Scottish Universities Research & Reactor Centre

Investigation of Spatial and Temporal Aspects of Airborne Gamma Spectrometry

Report on Phase III Survey of West Cumbria and Inner Solway Conducted June 2000

D.C.W. Sanderson, A.J. Cresswell, D.C. White, S. Murphy

February 2001

Commissioned work for the Department of the Environment, Transport and the Regions, Radioactive Substances Division, DETR Project Ref: RW 8/6/80

East Kilbride Glasgow G75 OQF Telephone: 01355 223332 Fax: 01355 229898

SUMMARY

An Airborne Gamma Spectrometry (AGS) survey of West Cumbria and the Inner Solway was conducted as part of a project investigating spatial and temporal aspects of AGS between 13th and 26th June 2000. The survey recorded some 70000 spectra from the NaI(Tl) detector with a 2s integration time, and 35000 spectra from the GMX detector with a 4s integration time. The results of this phase of survey work are presented here, and at later stages in the project will be compared with other data sets recorded prior to and during this project to investigate the effect of temporal changes over several years and between different seasons, and the effect of line spacing on data quality.

The survey of West Cumbria covered a 40×40km area with a 10×30km extension on the southern side with 500m line spacing, and a 50×50km area with 2.5 km line spacing. The ^{137}Cs activity distribution over the upland areas to the east of Sellafield is very similar to the distribution determined from the 1988 MAFF survey of the same area, consisting of activity derived from the Chernobyl accident and Windscale fire. The distribution of ^{40}K, ^{214}Bi and ^{208}Tl in these areas are consistent with expectations from variations in geology and soils, with high values on the exposed rocky high ground and lower levels on peaty ground. The highest dose rate in the inland areas correspond with the high ground, where there are elevated natural and ^{137}Cs activities. The dose rate distribution is most closely correlated to the uranium and thorium series activity distribution.

Some additional measurements were conducted around the Sellafield site to investigate some features observed in the March 2000 survey further, in particular the earlier survey had shown ^{137}Cs signals associated with an exposed section of the discharge pipeline. Work has been conducted to cover the pipeline since March, and the signal is no longer observed in the radiometric data.

Sodium iodide data had shown low level ^{60}Co signals on salt marshes around Ravenglass, corresponding to approximately 1-2 kBq m^{-2}, and some upland areas. These upland areas also have higher ^{40}K activities, raising the possibility that the small ^{60}Co signals are due to incomplete stripping of spectral interferences. There is less ^{40}K activity on the saltmarshes. In this survey both areas were revisited and spectra recorded from the Ge detector were examined for evidence of ^{60}Co activity peaks. Within the available statistical limits there was no evidence of ^{60}Co in either location.

The repeat survey of the Inner Solway area around Rockcliffe Marsh was conducted at 250 m line spacing; this area had been surveyed in April 1999 with a 50 m line spacing. The distribution of activity in this area measured in this survey is very similar to that determined from the earlier survey. The highest ^{137}Cs activities are observed on the salt marshes, particularly Rockcliffe and Burgh Marshes, with lower activities measured from exposed estuarine muds. There are reduced natural activities associated with small areas of wooded or wet peat moss lands.

ACKNOWLEDGEMENTS

The work presented here was funded by the Department of Transport, Environment and the Regions (DETR), the Environment Agency (EA), the Ministry of Agriculture, Fisheries and Food (MAFF), British Nuclear Fuels Ltd (BNFL), the Industry Management Committee (IMC) and the SNIFFER fund.

The aircraft used was supplied by PDG Helicopters Ltd, and flown by John Constable. We are grateful to Dr Paul McDonald of the Westlakes Research Institute for supplying liquid nitrogen to cool the Ge detectors. Iona Anthony and Iain Houston assisted with the field work.

CONTENTS

1. INTRODUCTION

This report documents the results of an airborne gamma ray survey conducted by the Scottish Universities Research and Reactor Centre between 13 and 26 June 2000 covering a 40×40 km area in NW Cumbria, a 50×50 km area in West Cumbria, and a 11×6 km area in the Inner Solway over Rockcliffe Marsh. The survey was carried out as part of a wider project commissioned by the Department of the Environment, Transport and the Regions (DETR), the Environment Agency (EA), the Ministry of Agriculture, Fisheries and Food (MAFF), and other agencies.

1.1 Airborne Gamma Spectrometry (AGS)

The AGS method is highly appropriate for large scale environmental surveys of areas of potentially contaminated ground. The methodology for aerial surveys is well established (Sanderson *et al*, 1994a, 1994b), and has been used by the SURRC team for a variety of purposes including environmental assessments of contamination (Sanderson *et al*, 1990a, 1990b); Chernobyl fallout mapping (Sanderson *et al*, 1989a, 1989b, 1990c, 1994c); baseline mapping around nuclear establishments (Sanderson *et al*, 1990d, 1992, 1993b, 1994d); the effects of marine discharges on coastal environments (Sanderson *et al*, 1994c); epidemiological studies (Sanderson *et al*, 1993a); and radioactive source searches (Sanderson *et al*, 1988b, 1991). In addition, the technique has been used by airborne survey teams from Scandinavia, Germany and France and other countries.

By operating suitable spectrometers from low flying aircraft, in this case a helicopter, it is possible to map the distribution of γ-ray emitting radionuclides at ground level. This has a number of advantages when compared with conventional methods. High sensitivity γ-ray detectors installed in the aircraft are capable of making environmental radioactivity measurements every few seconds, thus providing a sampling rate some 10^2-10^3 times greater than other approaches. The radiation detector averages signals over fields of view of several hundred metre dimensions, resulting in area sampling rates some 10^6-10^7 times greater than ground based methods. Sequences of γ-ray spectra, geographic positioning information and ground clearance data are recorded, and are used to quantify levels of individual radionuclides and the general γ-dose rate. The high mobility of the aircraft is also advantageous, as is its ability to operate over varied terrain, unimpeded by ground level obstacles or natural boundaries. Moreover, the remote sensing nature of the measurements minimises exposure of survey teams to contamination or radiation hazards. This results in a practical means of conducting surveys with total effective coverage, which can be used for rapid location of point sources or areas of radioactive contamination. This has important implications for environmental radioactivity studies, especially where there are time constraints, and is highly significant in emergency response situations.

The SURRC team has also utilised a combined detector system, utilising both a 16 litre NaI(Tl) detector and one or two cryogenically cooled germanium (Ge) semiconductor detectors, for airborne radionuclide monitoring. Whilst the use of NaI(Tl) detectors is well established and used frequently in airborne surveys, the use of Ge detectors is relatively new. Ge detectors have a much higher energy resolution than the NaI(Tl) scintillator detector, and

so are able to identify the nuclides contributing to the gamma ray spectrum, particularly where complex fission product sources are present. However, they are considerably less sensitive than NaI(Tl) requiring the use of longer integration times with a resulting loss of spatial resolution in all but the most active environments. In the current work a single 50% efficiency Ge (GMX) detector mounted inside the aircraft was used.

1.2 Project Aims

The aims of the overall project, of which the work reported here are the results of the second phase of field work, are to investigate the spatial and temporal influences on airborne gamma ray spectrometry (AGS) with particular reference to the effects of (i) line spacing, (ii) survey ground clearance, (iii) seasonality, and (iv) environmental change. Supplementary collaborative work involving experimental assessment of digital photogrammetry and satellite imagery is also taking place with scientists at the University of Glasgow and the University of Stirling respectively.

To investigate the spatial and temporal influences on AGS surveys of several regions in NW England and SW Scotland have been planned, and are being implemented. These areas will be surveyed using a range of linespacings from 50 m to 2.5 km with subsampling of these data sets to provide data for larger linespacing. To investigate seasonal effects the field work has been divided into a number of phases to be undertaken under different seasonal conditions. The area chosen for this study exhibits a range of radiation environments due to natural variations, Chernobyl fallout and Sellafield discharges; and encompasses wide variations in landscape with mountainous terrain, moorland, forest, pasture and estuarine environments. The SURRC AGS team have conducted radiometric surveys of parts of the area covered in this project on several occasions over a ten year period (Sanderson *et al*, 1989a, 1990d, 1994c) allowing evaluation of changes in the environment over a more extended period.

Table 1.1 lists the areas that it is planned to survey over the period of this project, with the linespacing to be used for each area. Areas A and B covering the inner Solway and Rockcliffe Marsh (50 and 250 m linespacing) were surveyed in April 1999, the preliminary results presented elsewhere (Sanderson *et al* 2000a). Areas E to I were surveyed in March 2000, with the results presented elsewhere (Sanderson *et al* 2000b). This report presents results from the survey of areas C and D, along with area A (at 250 m linespacing). Following the completion of survey work and preliminary analysis of the data comparisons between different data sets recorded during this project at various linespacing and differing seasonal conditions, along with comparison between these data and earlier data recorded in these areas will be conducted.

Area	Size (km)	OS bounds Sheet NY	Description	Line Spacing (m)
A	11×6	270590-370650	Rockcliffe, Burgh Marsh	50, 250
B	30×20	100500-400700	Inner Solway	250
C	40×40	000100-400500	NW Cumbria	500
D	50×50	SD000750-NY500250	NW England	2500
E	Coastline	Gretna-Duddon	Coastline with 4 lines at ~100 m spacing	n/a
F			Former RAF Carlisle site	50
G	25×5	St Bees-Eskmeals, 5km inland	Sellafield	100
H			Workington Harbour	50
I			Albright and Wilson plant, Whitehaven	50

Table 1.1: Survey areas for the project.

2. SURVEY DETAILS

2.1 Instrumentation

The system used consisted of a high volume 16 litre thallium doped sodium iodide (NaI(Tl)) spectrometer, a single 50% efficiency Ge semiconductor (GMX) detector, an electronics rack containing power supplies, nucleonics and computer, and two GPS systems. The first GPS system, a Navstar unit attached to the electronic rack and connected to the logging computer, was used to log aircraft position at the start and end of each spectrum recorded. The second system, a hand held Garmin unit, was programmed with waypoints for the survey grids and used by the pilot for navigation; this unit was not used for navigation during free flying, and was often turned off during these flights to conserve battery power. The aircraft used was a twin engine AS355 Squirrel helicopter fitted with a radar altimeter. A video camera was fitted on the inside of the aircraft, looking downward through the front window bubble in front of the electronics rack. This records a continuous record of each flight, from which a total video track or images of selected features could be extracted.

2.2 Deployment and Testing

The equipment consisting of the combined system of NaI(Tl) and Ge detector and associated instrumentation was installed in the helicopter at Cumbernauld airport on the 13th June, and tested prior to deployment for the survey. The tests included confirmation of the correct functioning of all components, calibration of the radar altimeter reading by means of a hover manoeuvre at the end of the runway, and initial background measurements.

2.3 Measurement Procedure

The detector system performance (gain, resolution and sensitivity) was checked at the start of each day, and trimmed as necessary. Background measurements were made over Ennerdale Water at the start or end of most survey flights, and are given in appendix A, table A.5. During flight the NaI(Tl) detector gain was monitored by using the ^{40}K peak at 1462 keV. Spectra were recorded from the NaI(Tl) spectrometer with a 2s integration time, and 4s for the GMX detector. Files containing 2 NaI(Tl) spectra and one GMX spectrum were written to disk, together with timing information, GPS positioning data and time-averaged radar altimetry data.

2.4 Calibration Measurements

The calibration manoeuvre, conducted on three separate occasions at Caerlaverock consisted of measurements undertaken while hovering at a series of altitudes above a calibration pattern. The pattern at Caerlaverock consists of concentric hexagons at 8, 32, 128 and 256 m from the central point. Cores were collected from this site in February 1992 and April 1999. In addition, short hover manoeuvres were conducted at the start and finish of each survey

flight over a field near Croasdale Farm that had been sampled in March 2000 (Sanderson *et al* 2000b).

The ^{137}Cs data has been calibrated to the Caerlaverock saltmarsh, where the activity is buried to an average mass depth of 15.7 g cm^{-2}. The resulting maps calibrated in this manner are comparable with the 1999 survey data. It is recognised that the calibration constants for individual nuclides are sensitive to mass-depth variations (Allyson, 1994, Tyler *et al*, 1996a). In areas with greater source depth (eg: uniform activity in ploughed areas or intertidal sediments) the integrated activities may be underestimated, whereas in areas with shallower source burial the activities will be overestimated. The calibration manoeuvre carried out over Croasdale farm, and the cores collected, will allow for a recalibration of the data to the terrestrial environment at a later date

2.5 Field Measurements

The survey tasks consisted of three survey areas; a 40×40 km area in NW Cumbria (Area C) flown with a 500m linespacing, a 50×50 km area in West Cumbria (Area D) flown with a 2.5 km linespacing, and an 11×6 km area in the Inner Solway over Rockcliffe Marsh (Area A) flown with a 250 m linespacing. In addition, a 500 m linespacing extension was surveyed on the southern side of area C, and a small 10×10 km area within area C was surveyed at 500 m linespacing with lines oriented perpendicular to the main survey. These areas are shown in figure 2.1.

In addition, calibration manoeuvres (detailed above) and a series of tie lines were flown. The tie lines were flown in a north-south at a range of altitudes covering all the areas due for survey during this phase of the project, and will be reflown during later survey phases to ensure comparability of data. Details of the survey flights, giving the number of files recorded and the area covered are given in appendix A, table A.6, with the flight track recorded by the Garmin GPS system used for navigation shown in figure 2.2; this unit was sometimes switched off when not in use so the track is incomplete. In total over 70000 NaI(Tl) spectra were recorded with 2 s integration times, and 35000 GMX spectra with 4 s integration times, with a total survey time of approximately 54 hours.

Operations were conducted from a cottage at Croasdale Farm near Ennerdale Water, where facilities were provided for refuelling the aircraft and initial data analysis.

2.6 Data Handling

Summary files, consisting of gross count rates for 6 windows (corresponding to ^{137}Cs, ^{60}Co, ^{40}K, ^{214}Bi, ^{208}Tl and total γ-dose rate), were produced from the data after each survey flight. All data were backed up onto ZIP disks at the end of each day, and restored to a separate computer for verification. Spectral data were replayed from restored data to verify backups prior to deletion of primary data from the logging computer.

With the exception of one flight in the evening of the 16th March, background values were

approximately constant throughout the survey period, and mean values were used to correct for the aircraft background during the data analysis. Stripping factors determined from measurements conducted in April 1999 prior to the previous phase of survey work were used to account for interferences between different γ-rays. Altitude correction coefficients were determined from the data recorded during the Caerlaverock calibration manoeuvre. Calibration factors for ^{137}Cs determined from data recorded over Caerlaverock during the previous survey in April 1999 (Sanderson *et.al.* 2000) gave activity levels on the merse at Caerlaverock consistent with values measured by sampling in 1999, and were used for initial data analysis in this survey. Theoretically derived calibration factors for the naturally occurring radioisotopes of ^{40}K, ^{214}Bi and ^{208}Tl were used. Due to the lack of measurable levels of ^{60}Co activity on the Caerlaverock site a calibration constant for this isotope could not be determined experimentally, and the activity is given as an altitude-corrected count rate. It has been estimated that an equivalent surface activity of 1 kBq m^{-2} would give a count rate of approximately 14cps in the 16 litre NaI(Tl) spectrometer at a ground clearance of 100 m (Sanderson *et al*, 1994e).

Some initial analysis was conducted in the field to check the quality of the data from each flight, and to facilitate the re-surveying of any lines as needed. This included preliminary mapping to identify any features requiring further attention. It was noted that on one survey flight, early evening 16th March comprising files DET21 and DEG22, the data included elevated ^{214}Bi activities probably as a result of contamination by radon gas and associated decay products. This area was surveyed again on the 18th March, file DETE4.

Spectral colour plots for the NaI(Tl) and GMX data were also produced. These plots show the sequence of spectra recorded, allowing the identification of spectral features other than those normally included in the spectral windows used for the summary data (eg: ^{41}Ar) or other anomalies (eg: microphonics in the GMX spectra).

In addition to the data recorded under high radon conditions, several flights included high altitude transits across the survey area or across inter-tidal areas under higher tidal conditions. These anomalous data, along with the background measurements, were excluded from the final data set which comprised a smaller number of summary files compiled from the good data. The resulting new summary files are given in appendix A, table A.6. Figure 2.3 shows the position of each measurement included in these summary data.

The average background recorded over Ennerdale Water was subtracted from the data in these files, spectral interferences stripped out and altitude and sensitivity calibration factors applied. The resulting calibrated data for ^{137}Cs (kBq m^{-2}), ^{60}Co (count rate normalized to 100 m ground clearance), ^{40}K, ^{214}Bi, ^{208}Tl (all Bq kg^{-1}) and the γ-dose rate (mGy a^{-1}) were mapped for each of the survey areas. The numerical data set contains more detail than can be expected to be seen in these maps.

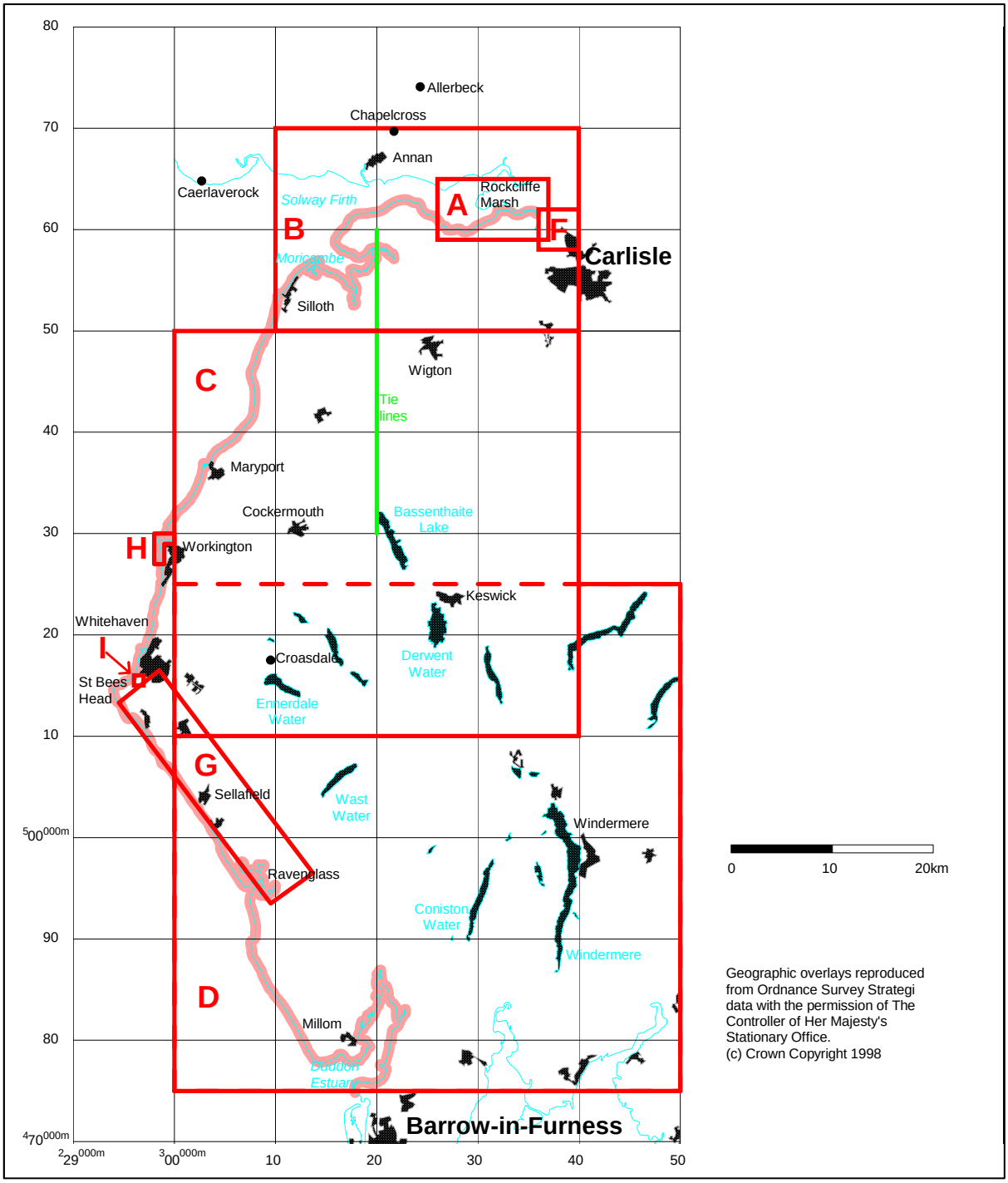

Figure 2.1: Survey areas for the project

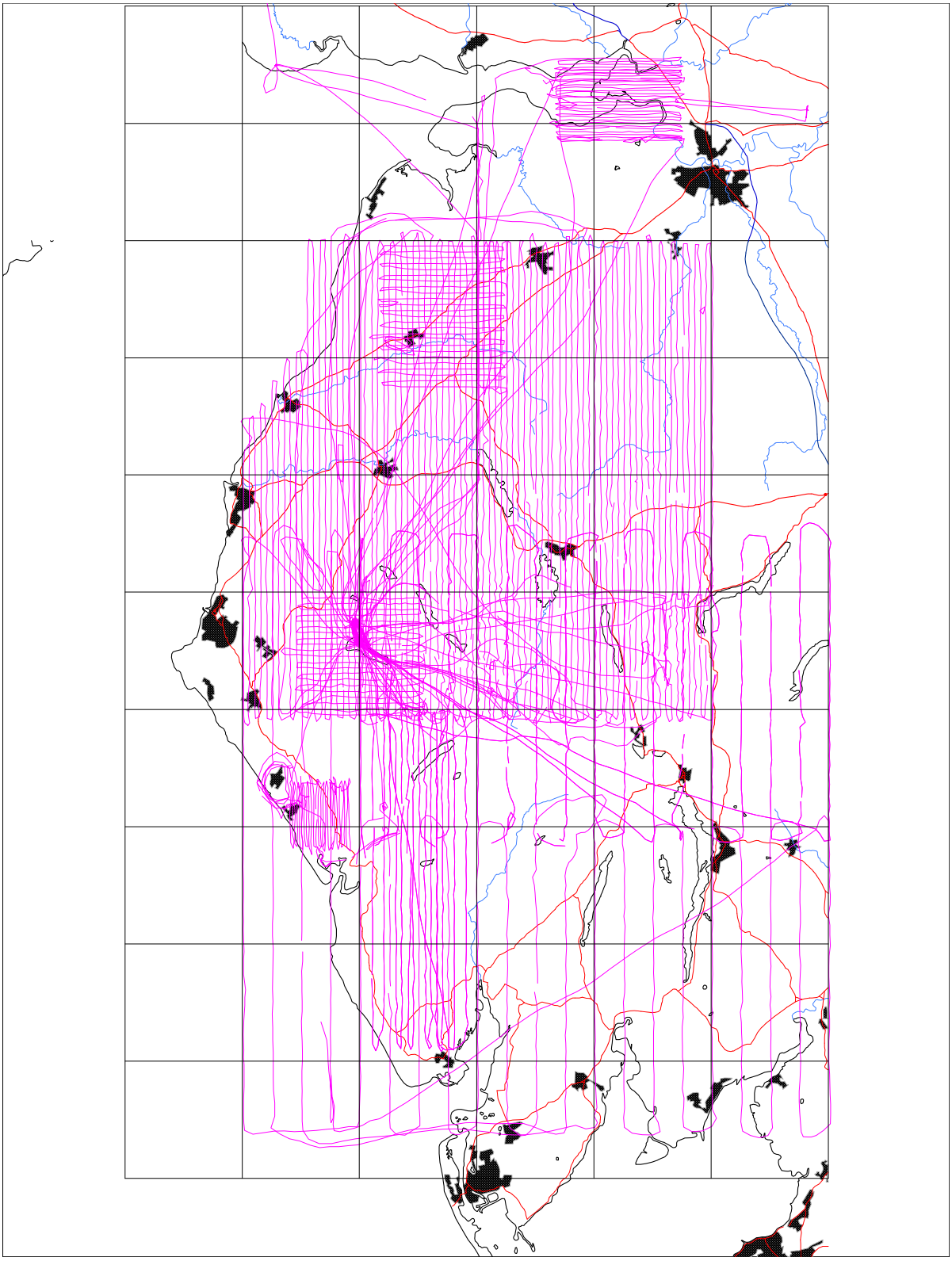

Figure 2.2: Flight lines recorded by GPS track for this survey.

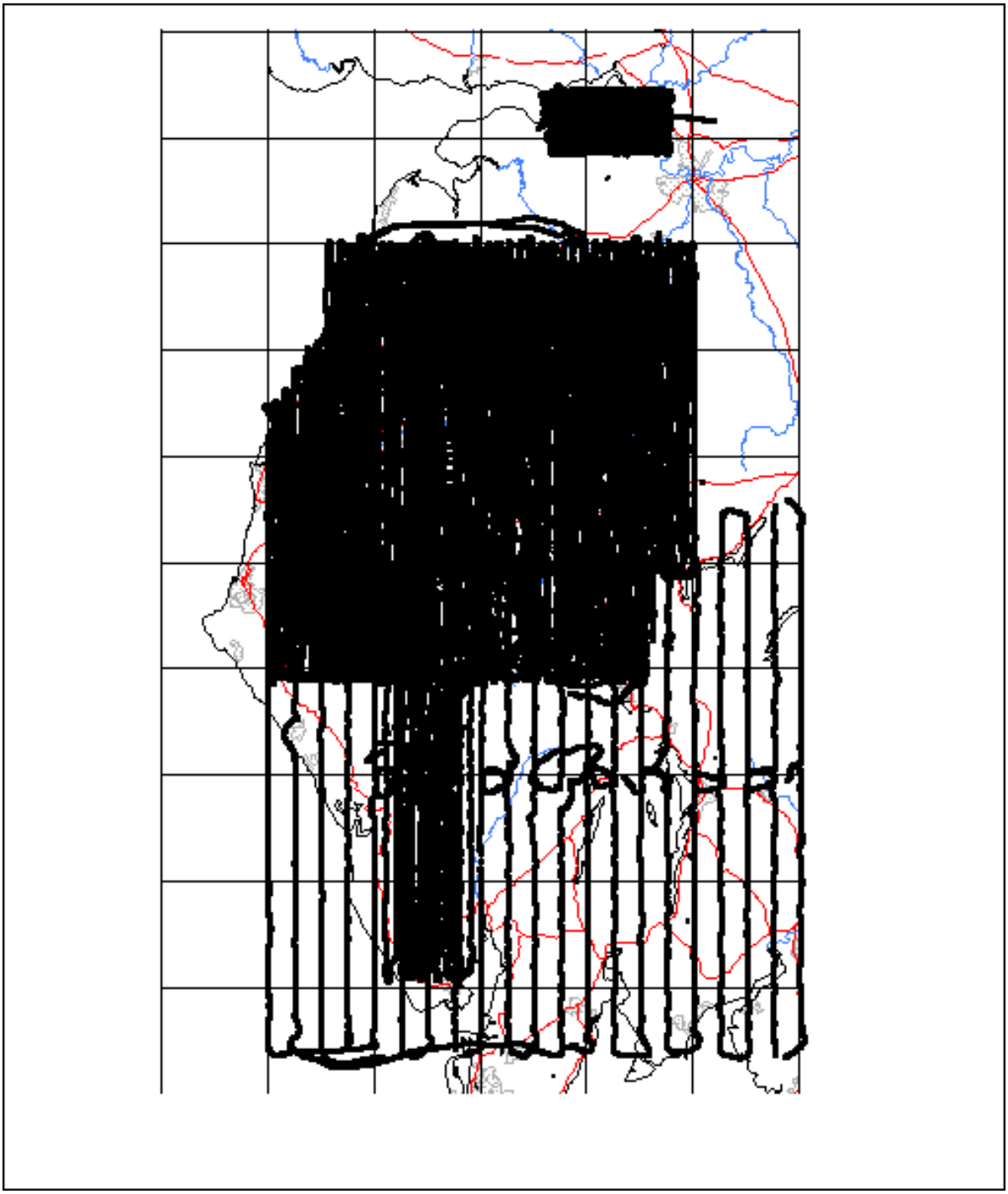

Figure 2.3: Measurement locations included in analysis.

3. RESULTS AND DISCUSSION

3.1 West Cumbria (Areas C and D)

The survey of West Cumbria consisted primarily of a 40×40 km area flown with 500 m linespacing (area C), and a 50×50 km area flown with 2.5 km linespacing (area D), with flight lines orientated north-south. In addition, a region to the south of area C covering the area surveyed in 1988 (Sanderson *et al* 1989a) was flown with a 500 m linespacing, some areas around Sellafield were re-surveyed, and two 10×10 km areas to the west of Ennerdale and the east of Maryport were surveyed at 500 m linespacing with flight lines orientated east-west to assess reproducibility from survey lines perpendicular to each other and to examine an artifact in the radiometric data observed in initial data processing. All these data are included in the following maps. Note that due to the range used in the distance-weighted interpolation used to generate these maps the lines associated with the 2.5 km linespacing data are wider than the field of view of the detector.

3.1.1 ^{137}Cs Distribution

The distribution of ^{137}Cs in west Cumbria is shown in figure 3.1. The distribution across the terrestrial environment reflects the known Chernobyl fallout pattern in the region, with a clear division running from the southeast to the northwest, with higher activities to the south and west of this line. The highest upland signals are on the high ground of Loweswater Fell to the north of Ennerdale Water, Copeland Forest and Ennerdale Fell to the south of Ennerdale Water, the Langdale Fells to the north of Coniston Water, and Black Coombe to the north of Millom. The distribution of ^{137}Cs over the upland areas to the east of Sellafield is very similar to the distribution of activity observed in 1988 (Sanderson *et al* 1989a).

High levels of ^{137}Cs activity are also observed on the salt marshes of the rivers Irt, Mite and Esk at Ravenglass, the Duddon Estuary to the north of Millom, Cartmel Sands and Grange-over-Sands on the northern side of Morecambe Bay and the River Kent. Additional ^{137}Cs activities associated with materials and activities within the Sellafield and Drigg sites are also evident, although the signal on the beach by Sellafield associated with the discharge pipeline observed in the March 2000 survey is no longer present following work since March to cover the exposed sections of the outlet pipe.

3.1.2 ^{60}Co Distribution

The distribution of ^{60}Co in west Cumbria is shown in figure 3.2. There are signals associated with the Sellafield and Drigg sites resulting from materials stored on the sites, and interferences from ^{41}Ar discharges to the northeast of the Sellafield site. There are minor signals in the upland areas, which correspond to areas of high ^{40}K activity and almost certainly represent incomplete spectral stripping. There appears to be low levels of ^{60}Co activity (around 1-2 kBq m^{-2}) on the saltmarshes of the rivers Irt and Mite which have low ^{40}K activity. Spectra recorded with the GMX detector in this location do not show the characteristic peaks due to ^{60}Co.

3.1.3 ^{40}K Distribution

The distribution of ^{40}K in west Cumbria is shown in figure 3.3. This reflects the geology of West Cumbria, with high ^{40}K activity associated with the higher fells, and substantially reduced activity associated with peaty moorland.

3.1.4 ^{214}Bi Distribution

The distribution of ^{214}Bi in West Cumbria is shown in figure 3.4. This also reflects the geology of the area, with high values in the central fells and reduced activity associated with the moorland.

3.1.5 ^{208}Tl Distribution

The distribution of ^{208}Tl in west Cumbria is shown in figure 3.5. This shows a very similar distribution to the ^{40}K activity.

3.1.6 γ-ray Dose Rate

The distribution of the γ-ray dose rate in west Cumbria is shown in figure 3.6. In the terrestrial environment this primarily reflects the variations in the activities of naturally occurring ^{40}K, ^{214}Bi and ^{208}Tl, with the Chernobyl derived ^{137}Cs contributing less to the dose rate. The precise contribution of ^{137}Cs to the dose in the upland areas isn't clear as the ^{137}Cs distribution is predominantly on the higher ground, which also tends to have higher natural activity levels. In the coastal areas the ^{137}Cs activity on the salt marshes and the anthropogenic signals from the Sellafield and Drigg sites dominate the dose rate.

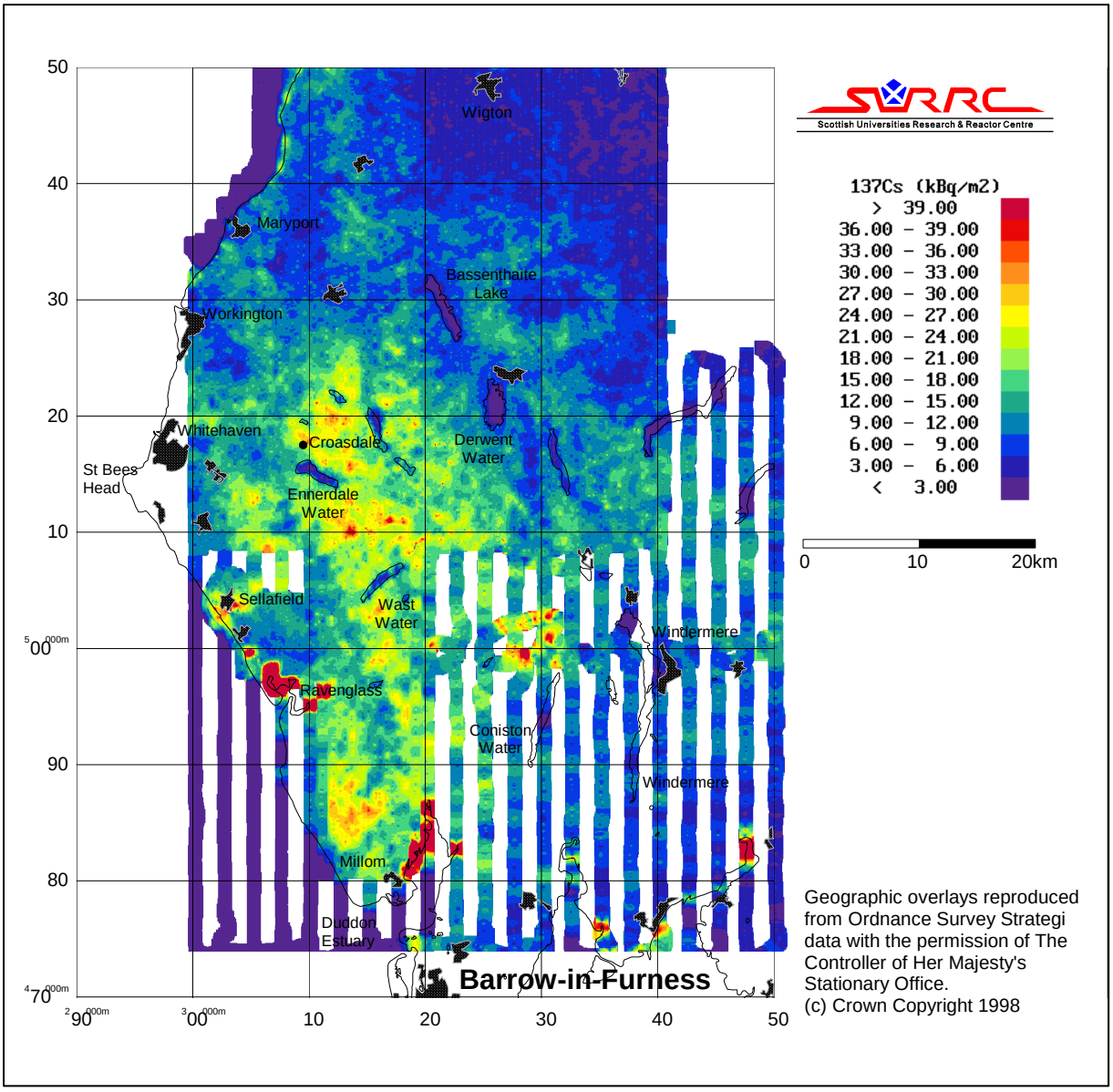

Figure 3.1: ^{137}Cs distribution for West Cumbria (areas C and D).

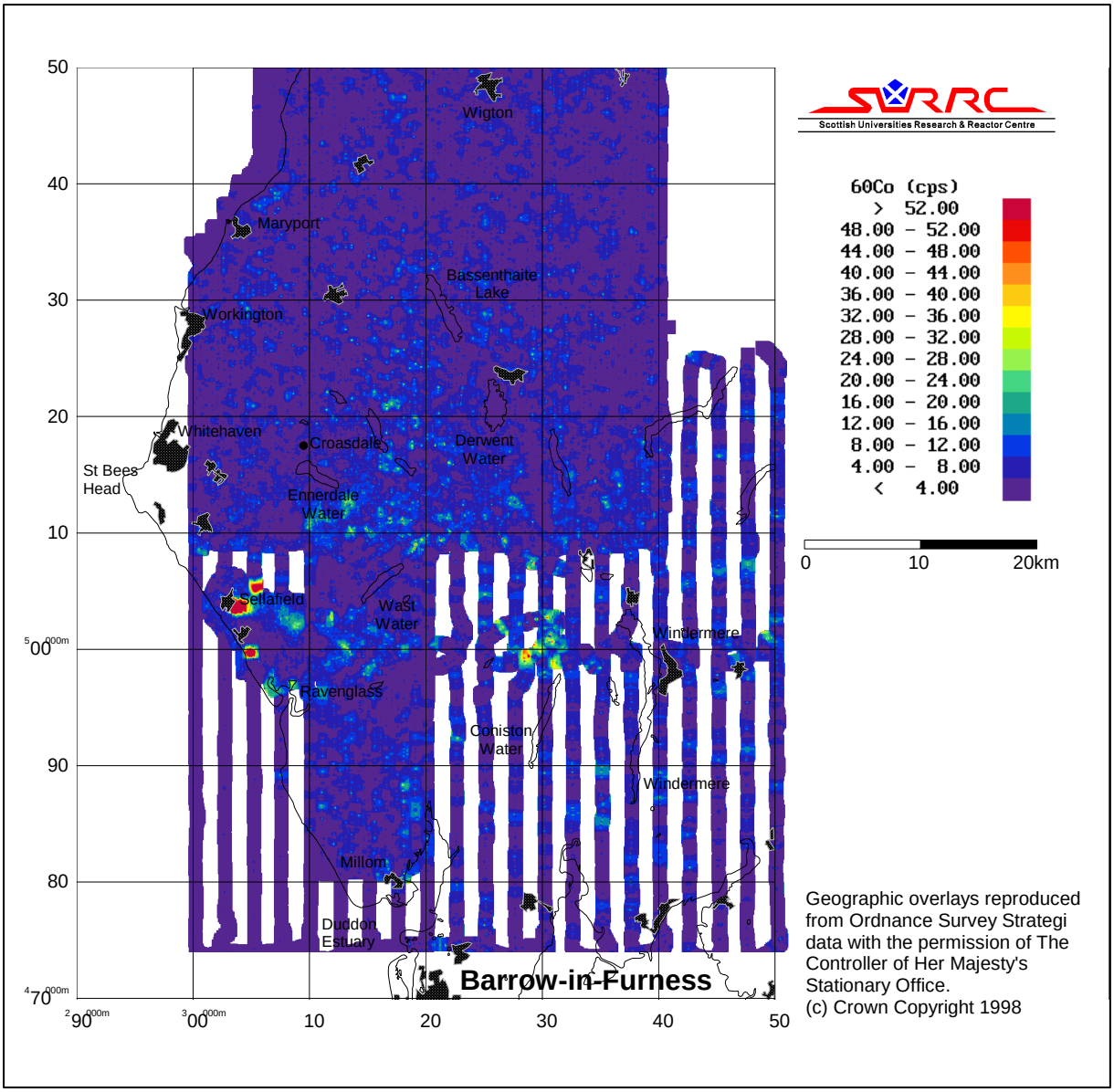

Figure 3.2: ^{60}Co distribution for West Cumbria (areas C and D).

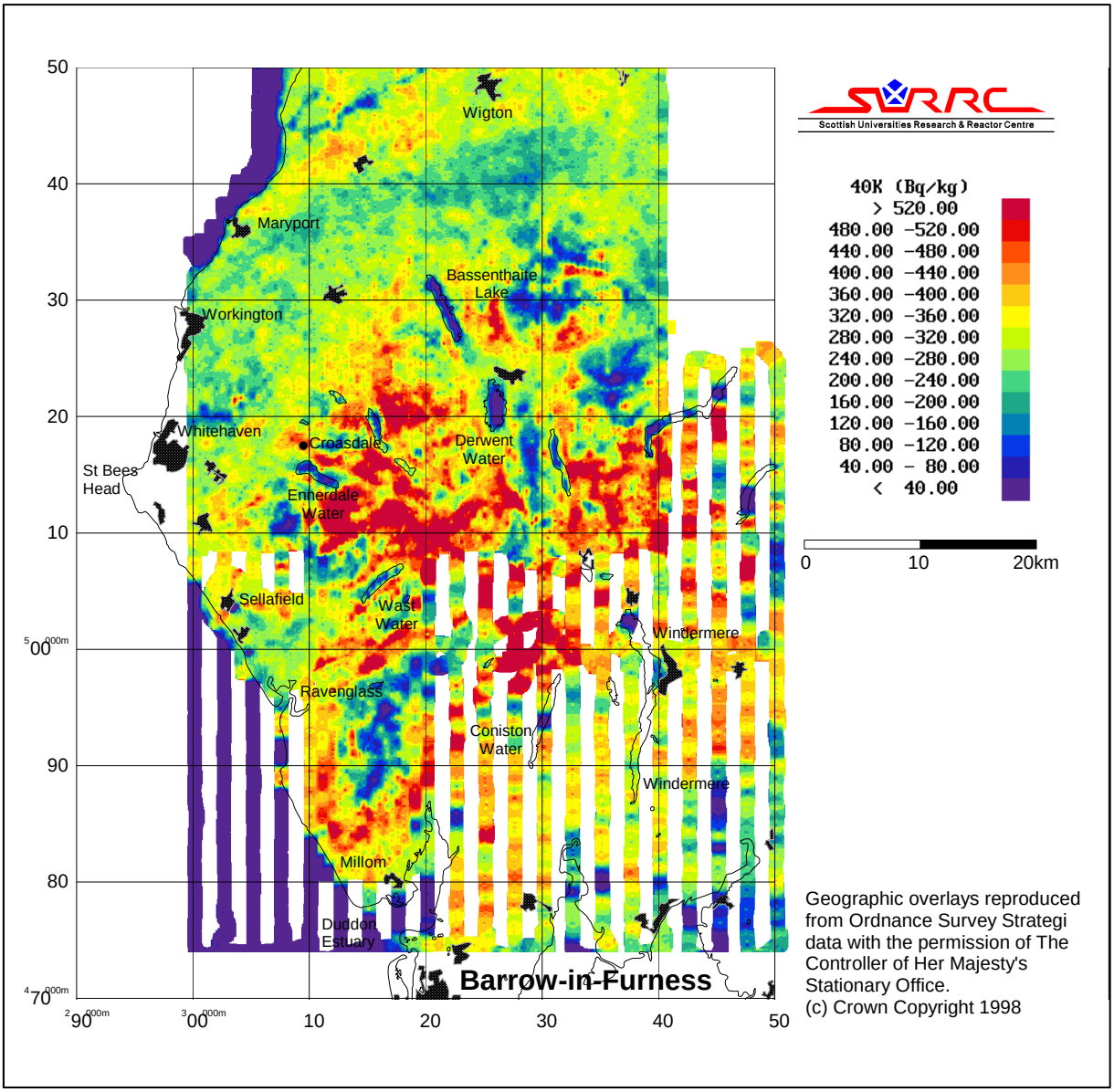

Figure 3.3: ^{40}K distribution for West Cumbria (areas C and D).

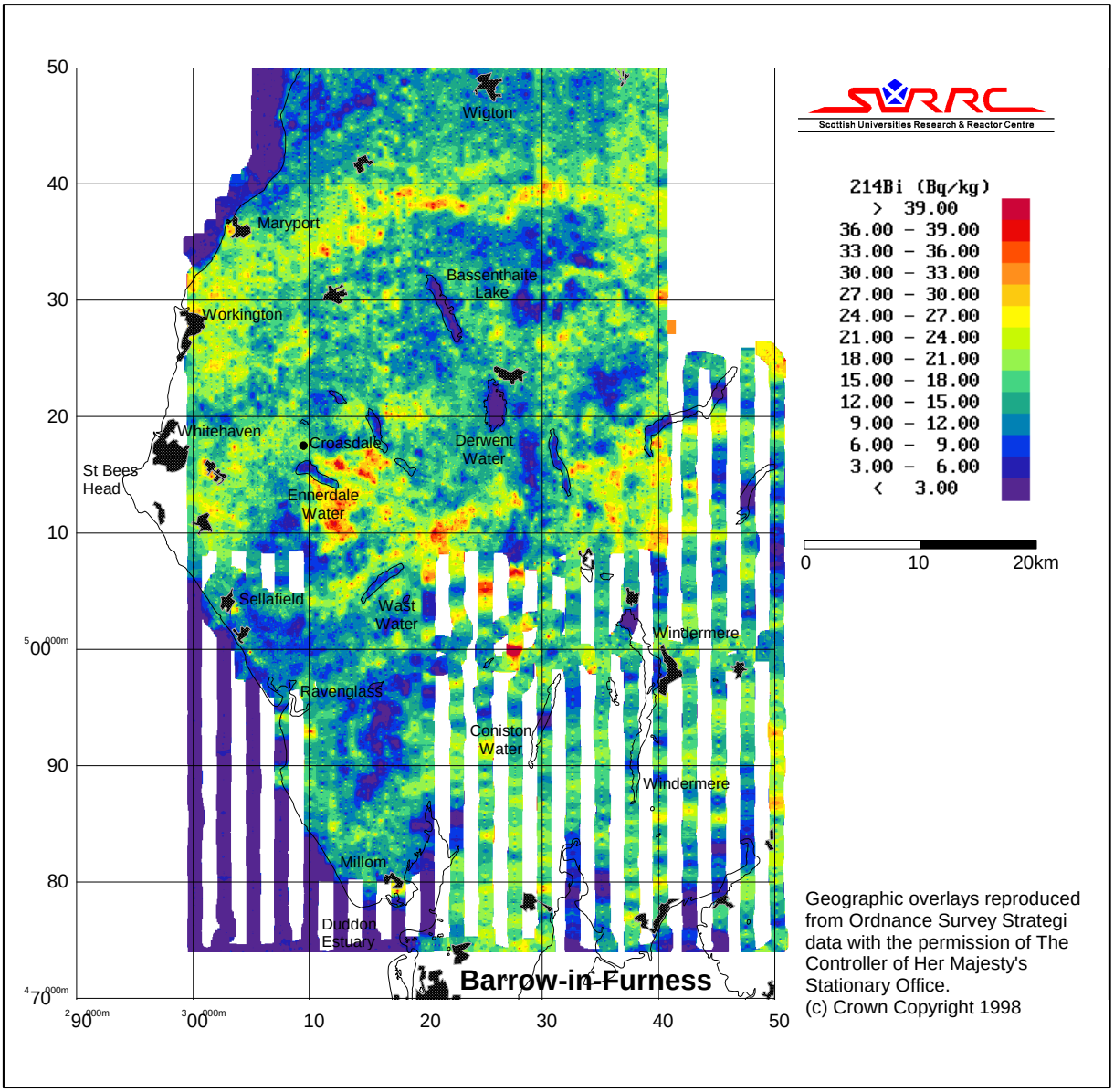

Figure 3.4: ^{214}Bi distribution for West Cumbria (areas C and D).

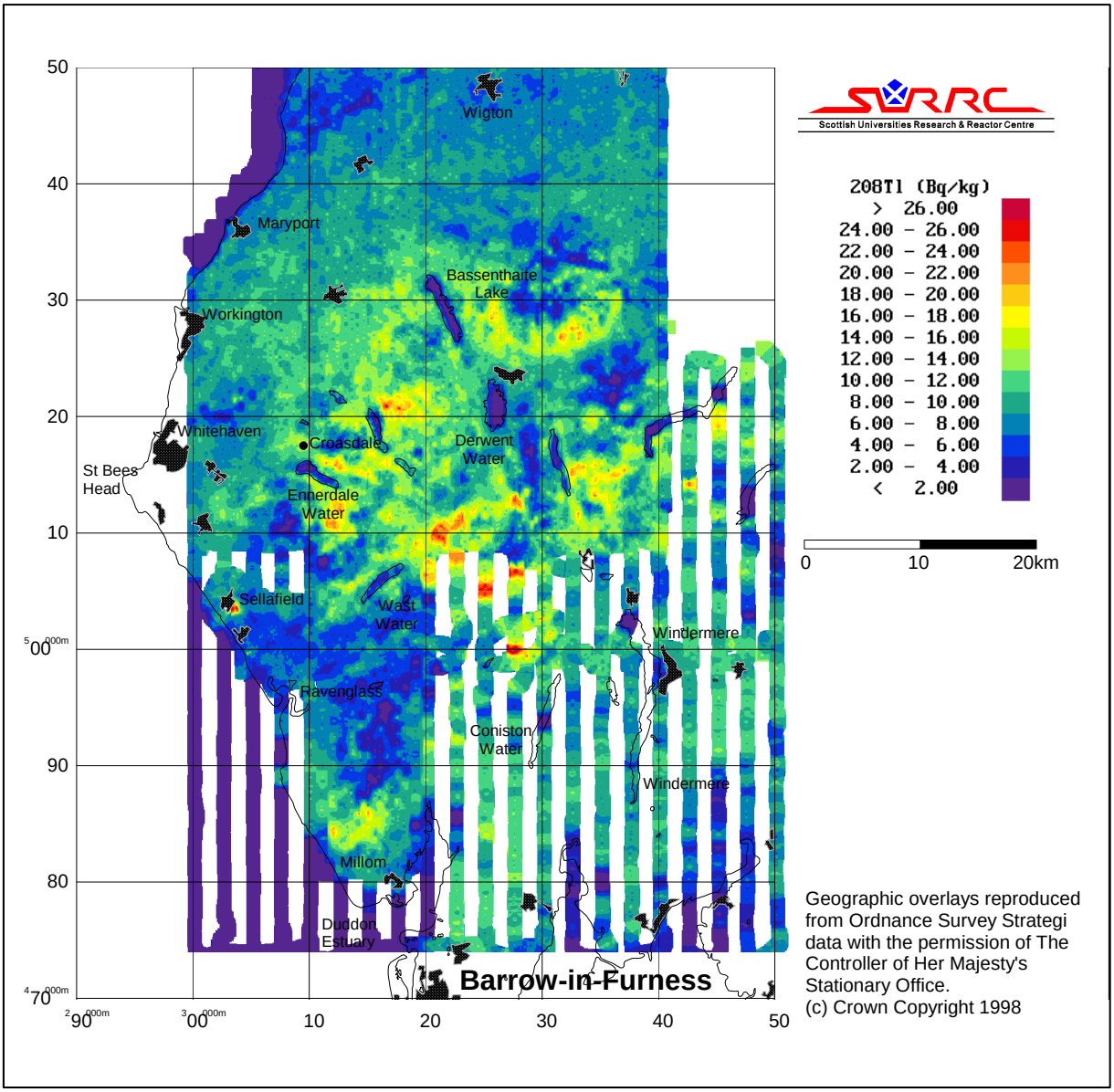

Figure 3.5: ^{208}Tl distribution for West Cumbria (areas C and D).

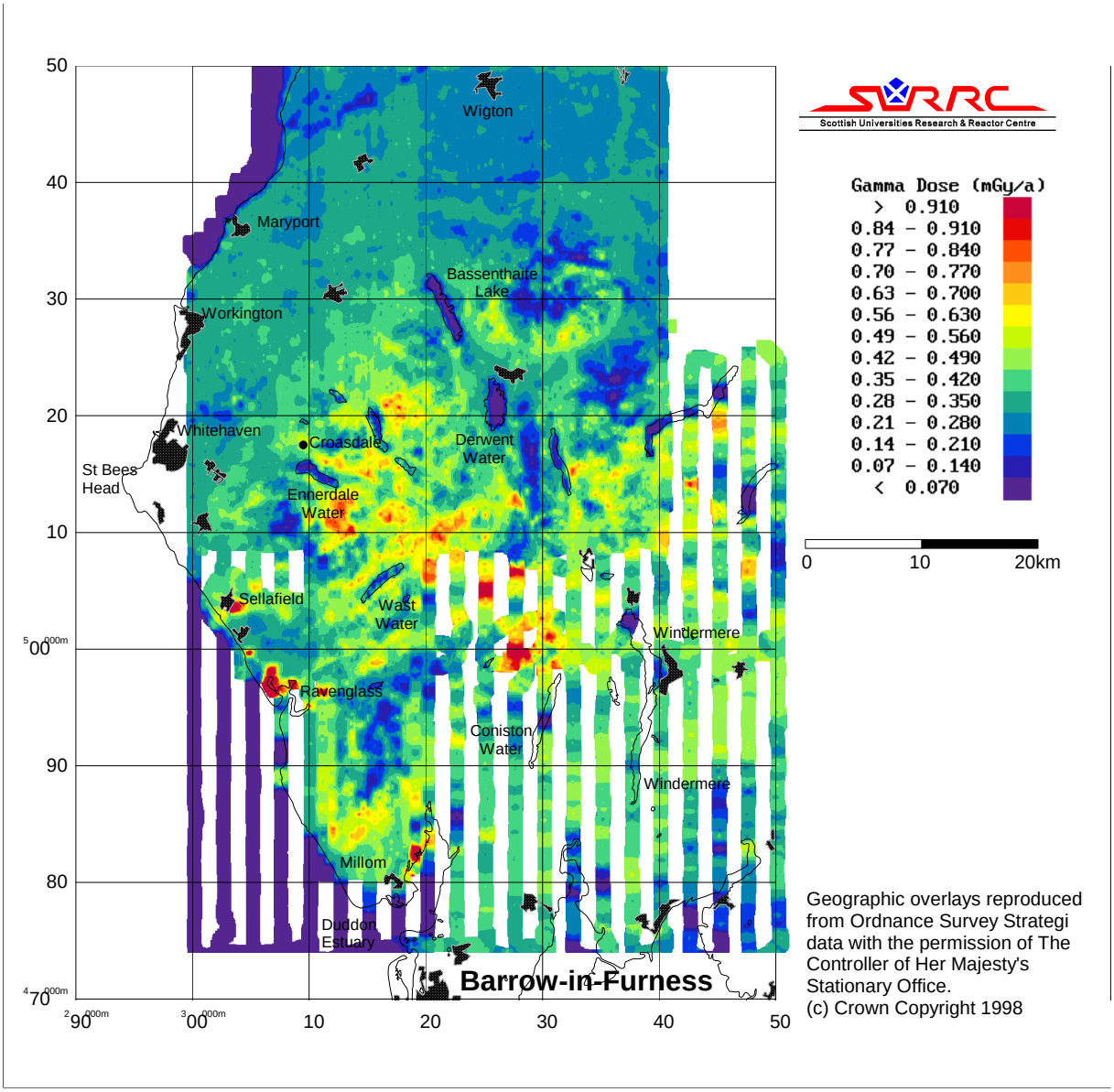

Figure 3.6: γ-ray dose rate for West Cumbria (areas C and D).

3.2 Inner Solway (Area A)

The Inner Solway survey covered the same 11×6 km area that had previously been surveyed in April 1999, on this occasion with a 250 m linespacing. The survey was conducted on 22nd June.

3.2.1 ^{137}Cs Distribution

The distribution of ^{137}Cs in the Inner Solway determined from this survey is shown in figure 3.7. The pattern of activity, with high levels on the salt marshes of Rockcliffe and Burgh Marshes and along the River Eden with lower levels on the muds and much lower levels on the terrestrial environments, is very similar to that observed in April 1999.

3.2.2 ^{40}K Distribution

The distribution of ^{40}K activity in the Inner Solway determined from this survey is shown in figure 3.8. The distribution is similar to that observed in April 1999, with slightly higher activity levels on the exposed muds than on the saltmarshes, elevated terrestrial levels near Rockcliffe and south of Drumburgh and lower terrestrial levels near Todhills and to the north of Rockcliffe corresponding to areas of woodland, and in the northwest of the survey area and west of Burgh by Sands, which are probably peat moss areas. There are slightly reduced ^{40}K levels associated with the courses of rivers, most notably the Eden above the intertidal limit and Powburgh Beck to the east of Burgh by Sands. The river channels through the estuarine mud flats are not as clear as observed in the earlier survey, possibly due to different tidal conditions or as a result of the wider linespacing.

3.2.3 ^{214}Bi Distribution

The distribution of ^{214}Bi activity in the Inner Solway determined from this survey is shown in figure 3.9. This shows the low levels of activity observed in the earlier survey, with slightly higher activities to the east of the Eden, the far eastern part of the survey here including the end of the railway line feature observed in the March 2000 survey.

3.2.4 ^{208}Tl Distribution

The distribution of 208Tl activity in the Inner Solway determined from this survey is shown in figure 3.10. This shows higher activity on the saltmarsh and terrestrial environments compared to the exposed estuarine muds.

3.2.5 γ-ray Dose Rate

The γ-ray dose rate distribution in the Inner Solway determined from this survey is shown in figure 3.11. This shows that the dose in this area is dominated by the ^{137}Cs distribution, especially on Rockcliffe and Burgh Marshes. There are also low dose rate areas corresponding to the lower ^{40}K activity areas and river channels.

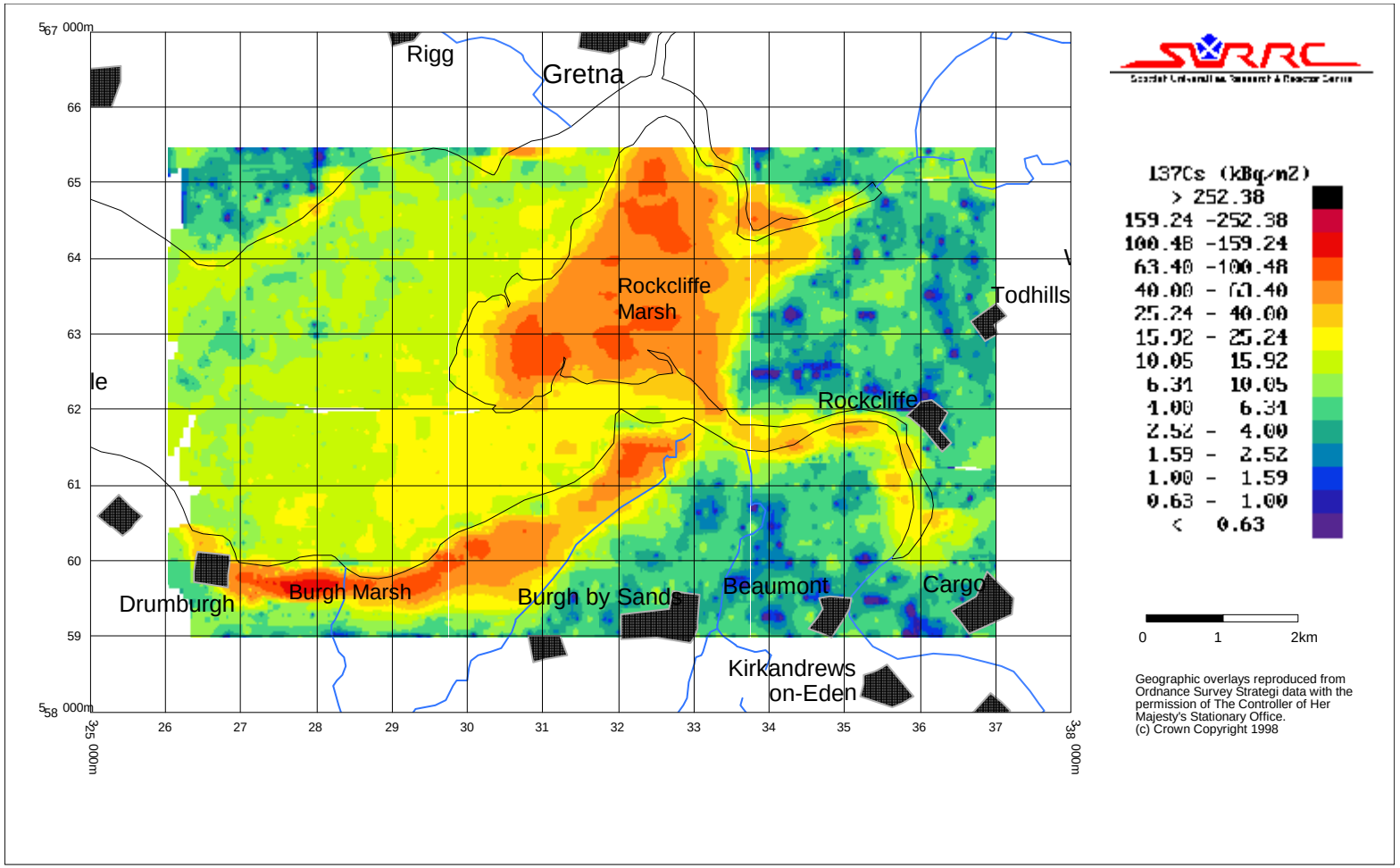

Figure 3.7: ^{137}Cs distribution for the Inner Solway (area A).

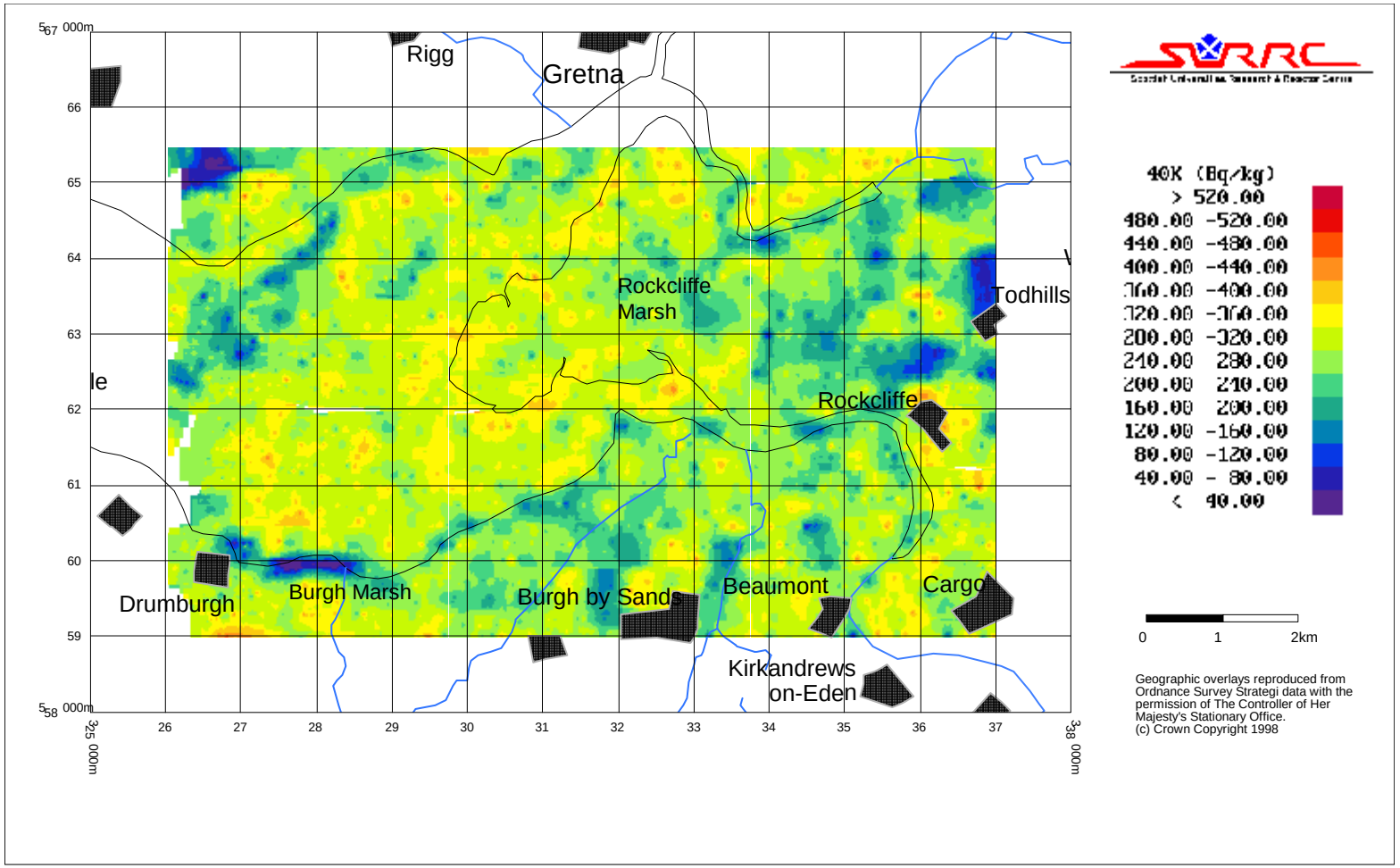

Figure 3.8: ^{40}K distribution for the Inner Solway (area A).

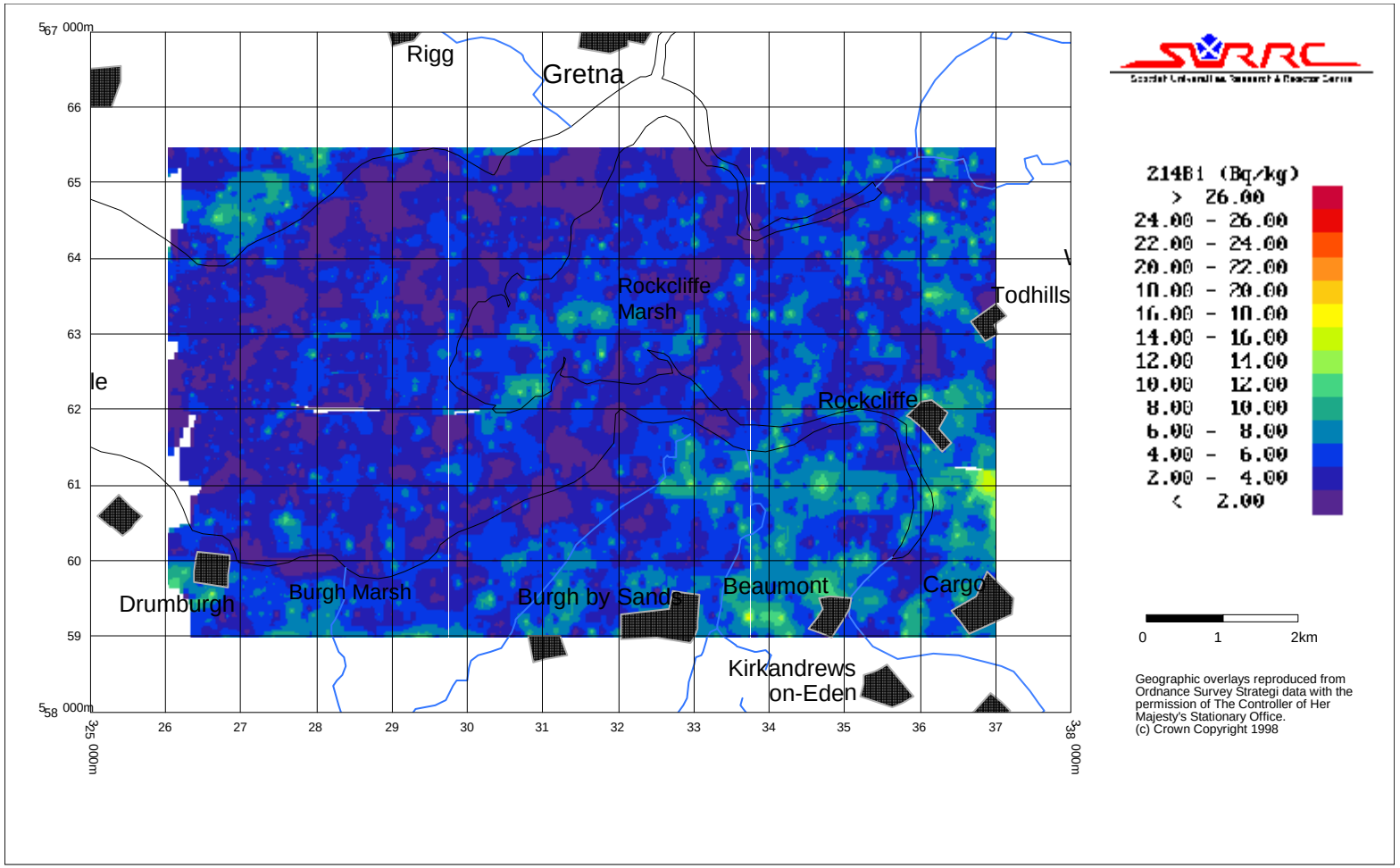

Figure 3.9: ^{214}Bi distribution for the Inner Solway (area A).

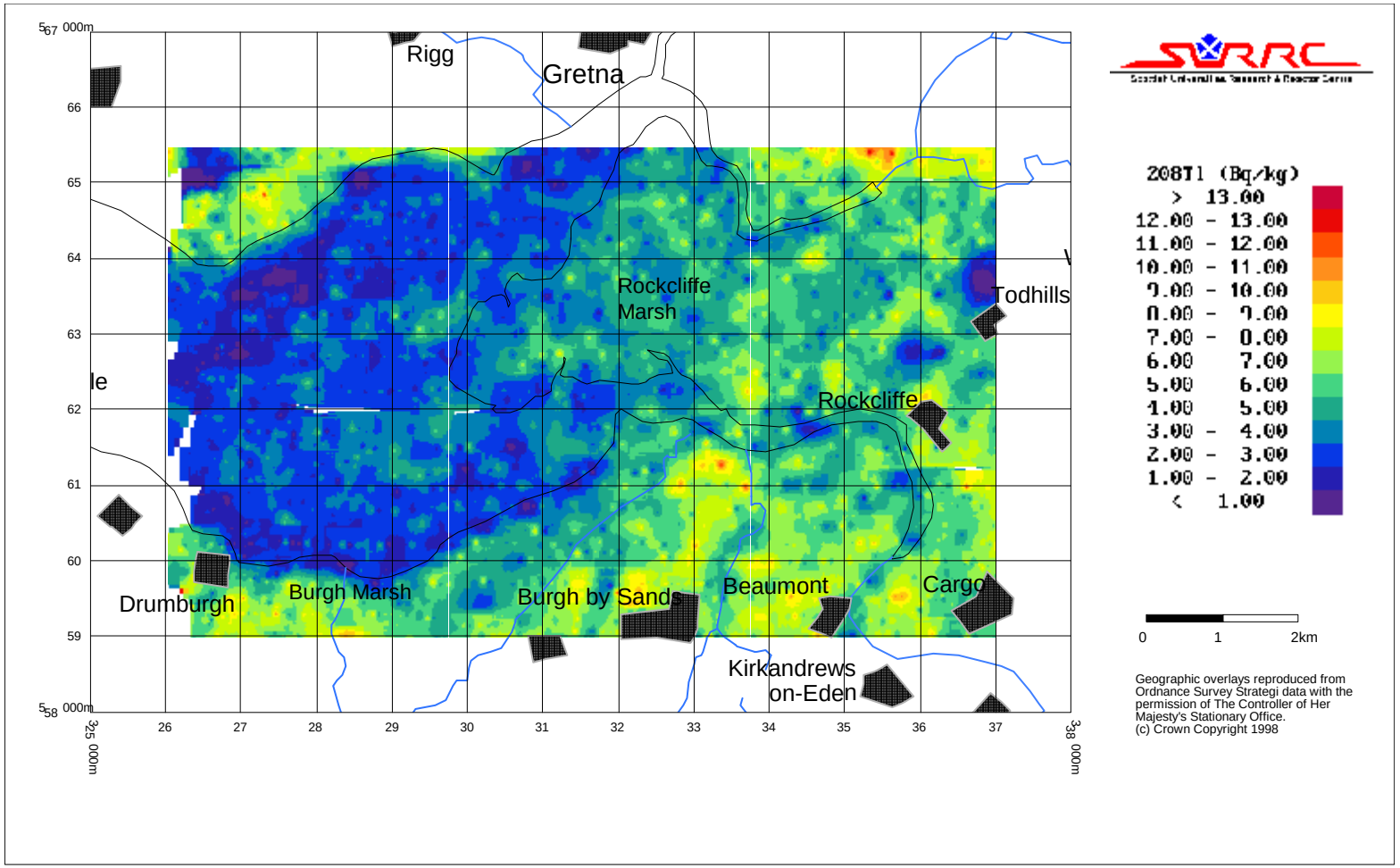

Figure 3.10: ^{208}Tl distribution for the Inner Solway (area A).

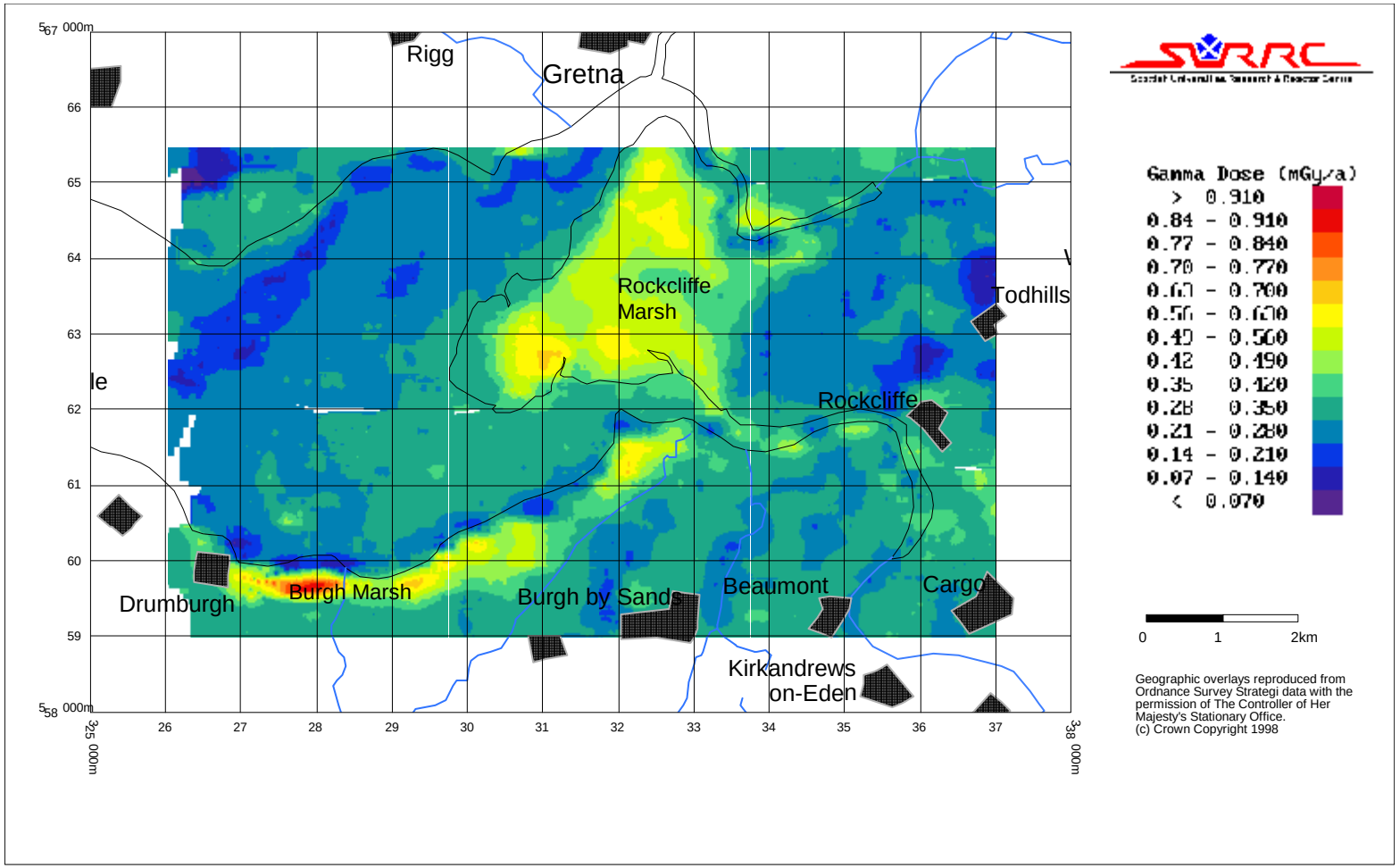

Figure 3.11: γ-ray dose rate for the Inner Solway (area A).

4. CONCLUSIONS

An Airborne Gamma Spectrometry (AGS) survey has been conducted of West Cumbria and part of the Inner Solway as part of an ongoing investigation into spatial and temporal aspects of AGS. A 40×40 km area of northwest Cumbria with a 10×30 km area to the south of this was surveyed at 500 m linespacing. A 50×50 km area of West Cumbria was surveyed at 2.5 km linespacing. The Inner Solway area, which had previously been surveyed in April 1999 at 50 m linespacing, was surveyed on this occasion with a 250 m linespacing. A total of some 70000 spectra were recorded from the NaI(Tl) detector and 35000 from the GMX detector, with 2 and 4 s integration times respectively.

The ^{137}Cs activity in these areas is derived from marine discharges from Sellafield accumulating on estuarine salt marshes and mud flats, with atmospherically deposited fallout from the Chernobyl and Windscale accidents on the upland areas inland. The ^{137}Cs activity distribution over the upland areas is very similar to the distribution determined from the 1988 MAFF survey. The ^{137}Cs distribution in the Inner Solway is also very similar to the survey in April 1999. An additional survey around the Sellafield site specifically to investigate signals observed in the March 2000 survey showed that a signal from an exposed section of pipeline has been removed from the radiometric results by work conducted to cover the pipeline since March.

There are low level ^{60}Co signals which have been observed on salt marshes around Ravenglass, corresponding to approximately 1-2 kBq m^{-2}, and some upland areas. These upland areas also have higher ^{40}K activities, so the ^{60}Co signals here are probably due to incomplete stripping of spectral interferences. There is very little ^{40}K activity on the saltmarshes, but long integration time spectra recorded from the Ge detector do not show any evidence of ^{60}Co activity.

The distribution of ^{40}K, ^{214}Bi and ^{208}Tl in these areas are due to variations in geology and soils, with high values on the exposed rocky high ground and lower levels on peaty ground.

In the coastal regions the γ-ray dose rate is dominated by the Sellafield derived ^{137}Cs activity. The higher dose rates inland corresponding to areas with higher natural signals, although the high ^{137}Cs activities in this area correspond to the higher ground which have higher natural activities making it harder to distinguish the contribution of natural and anthropogenic signals to the total γ-dose.

The data collected during this survey, along with the data from the previous two surveys in this project and data from earlier surveys, will be used to assess the effect of linespacing on AGS data and changes in the radiation environment over time.

5. REFERENCES

Allyson, J.D. (1994). PhD Thesis. Environmental γ-ray Spectrometry: Simulation of Absolute Calibration of *in-situ* and Airborne Spectrometers from Natural and Anthopogenic Sources. University of Glasgow.

Grasty, R.L., Kosanke, K.L., Foote, R.S. (1979). Fields of View of airborne gamma-ray detectors. Geophysics, 44(8).

Sanderson, D.C.W., East, B.W., Robertson, I., Scott, E.M. (1988). The use of Aerial Radiometrics in the search for a lost ^{137}Cs source, SURRC report.

Sanderson, D.C.W. & Scott, E.M. (1989a). An aerial radiometric survey in West Cumbria in 1988, MAFF Food Science Report N611.

Sanderson, D.C.W., East, B.W., Scott, E.M. (1989b). Aerial radiometric survey of parts of North Wales in July 1989, SURRC report 8901.

Sanderson, D.C.W., Scott, E.M., Baxter, M.S. (1990a). Use of Airborne Radiometric Measurements for Monitoring Environmental Radioactive Contamination, IAEA SM-306/138, 411-421, Vienna.

Sanderson, D.C.W, Scott, E.M., Baxter, M.S. (1990b). The use and potential of aerial radiometrics for monitoring environmental radioactivity, in "Nuclear Contamination of Water Resources", Institute of Civil Engineers, pages 99-106.

Sanderson, D.C.W., Allyson, J.D., Martin, E., Tyler, A.N., Scott, E.M. (1990c). An Aerial Gamma-ray Survey of Three Ayrshire Districts. Commissioned by the District Councils of Cunninghame, Kilmarnock and Loudoun, and Kyle and Carrick, SURRC 9001.

Sanderson, D.C.W., Allyson, J.D., Cairns, K.J., MacDonald, P.A. (1990d). A brief aerial survey in the vicinity of Sellafield in September 1990, SURRC report 9101.

Sanderson, D.C.W. and Allyson, J.D. (1991). An aerial gamma ray search for a missing ^{137}Cs source in the Niger Delta, SURRC report.

Sanderson, D.C.W., Allyson, J.D., Tyler, A.N. (1992). An aerial gamma ray survey of Chapelcross and its surroundings in February 1992, SURRC report 9201.

Sanderson D.C.W., Scott E.M., Baxter M.S., Martin E., Ni Riain S. (1993a). The use of aerial radiometrics for epidemiological studies of leukaemia, Scottish Universities Research & Reactor Centre, East Kilbride, 165p.

Sanderson, D.C.W., Allyson, J.D., Tyler, A.N. (1993b). An aerial gamma ray survey of Springfields and the Ribble Estuary in September 1992, SURRC report 9301.

Sanderson, D.C.W., Allyson, J.D., Tyler, A.N., Teasdale,I. (1993c). An airborne gamma ray survey of the Duddon Estuary in February 1993. SURRC, East Kilbride. 6pp.

Sanderson, D.C.W., Allyson, J.D., Tyler, A.N., Scott, E.M. (1994a). Environmental Applications of Airborne Gamma Spectrometry. IAEA Technical Committee Meeting on the Use of Uranium Exploration Data and Techniques in Environmental Studies, Vienna, Austria 9-12 Nov. 1993.

Sanderson, D.C.W., Allyson, J.D., Tyler, A.N. (1994b). Rapid Quantification of Radiometric Data for Anthropogenic and Technologically Enhanced Natural Nuclides. IAEA Technical Committee Meeting on the Use of Uranium Exploration Data and Techniques in Environmental Studies, Vienna, Austria 9-12 Nov. 1993.

Sanderson D.C.W., Allyson J.D., Tyler A.N., Ni Riain S., Murphy S. (1994c). An Airborne Gamma Ray Survey of parts of SW Scotland, Scottish Universities Research & Reactor Centre, East Kilbride, 118p.

Sanderson, D.C.W., Allyson, J.D., Riain, S. Ni, Gordon, G., Murphy, S., Fisk, S. (1994d). An Aerial Gamma Ray Survey of Torness Nuclear Power Station 27-30 March 1994. SURRC Report.

Sanderson, D.C.W., Allyson, J.D., Gordon, G., Murphy, S., Tyler, A.N., Fisk, S. (1994e). An Aerial Gamma Ray Survey of Hunterston Nuclear Power Station on 14-15th April and 4th May 1994. SURRC Report.

Sanderson, D.C.W., Allyson, J.D., Toivonen, H., Honkamaa, T. (1997a). Gamma Ray Spectrometry Results from Core Samples Collected for RÉSUMÉ 95, September 1995, Scottish Universities Research and Reactor Centre, East Kilbride, 51p.

Sanderson, D.C.W., Allyson, J.D., McConville, P., Murphy, S., Smith, J. (1997b). Airborne Measurements Conducted during an International Trial in Finland. In: RÉSUMÉ 95: ". Published by NKS-Secretariat, FRIT, Denmark. pp237-253.

Sanderson, D.C.W., Cresswell, A.J., McCleod, J., Murphy, S. (2000). Investigation of Spatial and Temporal Aspects of Airborne Gamma Spectrometry. Report on Phase I Survey Conducted April 1999. SURRC Report.

Tyler, A.N., Sanderson, D.C.W., Scott, E.M., Allyson, J.D. (1996a). Accounting for spatial variability and fields of view in environmental gamma-ray spectrometry. Journal of Environmental Radioactivity, 33 (3). pp213-235.

Tyler, A.N., Sanderson, D.C.W., Scott, E.M. (1996b). Estimating and accounting for ^{137}Cs source burial through *in-situ* gamma spectrometry in salt marsh environments. Journal of Environmental Radioactivity, 33 (3). pp195-212.

APPENDICES

Appendix A: Summary of Detector Calibration and Data Processing

1) Detector and Data Collection System

16 litre NaI(Tl) detector array (4 crystal pack):
Serial numbers: IA510, JA894, IV43, HR762
EHT: 1000V (nominal)

Single 50% efficiency Ge semiconductor (GMX) detector operated in parallel with scintillation detector:
Serial number: 32-TN30665A (EHT: -3000V)

Window	Radionuclide	Channel range
1	^{137}Cs (661 keV)	95-128
2	^{60}Co (1172 keV)	170-208
3	^{40}K (1461 keV)	220-270
4	^{214}Bi (1764 keV)	270-318
5	^{208}Tl (2615 keV)	390-480
6	Total > 450 keV	75-500

Table A.1: Spectral windows for NaI(Tl) detector

	^{137}Cs	^{60}Co	^{40}K	^{214}Bi	^{208}Tl
^{137}Cs	1	0.001	0	0	0
^{60}Co	0.411	1	0.241	0.04	0.02
^{40}K	0.594	0.483	1	0	0
^{214}Bi	0.644	0.606	0.615	1	0.033
^{208}Tl	2.681	0.644	0.706	0.438	1

Table A.2: Stripping ratios measured April 1999

Window	Radionuclide	Exponential Altitude Coefficient	Slope of Calibration Line	Calibration Intercept
1	^{137}Cs	0.0126	0.282	0.0
2	^{60}Co	0.01	1.0	0.0
3	^{40}K	0.0103	6.767	0.0
4	^{214}Bi	0.00837	3.164	0.0
5	^{208}Tl	0.0101	0.4715	0.0
6	γ-dose rate	0.0104	0.0007	0.0

Table A.3: Calibration Constants

Date	Resolution at 661 keV (%)	Gross ^{137}Cs count rate	Net ^{137}Cs count rate
15/3/2000	9.4	2417	1710
16/3/2000	9.3	2493	1775
17/3/2000	9.3	2476	1765
18/3/2000	9.6	2453	1755
19/3/2000	9.4	2462	1747
20/3/2000	9.3	2462	1739
21/3/2000	9.2	2429	1709
22/3/2000	9.5	2404	1687

Table A.4: 16 litre NaI(Tl) detector daily performance check

Date	Time	ch1	ch2	ch3	ch4	ch5	ch6
13/6/00	1935	39.7±4.4	16.1±1.9	15.6±3.3	8.1±2.5	6.8±2.1	158±8
14/6/00	0935	36.1±7.7	14.6±3.9	15.1±2.8	7.1±2.2	6.9±1.5	146±24
	1200	35.6±4.1	14.8±3.5	15.4±2.3	8.0±2.0	8.1±1.5	150±14
	1305	39.9±7.5	13.6±2.2	15.7±2.7	7.8±2.7	9.1±2.0	151±20
	1540	52.8±5.1	19.5±3.1	19.5±1.9	9.4±3.9	9.7±1.6	202±12
	1650	38.0±3.8	16.9±3.3	15.9±2.1	7.8±2.2	8.5±2.1	155±11
	1805	43.8±7.3	16.6±4.2	19.0±2.8	8.7±2.1	9.1±1.9	173±20
15/6/00	0940	33.2±4.9	14.2±2.8	13.9±3.1	8.4±2.1	8.1±1.7	133±11
	1215	32.5±4.7	11.9±2.3	14.3±2.8	7.8±1.9	7.2±1.8	131±9
	1400	30.7±5.1	12.4±2.8	14.1±2.9	6.7±1.5	7.4±1.8	128±14
	1645	33.4±3.0	13.1±2.1	15.4±2.3	7.0±2.3	7.8±2.8	140±10
	1730	29.5±4.2	12.8±2.9	14.2±2.8	6.1±1.8	7.0±1.8	124±9
	1925	32.5±3.6	12.6±1.2	13.7±3.7	7.4±1.8	7.1±2.1	134±12
16/6/00	1040	31.8±3.8	11.3±2.6	14.0±2.4	8.2±1.9	7.1±2.1	132±11
	1235	43.6±6.7	16.4±2.3	19.1±1.9	8.6±1.9	7.8±2.3	178±22
	1415	36.2±4.0	13.7±4.0	15.2±2.5	8.7±1.8	7.2±2.1	152±10
	1620	45.2±4.2	20.0±2.9	22.0±3.3	9.4±2.2	7.1±1.6	192±12
17/6/00	0850	32.9±3.8	11.9±1.6	13.6±3.6	8.0±2.8	8.0±2.2	132±8
	1100	37.8±4.0	14.6±2.7	16.6±3.0	8.7±1.3	7.0±1.6	148±10
	1225	32.3±3.3	12.5±2.8	17.2±3.5	7.7±3.0	7.2±1.0	137±7
	1425	48.0±4.2	19.9±4.6	21.2±4.4	9.8±2.1	7.1±1.8	191±12
	1606	44.3±4.8	19.8±2.6	18.7±2.3	11.1±1.9	8.1±2.1	184±14
18/6/00	0855	40.6±3.7	16.3±3.4	17.4±2.5	9.8±2.0	8.5±2.2	158±8
	1055	38.0±4.4	14.9±2.8	16.3±2.3	9.1±2.1	8.5±1.2	154±9
	1200	32.5±5.5	14.3±2.7	14.4±1.6	8.8±2.4	6.6±1.7	137±10
	1405	45.0±6.6	19.1±4.1	18.7±3.7	11.1±2.6	8.1±2.3	179±19

Date	Time	ch1	ch2	ch3	ch4	ch5	ch6
21/6/00	1535	27.8±3.5	11.8±3.4	14.2±1.8	7.1±1.8	7.3±1.4	120±7
	1755	30.5±2.1	13.4±2.6	14.3±2.1	7.8±1.9	6.4±2.4	127±6
22/6/00	1115	34.8±4.0	14.3±3.2	15.8±4.1	7.5±1.3	6.7±1.6	157±12
	1545	33.7±3.9	14.8±3.6	15.4±3.7	8.5±2.3	7.4±1.7	166±14
	1620	31.2±4.8	12.6±2.6	13.8±2.4	7.3±1.9	7.4±1.4	155±9
	1905	37.0±6.0	14.9±1.0	15.1±2.7	7.1±1.5	7.5±2.1	178±12
23/6/00	0915	30.4±7.1	14.1±2.5	16.0±3.4	6.8±1.7	6.7±2.2	150±22
	1145	35.0±7.2	13.3±2.6	18.9±1.0	8.1±2.0	7.8±1.5	146±15
	1250	30.6±3.0	12.1±2.5	15.8±3.2	7.1±2.4	6.5±1.5	148±9
	1455	31.8±7.0	15.7±3.3	16.6±2.7	7.2±1.2	7.2±2.0	171±15
24/6/00	0915	31.5±6.6	13.9±2.3	15.8±3.1	6.9±1.9	6.7±2.0	150±20
	1145	32.8±4.3	13.0±2.3	18.9±1.0	8.0±2.0	7.6±1.3	169±8
	1250	31.0±3.1	12.3±2.4	15.8±2.1	7.4±2.3	6.7±1.6	150±9
	1455	32.5±6.9	15.7±3.1	16.4±2.6	7.1±1.2	7.2±1.9	172±15
	1600	27.5±5.0	12.4±2.0	13.3±3.2	6.0±0.8	6.2±2.4	138±16
	1745	34.3±2.9	13.1±3.2	16.7±2.9	7.3±2.1	6.7±2.2	166±8
25/6/00	1025	28.8±4.0	13.9±2.6	16.1±3.0	7.8±2.1	7.6±1.4	151±12
	1220	34.0±3.7	13.8±2.5	16.8±3.3	9.3±2.0	8.1±1.8	167±15
26/6/00	1330	30.0±4.6	11.2±2.8	13.8±1.9	7.1±1.6	6.9±1.8	142±13
	1515	28.8±5.0	12.2±1.9	15.1±2.8	7.5±1.8	7.4±2.3	151±14
Means							
all values		34.5±7.0	14.2±3.6	15.9±3.5	7.9±2.2	7.4±1.9	151±22
low		31.6±4.9	13.1±2.8	15.1±3.1	7.5±2.0	7.2±1.9	144±18
high		41.2±6.5	16.7±3.9	17.7±3.6	8.9±2.3	7.8±2.0	167±22

Table A.5: Background readings recorded over Ennerdale Water

Date	Root file name	Number of files	Comments
13/6/00	CAL05	147	Flight from Cumbernauld, calibration manoeuvre at Caerlaverock
	CAL06	64	Background readings
	DETC1	716	Background readings, waypoints C041-C046
14/6/00	DETC2	907	Background readings, waypoints C047-C056
	DETC3	638	Waypoints C057-C062, background readings
	DETC4	848	Background readings, waypoints C063-C064, C021-C032
	DETC5	360	Waypoints C065-C070, background readings
	DETC6	628	Background readings, waypoints C071-C078
15/6/00	DETC7	993	Background readings, waypoints C079-C086
	DETC8	981	Waypoints C087-C094, background readings
	DETC9	905	Background readings, waypoints C095-C102
	DEC10	962	Waypoints C103-C112
	DEC11	323	Waypoints C113-C114, background readings
	DEC12	694	Background readings, waypoints C115-C116, C033-C036
	DEC13	860	Waypoints C035-C040, C117-C118, background readings
16/6/00	DEC14	946	Background readings, waypoints C119-C126
	DEC15	571	Waypoints C127-C130, background readings
	DEC16	999	Background readings, waypoints C131-138
	DEC17	649	Waypoints C139-C142, background readings
17/6/00	DEC18	898	Background readings, waypoints C143-C146, C001-C002
	DEC19	840	Waypoints C003-C014, background readings
	DEC20	791	Background readings, waypoints C015-C020, J001-J002
	DEC21	997	Background readings, waypoints C163-C175
	DEC22	327	Waypoints C175-178, background readings
18/6/00	DEC23	878	Background readings, waypoints J003-J020
	DEC24	793	Waypoints J021-J042, background readings
	DEC25	819	Background readings, waypoints C179-C196
	DEC26	527	Tie lines, calibration manouevre at Caerlaverock, background

21/6/00	DETD1	941	Background readings, waypoints D001-D002, D009-D016
	DETD2	948	Waypoints D017-D024, D003-D004, background readings
22/6/00	DEA01	440	Background readings, tie line
	DEA02	881	Waypoints A001-A022
	DEA03	842	Waypoints A023-A050
	DEA04	106	Background readings
	DEA05	530	Background readings, waypoints D005-D-006
	DETD3	899	Waypoints D025-D040
	DETD4	116	Waypoints D041-D042
	DEA06	377	Waypoints D007-D008, background readings
23/6/00	DETD5	911	Background readings, waypoints D043-D052
	DETD6	936	Waypoints D053-D064
	DETD7	37	Background readings
	DETD8	861	Background readings, waypoints D065-D074
	DETG9	119	Waypoints D075-D076
	DED10	559	Waypoints M001-M008, background readings
24/6/00	DED11	847	Background readings, waypoints M009-M020
	DED12	539	Waypoints M021-M024, background readings
25/6/00	DED13	973	Background readings, waypoints K001-K032
	DED15	613	Waypoints K033-K050, background readings
25/6/00	DED16	989	Background readings, waypoints L001-L052
	DED17	469	Background readings
	DED18	922	Background readings, waypoints A101-A112, K102-K112
	DED19	169	Background readings, calibration manoeuvre at Croasdale

Table A.6: Summary of data files

Filename	Number of records	Formed from files
DETRC01	1340	DETC1030-357,359-700
DETRC02	1678	DETC2030-380,420-907
DETRC03	1192	DETC3001-520,535-610
DETRC04	2358	DETC4020-848, DETC5001-350
DETRC05	1182	DETC6020-610
DETRC06	1910	DETC7040-993
DETRC07	1880	DETC8001-940
DETRC08	1692	DETC9060-905
DETRC09	2424	DEC10001-962, DEC11001-250
DETRC10	2700	DEC12105-694, DEC13001-760
DETRC11	1796	DEC14040-130,140-946
DETRC12	1080	DEC15001-540
DETRC13	1940	DEC16030-999
DETRC14	1060	DEC17001-530
DETRC15	2720	DEC18160-560,750-898, DEC19001-790
DETRC16	1022	DEC20040-530
DETRC17	2026	DEC21155-997, DEC22001-170
DETRC18	1400	DEC25120-819
DETRJ01	202	DEC20630-730
DETRJ02	2618	DEC23310-878, DEC24001-740
DETRD01	1724	DETD1080-941
DETRD02	1800	DETD2001-900
DETRD03	2300	DEA05280-530, DETD3001-899
DETRD04	594	DETD4001-116, DEA06130-310
DETRD05	1764	DETD5030-911
DETRD06	1860	DETD6001-930
DETRD07	1622	DETD8170-861, DETG9001-119

Filename	Number of records	Formed from files
DETRA01	2634	DEA02140-285,380-485,535-851, DEA03001-635,690-750,790-842
DETRA02	622	DED18200-510
DETRM01	1002	DED10010-510
DETRM02	2066	DED11050-847, DED12140-264,271-380
DETRK01	2588	DED13160-973, DED15001-480
DETRL01	2580	DED16090-989, DED17001-390

Table A.7: Compiled summary files