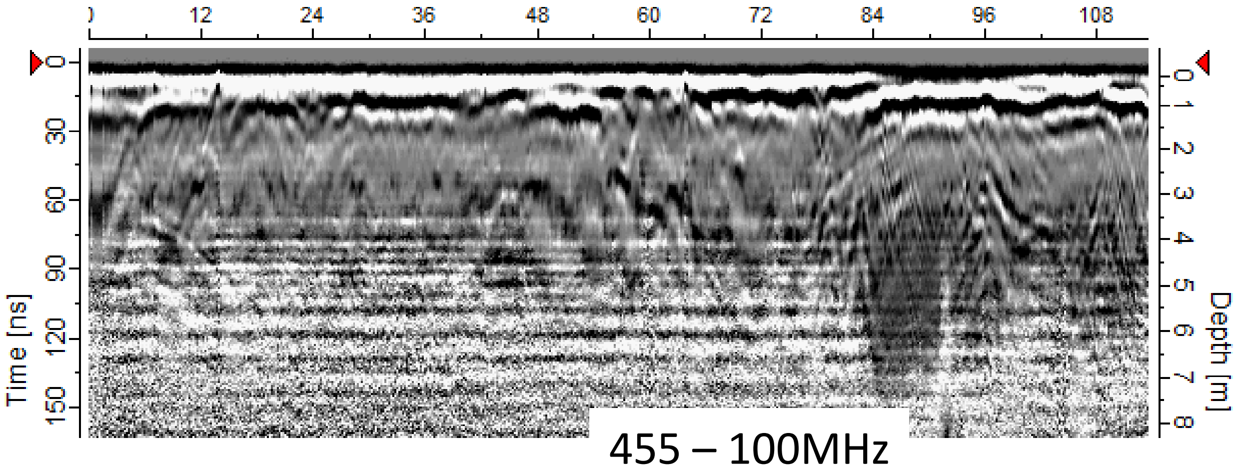
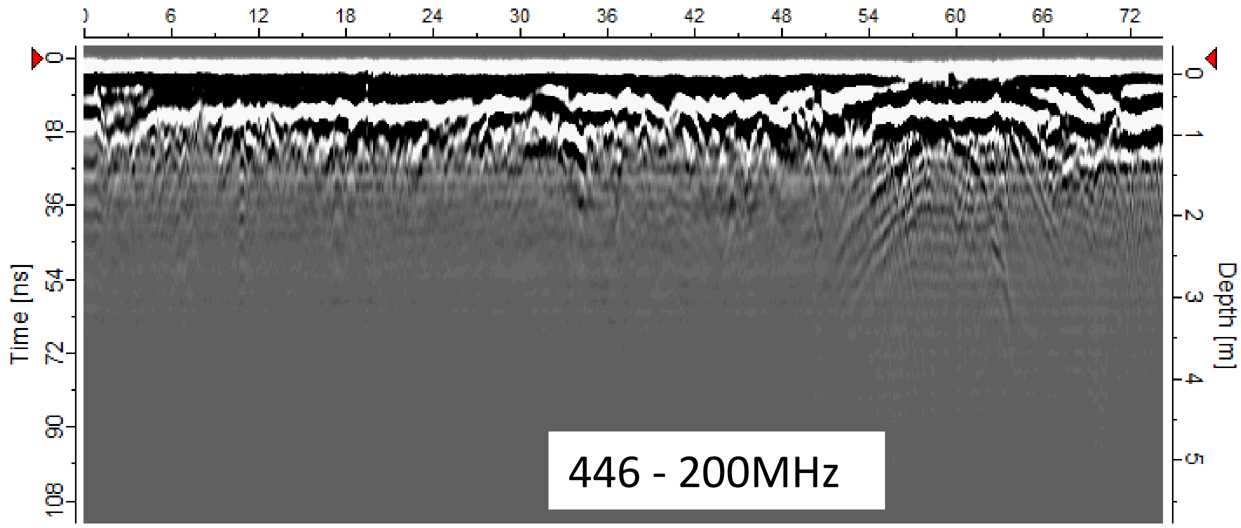
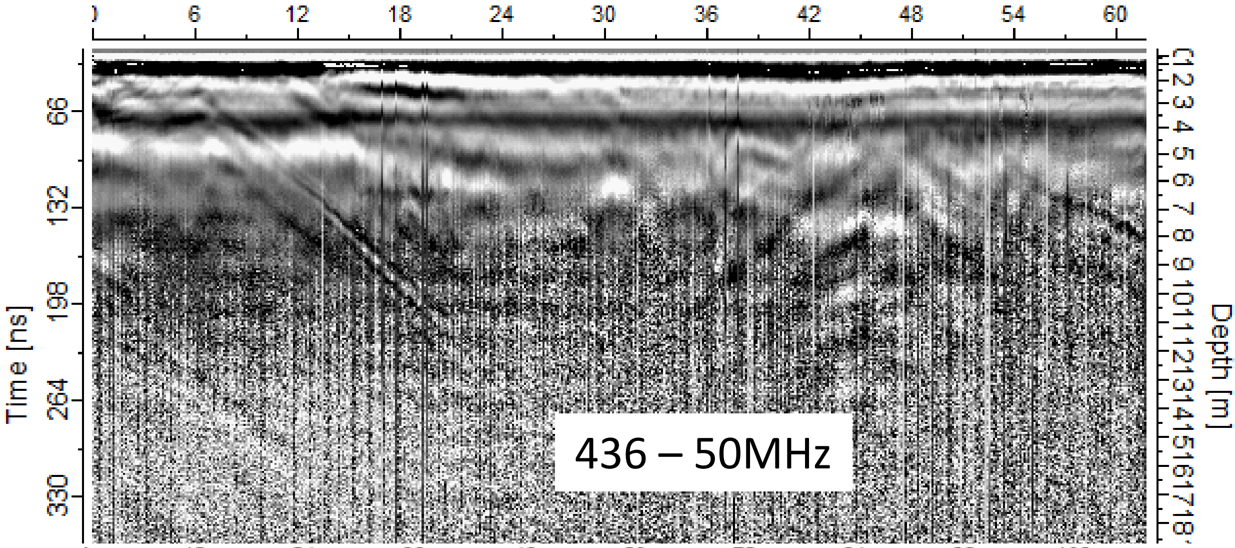
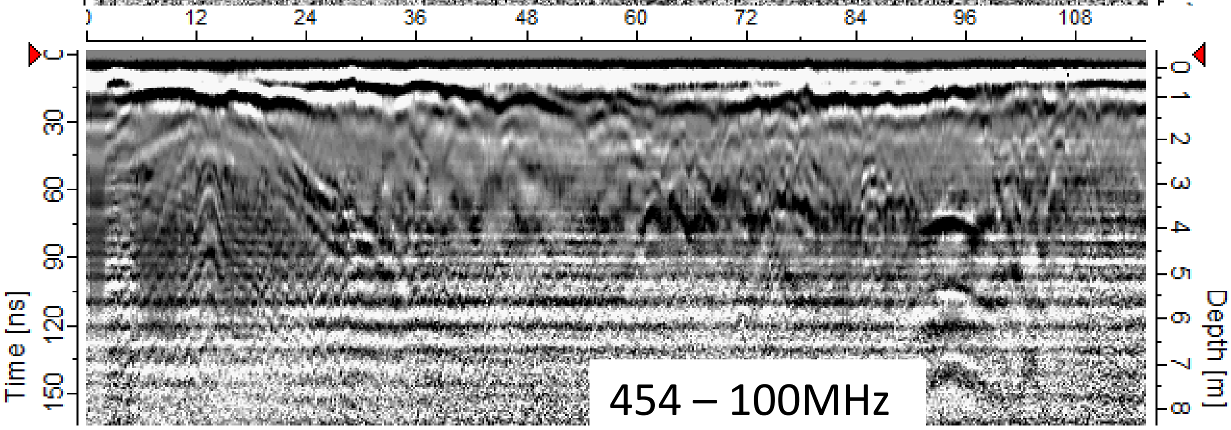
Depth [m]

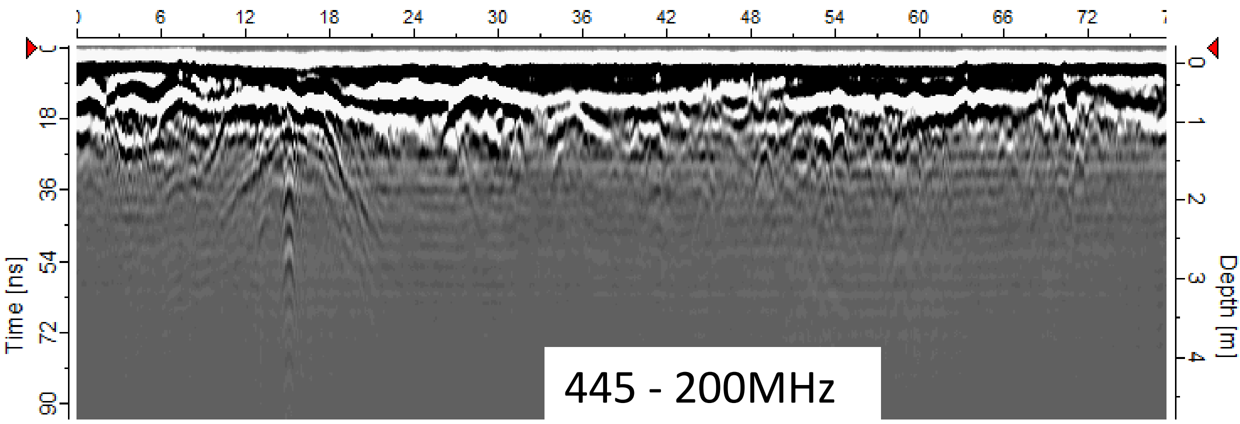

437 – 50MHz
Time [ns]
Depth [m]


455 – 100MHz
Time [ns]
Depth [m]


446 - 200MHz
Time [ns]
Depth [m]


436 – 50MHz
Time [ns]
Depth [m]


454 – 100MHz
Time [ns]
Depth [m]


445 - 200MHz
Time [ns]
Depth [m]

Appendix C: Down profile gamma spectrometry results

Stirling Calibration Site: Stirling University

Background activities for ^{214}Bi wet weight ranged from 10 to 14 Bq kg^{-1} (wet weight) The 609keV to 1764 keV ratio was on average 5.2, although the low counting statistics (low background) resulted in a standard error of ± 2.4 cps.

Dalgety Bay

Site 1

NT 16441 83062

Site 1	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	609 keV	1 σ	1730 keV	1 σ	Ratio	1 σ
10	**1.11**	0.106	**0.21**	0.035	**5.20**	1.00
20	**1.10**	0.104	**0.17**	0.032	**6.47**	1.37
30	**1.14**	0.102	**0.28**	0.036	**4.15**	0.65
40	**1.00**	0.104	**0.25**	0.034	**3.99**	0.69
50	**1.32**	0.107	**0.17**	0.032	**7.98**	1.70
60	**0.96**	0.097	**0.17**	0.030	**5.74**	1.19
70	**0.63**	0.086	**0.12**	0.026	**5.44**	1.45
80	**0.58**	0.080	**0.12**	0.026	**4.80**	1.21
90	**0.68**	0.083	**0.15**	0.028	**4.48**	0.98
100	**0.70**	0.084	**0.16**	0.027	**4.31**	0.88
110	**0.72**	0.083	**0.08**	0.025	**8.97**	2.98
120	**0.82**	0.089	**0.12**	0.027	**6.99**	1.78
130	**0.81**	0.093	**0.18**	0.030	**4.49**	0.90

Site 1 was successfully augured to 130cm depth. The results demonstrate typical background (up to 20 Bq kg$^{-1}_{wet}$) characteristics (also similar to Stirling's calibration site) with no evidence of any elevated ^{226}Ra related activity and no suggestion of a point source. A metal object was recovered at 8cm, but there was no radioactivity associated with it. This is a useful profile to compare others against.

Site 2

NT 16444 83061

Site excavated to 30 cm and 6 particles removed from site 2, each with counts between 200 cps and 400 cps (RT 30). Once particles were removed, gross gamma counts returned to background. These counts relate to ^{226}Ra sources of around a few kBqs.

Site 3

NT 16423 83040

Site excavated and contaminated soil removed reducing the radioactive signal of this site to background.

Site 4

NT 16474 83053

Site 4	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	609 keV	1 σ	1730 keV	1 σ	Ratio	1 σ
80	**2.25**	0.12	**0.37**	0.035	**6.15**	0.67
90	**2.11**	0.074	**0.32**	0.023	**6.58**	0.52

Site manually excavated. Surface activity was high with between 200-900 cps (RT 30). The RT 30 attributed these excess counts to the presence of ^{226}Ra. These were measured 5 cm depth, which indicates surface contamination. However, this could not be isolated to a specific point source. Further excavation with the auger permitted an additional two measurements at 80 and 90 cm depth using the 50 mm x 50 mm NaI(Tl) detector. The counts indicated a slightly elevated presence of ^{226}Ra compared with site 1 (2 to 3x background).

Sites 5 – 7

Figure C1. Showing the excavation at sites 5 to 7

Site 5

NT 16463 83083

Site 5	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	609 keV	1 σ	1730 keV	1 σ	Ratio	1 σ
100	**3.17**	0.18	**1.02**	0.068	**3.12**	0.27
120	**5.81**	0.20	**1.59**	0.078	**3.66**	0.22
140	**6.96**	0.19	**1.73**	0.074	**4.03**	0.20
160	**7.14**	0.17	**1.85**	0.065	**3.85**	0.16
180	**4.77**	0.12	**1.05**	0.044	**4.53**	0.22
190	**3.81**	0.092	**1.08**	0.035	**3.54**	0.14
200	**5.31**	0.11	**1.22**	0.041	**4.33**	0.17

RT 30 count rates from the surface ranged from 580 to 720 cps from 20-55 cm depth – indicating a relatively uniform distribution of elevated ^{226}Ra activity with depth. Results from 100-200 cm depth with the 50 mm x 50 mm NaI(Tl) detector provide some indication of a point source, commensurate with a particle of activity around 20 kBq at 120 cm. Overall activity levels within the contaminated layer ranged up to 150 Bq kg^{-1} for ^{226}Ra, but may also be associated with particles of ^{226}Ra activity of a few kBqs.

Site 6

NT 16462 83085

Site 6	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	609 keV	1 σ	1730 keV	1 σ	Ratio	1 σ
60	**8.68**	0.25	**2.54**	0.10	**3.42**	0.17
80	**8.90**	0.26	**2.60**	0.10	**3.42**	0.17
100	**10.15**	0.26	**2.62**	0.10	**3.87**	0.18
120	**5.81**	0.22	**1.74**	0.086	**3.33**	0.21
140	**5.30**	0.20	**1.43**	0.080	**3.72**	0.25
160	**5.43**	0.20	**1.36**	0.078	**4.01**	0.28
180	**6.24**	0.21	**1.66**	0.083	**3.77**	0.23
200	**6.90**	0.22	**1.59**	0.084	**4.34**	0.27
220	**4.62**	0.20	**1.14**	0.073	**4.05**	0.31

RT 30 count rates at the surface ranged from 630 to 740 cps from 30-60 cm depth indicating a relatively uniform distribution of elevated ^{226}Ra activity at depth. From 60 cm downwards the results indicate the presence of two point sources, one at 100 cm and one at 140 cm depth. Again the activity is likely to be of the order of 20-30 kBq. Overall activity levels within the contaminated later ranged up to 200 Bq kg^{-1} for ^{226}Ra.

Site 7

NT 16466 83088

Site 7	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	609 keV	1 σ	1730 keV	1 σ	Ratio	1 σ
60	**2.07**	0.31	**0.53**	0.11	**3.93**	**1.02**
70	**3.61**	0.17	**0.84**	0.061	**4.30**	**0.37**
90	**2.39**	0.15	**0.67**	0.055	**3.56**	**0.37**
110	**2.79**	0.15	**0.60**	0.054	**4.66**	**0.49**
130	**2.48**	0.15	**0.52**	0.053	**4.77**	**0.57**
150	**4.60**	0.19	**1.19**	0.072	**3.85**	**0.28**
165	**14.29**	0.29	**3.08**	0.112	**4.63**	**0.19**
180	**16.05**	0.31	**3.67**	0.120	**4.38**	**0.17**
200	**9.02**	0.25	**2.50**	0.099	**3.61**	**0.18**

Following excavation to about 50 cm, an augured hole was provided deeper penetration into the contaminated layer. Whilst there was no strong evidence for point sources at this site, ^{226}Ra activity concentrations measured up to 300 Bq kg^{-1}. However, this could also represent multiple small sources of a few kBqs.

Site 10

NT 16477 83065

Site 10	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	609 keV	1 σ	1730 keV	1 σ	Ratio	1 σ
120	**0.60**	0.055	**0.13**	0.017	**4.45**	**0.70**

Excavated site to 120 cm. No evidence of contamination was detected at this depth.

Site 11

NT 16470 83057

Site on the southern edge of the made ground. Slightly elevated RT 30 counts: 150cps.

Site 12

NT 16479 83062

Site 12	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	609 keV	1 σ	1730 keV	1 σ	Ratio	1 σ
35	**1.24**	0.085	**0.14**	0.024	**8.72**	**1.58**

Site on the south-eastern edge of the headland. Excavated by hand to enable the penetration of the 50 mm x 50 mm NaI(Tl) detector to 35 cm. No ^{226}Ra contamination was detected.

Site 13

NT 16477 83052

Site 13	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	609 keV	1 σ	1730 keV	1 σ	Ratio	1 σ
55	**1.89**	0.081	**0.32**	0.026	**5.88**	**0.54**

Site on the southern edge of the headland. Excavated by hand to enable the penetration of the 50mm x 50 mm NaI(Tl) detector to 55 cm. Whilst a little elevated, no significant ^{226}Ra contamination was detected. However, the RT30 detected elevated count rates at this site on the edge of the made ground within the rocks (rip-rap).

Site 14

NT 16457 83042

Site 14	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	609 keV	1 σ	1730 keV	1 σ	Ratio	1 σ
40	**0.85**	0.11	**0.18**	0.035	**4.83**	**1.17**

Site on the southern edge of the headland. Excavated by hand to enable the penetration of the 50mm x 50 mm NaI(Tl) detector to 40 cm. No contamination was detected.

Site 15

NT 16434 83075

Site 15	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
60	**1.15**	0.11	**0.17**	0.033	**6.57**	**1.39**
100	**0.79**	0.090	**0.12**	0.028	**6.72**	**1.78**
120	**0.73**	0.071	**0.13**	0.024	**5.57**	**1.14**

Site to the western side of the club house (raised bank in front of the clubhouse). The site was easily augured enabling the penetration of the 50mm x 50 mm NaI(Tl) detector to 120 cm. No significant ^{226}Ra contamination was detected.

Site 16

NT 16468 83056

Site 16	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
100	**1.63**	0.062	**0.30**	0.020	**5.47**	0.42

Site excavated by hand to enable a single measurement of the 50mm x 50 mm NaI(Tl) detector at 100cm depth. ^{226}Ra activity was estimated at 24 Bq kg^{-1} for ^{226}Ra, which indicates that there was no significant contamination.

Site 17

NT 16467 83060

Site 17	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
100	**0.91**	0.056	**0.12**	0.016	**7.28**	**1.04**

Site excavated by hand to enable a single measurement of the 50mm x 50 mm NaI(Tl) detector at 100cm depth. No ^{226}Ra contamination was detected.

Site 18

NT 16453 83040

Site 18	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
110	**1.90**	0.11	**0.40**	0.036	**4.80**	**0.51**
135	**2.31**	0.14	**0.47**	0.048	**4.92**	**0.59**

Site excavated by hand on the southern edge of the headland to permit two measurements of the 50mm x 50 mm NaI(Tl) detector at 110cm and 135 cm depth. Slightly elevated ^{226}Ra contamination activity was detected, around 2-3x background. The RT30 was used to detect and recover a ^{226}Ra source from this location.

Site 19

NT 16472 83081

Core 19	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
20	**1.35**	0.089	**0.15**	0.025	**8.87**	1.59

Site excavated by hand on the eastern edge of the headland. No significant ^{226}Ra contamination was detected.

Site 20

NT 16471 83079

Site 20	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
135	**0.73**	0.089	**0.13**	0.028	**5.72**	**1.42**

Site excavated by hand on the eastern edge of the headland. No ^{226}Ra was contamination detected.

Site 21

NT 16461 83081

Site 21	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
30	**4.15**	0.17	**0.88**	0.061	**4.72**	0.38
50	**5.92**	0.21	**1.27**	0.076	**4.67**	0.32
70	**5.30**	0.20	**1.20**	0.076	**4.40**	0.32
90	**6.51**	0.21	**1.60**	0.081	**4.08**	0.25
110	**10.02**	0.25	**2.48**	0.096	**4.04**	0.19
130	**16.00**	0.32	**4.10**	0.13	**3.90**	0.15
150	**7.32**	0.18	**1.95**	0.069	**3.75**	0.16
170	**4.96**	0.17	**1.21**	0.065	**4.10**	0.26
190	**4.33**	0.16	**0.92**	0.056	**4.68**	0.33

Site augured into the eastern side of the earth bank in front of the clubhouse. ^{226}Ra contamination was detected with depth up to 330 Bq kg^{-1}. The data either a single particle of around 10-20 kBq or, because of the reduced ratio at 150 cm depth, two or more particles of around 5-10 kBq above and below this point. Alternatively, this may relate to areas of stratification: 1) 30-310 cm of about 400 Bq kg^{-1}; 2) >170 cm of around 400 Bq kg^{-1}.

Site 22

NT 16458 83077

Site 22	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
90	**5.54**	0.20	**1.38**	0.077	**4.02**	0.27
135	**2.19**	0.14	**0.57**	0.048	**3.88**	0.41

Site augured into the eastern side of the earth bank in front of the clubhouse. ^{226}Ra contamination was detected with depth up to 110 Bq kg^{-1}. A particle of few kBq could also have given a similar response, but it was not possible to establish which caused the elevated count rate.

Site 23

NT 16451 83057

Site 23	**^{214}Bi**				**609 keV / 1764 keV**	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
60	**1.01**	0.083	**0.10**	0.025	**9.67**	2.50
90	**2.96**	0.13	**0.57**	0.043	**5.20**	0.45

Site augured into the centre of the headland area. Higher background counts were suggesting elevated ^{226}Ra contamination to about double background at 90 cm depth.

Site 24

NT 16478 83057

Site 24	**^{214}Bi**				**609 keV / 1764 keV**	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
120	**1.82**	0.14	**0.29**	0.041	**6.21**	0.99
130	**1.75**	0.13	**0.23**	0.041	**7.44**	1.40
140	**1.78**	0.12	**0.28**	0.035	**6.45**	0.92

Site excavated by hand, towards the south eastern corner of the headland. Excavation was hindered by concrete slabs (Figure 4) at 80 cm. No significant ^{226}Ra contamination was detected, but an aircraft dial (no ^{226}Ra activity detected) was recovered from this site.

Site 25

NT 16458 83076

Site 25	**^{214}Bi**				**609 keV / 1764 keV**	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
20	**2.55**	0.14	**0.53**	0.049	**4.80**	0.52
40	**3.38**	0.14	**0.85**	0.051	**3.96**	0.29
70	**2.55**	0.15	**0.61**	0.050	**4.19**	0.42

Site augured to 70 cm depth. Further penetration by augur was not possible. Slightly elevated ^{226}Ra concentrations, up to 70 Bq kg^{-1} were detected. It is possible that this location delimits the southern edge of the ^{226}Ra contaminated lens of waste material.

Core 26

NT 16456 83041

Core 26	^{214}Bi				609 keV / 1730 keV	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
25	**3.21**	0.12	**0.72**	0.042	**4.43**	**0.30**
135	**1.45**	0.089	**0.23**	0.027	**6.32**	**0.85**

Site was excavated by hand on the southern edge of the headland and two measurements oat 25 cm and 135 cm depth were made using the 50mm x 50 mm NaI(Tl) detector. Possible elevated ^{226}Ra contamination was detected at the surface (60 Bq kg^{-1}).

Core 27

NT 16447 83071

Core 27	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
20	**4.58**	0.17	**0.94**	0.064	**4.87**	0.38
30	**4.75**	0.18	**1.07**	0.067	**4.44**	0.33
40	**4.53**	0.19	**1.21**	0.072	**3.74**	0.27
50	**4.91**	0.18	**1.17**	0.071	**4.21**	0.30
60	**4.22**	0.15	**0.95**	0.057	**4.46**	0.31
80	**1.67**	0.093	**0.35**	0.032	**4.77**	0.51
100	**1.11**	0.098	**0.24**	0.033	**4.58**	0.74
120	**0.94**	0.075	**0.22**	0.025	**4.21**	0.59
140	**0.94**	0.094	**0.17**	0.030	**5.45**	1.10

Site augured just to the west of the path in front of the club house. The results indicate that there may be two stratified layers of contamination: 1) 20-30 cm (80 Bq kg^{-1}); 2) 50-60 cm (up to 100 Bq kg^{-1}). Two particles of around a few kBq could produce the same result.

Core 28

NT 16467 83077

Core 28	^{214}Bi				609 keV / 1764 keV	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
90	**0.46**	0.074	**0.12**	0.024	**3.70**	0.94
100	**0.74**	0.076	**0.06**	0.021	**11.62**	4.08
115	**0.68**	0.077	**0.11**	0.024	**6.41**	1.60
135	**0.59**	0.071	**0.16**	0.024	**3.74**	0.73
155	**0.48**	0.071	**0.09**	0.021	**5.62**	1.59
175	**0.51**	0.070	**0.06**	0.019	**8.95**	3.21

Site augured to 175 cm depth following initial excavation by hand to 80cm. No elevated ^{226}Ra concentrations were detected. It is possible that this location delimits the southern edge of the ^{226}Ra contaminated lens of waste material.

Core 30

NT 16461 83086

Core 30	**^{214}Bi**				**609 keV / 1764 keV**	
Depth (cm)	**609 keV**	**1 σ**	**1730 keV**	**1 σ**	**Ratio**	**1 σ**
30	**8.31**	0.22	**1.88**	0.084	**4.42**	0.23
70	**5.88**	0.21	**1.47**	0.080	**3.99**	0.26
100	**10.96**	0.27	**2.74**	0.11	**4.00**	0.18
120	**7.63**	0.23	**2.27**	0.093	**3.37**	0.17
140	**6.92**	0.23	**1.96**	0.090	**3.53**	0.20

Site augured to 140 cm, and ^{226}Ra contamination was detected along the entire length of the hole. The activities were in excess of 200 Bq kg^{-1}. There was a suggestion of a ^{226}Ra contaminated particle of around 20 kBq that may be present in the vicinity of the 140 cm depth measurement.