Scottish Universities Research & Reactor Centre

Investigation of Spatial and Temporal Aspects of Airborne Gamma Spectrometry

Preliminary Report on Phase II Survey of the Sellafield Vicinity, the Former RAF Carlisle site, the Albright & Wilson Plant, Workington Harbour and the Cumbrian Coastline Conducted March 2000

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

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

SUMMARY

An Airborne Gamma Spectrometry (AGS) survey of parts of West Cumbria and North West England has been conducted as part of a project investigating spatial and temporal aspects of AGS. The preliminary 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.

The survey conducted between the 14th and 22nd March 2000 covered a 25×5km region around Sellafield, the Cumbrian coastline, the former RAF Carlisle site, the Albright & Wilson plant near Whitehaven and Workington Harbour. In total some 47000 spectra were recorded from the NaI(Tl) spectrometer with a 2s integration time, and 23500 spectra from a 50% efficiency Ge semiconductor (GMX) spectrometer with a 4s integration time, with a total flight time of 38 hours. The data recorded have been used to map the distribution of ^{137}Cs, ^{60}Co, ^{40}K, ^{214}Bi, ^{208}Tl and the γ-ray dose rate within the survey areas.

The ^{137}Cs activity has been calibrated to the activity and mass depth distribution on the Caerlaverock Merse measured from cores collected in April 1999 for the first phase of survey. Working maps calibrated in this manner are comparable with the 1999 survey data. It is recognised that the calibration is sensitive to variations in source mass depth in other locations.

The survey of the Sellafield area has shown signals in the immediate vicinity of the Sellafield complex associated with direct shine from plant and stored materials on site along with atmospheric discharges of ^{16}N and ^{41}Ar from the Calder Hall reactors. There are also signals from material stored in the ISO compound at the Drigg site, as well as from containers of low level waste material on railway sidings to the south east of the storage area.

The estuarine salt marshes of the rivers Irt, Mite and Esk are contaminated by ^{137}Cs and low levels of ^{60}Co, there is evidence of activity along the Esk above the intertidal limit possibly as a result of deposition of marine sediments following recent floods. There is also ^{137}Cs contamination of the beach by Sellafield, and shingle and rock surfaces to the north towards St. Bees. There is ^{137}Cs contamination on upland areas near Sellafield especially Muncaster Fell where the activity is apparently concentrated on the flanks rather than the top of the fell due to the deposition of atmospheric discharges from Sellafield, including the Windscale fire, with a contribution from the Chernobyl accident. The upland areas of Irton Pike and Muncaster Fell show ^{60}Co contamination, although these areas also have elevated ^{40}K levels and the apparent ^{60}Co distribution may reflect interferences from ^{40}K. Further work, including analysis of the GMX spectra, will be needed to confirm these upland signals. Most of these features had been observed previously, but are defined more clearly here due to the greater spatial resolution.

The coastline survey has shown ^{137}Cs contamination in estuarine salt marshes further from the site; in the Duddon Estuary, around Moricambe Bay and along the southern side of the Solway Firth. The salt marshes in the Duddon Estuary are also slightly contaminated by ^{60}Co.

A survey of the former RAF Carlisle site has shown no evidence of residual radium contamination above the limit of detection of this technique. There is, however, an anomalous

^{214}Bi signal associated with the railway line, which it is assumed results from the use of industrial waste material in the construction of the line.

Anomalies in the uranium series ^{214}Bi activity distribution were also observed associated with non-nuclear sites. These sites include the Albright and Wilson plant near Whitehaven, and the steel works just south of Workington. In addition, some further sites were identified during the course of the survey associated with industrial slag material:

- Two features were observed near Millom, one associated with industrial wastes in a disused quarry to the south of the town (SD177792) and the other with a larger area of industrial wastes to the east of the town (SD183805).
- Another similar area of industrial wastes was identified near the pier at Askam in Furness (SD807773), on part of which a housing estate has recently been built.
- A few features were observed near Cleator Moor and Frizington, the latter was found to be due to a small dump.

Some further investigation into the nature of these sites, and any potential environmental or radiological impact, may be advisable.

The data sets generated in this survey provide an abundant resource to define the radiological contexts of these survey areas. Further analysis of the data will take place at later stages of the project.

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1. INTRODUCTION

This report documents the results of an airborne gamma ray survey conducted by the Scottish Universities Research and Reactor Centre between 14 and 22 March 2000 covering a 25×5 km area around the Sellafield site, the coastline from Duddon to Gretna and high spatial resolution surveys of the former RAF Carlisle site, the Albright and Wilson plant at Whitehaven and Workington Harbour. The survey was carried out as the second phase 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 50m to 2.5km 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 250m linespacing) were surveyed in April 1999, the preliminary results presented elsewhere (Sanderson *et al* 2000). This report presents initial results from areas E to I surveyed in March 2000. Areas C and D, along with area A (at 250 m linespacing) will be surveyed during a third phase of field work in the summer of 2000. Following the completion of survey work and preliminary analysis of the data collected in the summer 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	10×6	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 of 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 March, and tested on the 14th 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 table 2.1. 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 two separate occasions at Caerlaverock and once at Croasdale, consisted of measurements conducted while hovering at a series of altitudes above a calibration pattern. The pattern at Caerlaverock consists of concentric hexagons at 8, 32, 128 and 256m from the central point. Cores were collected from this site in February 1992 and April 1999. The calibration pattern at the field near Croasdale Farm consisted of two hexagons at 8 and 16m, soil cores were collected from the field for later analysis in the laboratory.

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 major survey task was a survey of the vicinity of the Sellafield site, comprising a 25×5 km box parallel to the coast between St. Bees Head and Eskmeals, to be flown at 100 m linespacing with particular interest to be taken of pigeon roost sites in the local woodlands; this was designated area G. The other survey tasks were: a coastline survey consisting of flight lines approximately 100 m apart covering the land, beach and sea between Duddon Sands and Gretna (area E); and 50 m linespacing surveys of the former RAF Carlisle site (area F), Workington Harbour (area H) and the Albright and Wilson plant at Whitehaven (area I). 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 direction 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 table 2.2, 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 some 47000 NaI spectra were recorded with 2 s integration times, and 23500 GMX spectra with 4 s integration times. The survey of the Sellafield vicinity (area G) took approximately 19h, with 10h for the coastline (area E), 4.5h for RAF Carlisle (area F), 2.5h for the Albright and Wilson plant and Workington Harbour (areas H and I). Including the transfer of the aircraft from Cumbernauld, a total survey time of approximately 38 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 100m (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 table 2.3. 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.

Date	File	ch1	ch2	ch3	ch4	ch5	ch6
14/3/00	DETG3	39.0±4.8	14.7±2.7	16.3±3.3	7.0±1.8	7.0±2.1	150±11
15/3/00	DETG4	36.6±5.9	15.1±2.5	16.0±2.4	6.8±2.0	7.8±1.9	146±14
	DETG6	38.8±5.4	15.2±3.0	17.4±3.6	7.6±1.6	7.6±2.2	157±16
16/3/00	DEG10	33.3±4.8	14.2±2.3	16.1±2.3	6.1±2.1	6.8±2.2	138±13
	DEG13	38.4±5.4	14.5±2.0	16.0±2.5	7.5±1.5	6.8±1.7	148±8
	DET21	41.9±5.8	19.7±3.8	16.5±2.8	10.7±2.3	7.6±1.8	175±19
17/3/00	DEG23	39.1±5.0	16.4±2.6	16.7±2.7	7.7±2.1	7.8±1.7	155±112
	DETE1	42.5±5.6	16.5±3.2	17.8±3.6	8.0±1.5	7.5±3.3	164±20
18/3/00	DETE3	41.4±4.7	17.1±2.5	17.0±2.6	8.8±2.1	7.5±1.2	163±10
	DETE5	41.6±3.5	16.7±1.8	16.8±2.6	7.9±2.7	7.5±2.3	160±8
20/3/00	DETI1	41.7±3.8	16.6±2.8	19.0±2.7	7.9±1.6	8.2±3.0	165±13
	DETI2	36.8±4.3	15.3±1.8	17.4±2.4	6.4±1.0	6.9±1.9	152±7
	DEG24	41.9±5.1	16.1±2.1	19.9±5.2	7.1±2.2	6.9±1.5	165±12
21/3/00	DETE7	41.7±3.8	16.0±2.5	19.3±4.3	7.4±1.4	7.0±1.5	168±11
22/3/00	DETE8	38.9±1.1	13.3±1.0	18.0±4.5	5.5±1.5	7.4±0.5	155±5
mean (exc. DET21)		39.0±5.4	15.5±2.6	17.0±3.2	7.3±1.9	7.3±2.0	154±15

Table 2.1: Background readings recorded over Ennerdale Water

Date	Root file name	Number of files	Comments
14/3/00	DETX1	480	Flight from Cumbernauld, calibration manoeuvre at Caerlaverock
	DETG1	718	Northern section, waypoints SN001-024
	DETG2	976	Northern section, waypoints SN025-056
	DETG3	285	Northern section, waypoints SN057-064. Background readings
15/3/00	DETG4	736	Background readings. Northern section, waypoints SN061-082
	DETG5	940	Southern section, waypoints SS001-004, 021-040. Drigg
	DETG6	509	Background readings. Northern section, waypoints SN081-094
	DETG7	208	Northern section, waypoints SN095-100
	DETG8	181	Southern section, waypoints SS041-046
	DETG9	627	Southern section, waypoints SS047-068
16/3/00	DEG10	439	Southern section, waypoints SS069-084
	DEG11	325	Southern section, waypoints SS085-094
	DEG12	652	Southern section, waypoints SS095-100 Central section, waypoints SC021-036
	DEG13	300	Central section, waypoints SC037-044
	DEG14	131	Central section, waypoints SC045-050
	DEG16	23	Central section, waypoints SC051-052
	DEG17	370	Central section, waypoints SC053-080, 001-004
	DEG18	262	Central section, waypoints SC005-014
	DEG19	150	Central section, waypoints SC015-020
	DET21	994	Central section, waypoints SC081-100 + freeflight Southern section, waypoints SS001-016 High ^{214}Bi (radon)
	DEG22	278	Southern section, waypoints SS017-020 + freeflight High ^{214}Bi (radon)

17/3/00	DEG23	803	Background readings. Central section, waypoints SC101-140 Free flight Sellafield perimeter
	DETE1	931	Background readings. Coastline St. Bees-Duddon (single line). Duddon Sands
	DETE2	634	Coastline Duddon-St. Bees (3 lines)
18/3/00	DETE3	988	Background readings. Coastline St. Bees-Duddon (single line) ^{214}Bi anomalies at Askam and Millom
	DETE4	999	Central section, waypoints SC081-106 Southern section, waypoints SS001-020. Free flight over beach
	DETE5	846	Background readings. Coastline St. Bees-Maryport (5 lines)
	DETE6	496	Coastline Maryport-Silloth (5 lines)
20/3/00	DETI1	464	Background readings. Albright & Wilson plant
	DETH1	708	Workington Harbour
	DETI2	202	Cleator Moor ^{214}Bi anomaly
	DEG24	500	Free flight; woodlands
	DEG25	926	Free flight; woodlands, Irton Park & Muncaster Fell
21/3/00	DETE7	699	Background readings. Coastline Silloth-(4 lines) River Eden-E edge Burgh Marsh (5 lines)
	DETF1	688	Carlisle, waypoints CR121-162
	DETF2	985	Carlisle, waypoints CR001-058
	DETF3	596	Carlisle, waypoints CR059-100
	DETF4	493	Carlisle, waypoints CR101-120
22/3/00	DETE8	999	Background readings. Coastline Silloth-W edge Burgh Marsh
	DETE9	999	Fill-in flying over merses. Caerlaverock calibration manoeuvre. Tie lines
	DEE10	60	Calibration manoeuvre at Croasdale

Table 2.2: Summary of survey data files

Filename	Number of records	Formed from files
DETRG01	1436	DETG1001-718
DETRG02	2480	DETG2001-976, DETG3001-264
DETRG03	1334	DETG4070-736
DETRG04	1854	DETG5001-927
DETRG05	2610	DETG6090-509, DETG7001-184, DETG8030-180, DETG9001-550
DETRG06	2248	DEG10090-466, DEG11001-165, DEG11250-325, DEG12003-165, DEG12210-652
DETRG07	2304	DEG13085-300, DEG14001-131, DEG16001-023, DEG17001-370, DEG18001-262, DEG19001-150
DETRG08	2406	DET21070-994, DEG22001-278
DETRG09	1564	DEG23022-803
DETRG10	1680	DETE4001-840
DETRG11	962	DEG24020-500
DETRG12	1852	DEG25001-926
DETRE01	1744	DETE1060-931
DETRE02	1268	DETE2001-634
DETRE03	1886	DETE3205-988, DETE4840-999
DETRE04	2566	DETE5060-846, DETE6001-496
DETRE05	1130	DETE7100-130, DETE7145-170, DETE7176-199, DETE7205-225, DETE7231-248, DETE7255-699
DETRE06	2580	DETE8010-999, DETE9001-300
DETRHI	2646	DETI1020-436, DETHI001-708, DETI2001-170
DETRF01	1376	DETF1001-688
DETRF02	1970	DETF2001-985
DETRF03	1192	DETF3001-596
DETRF04	986	DETF4001-493

Table 2.3: Compiled summary files

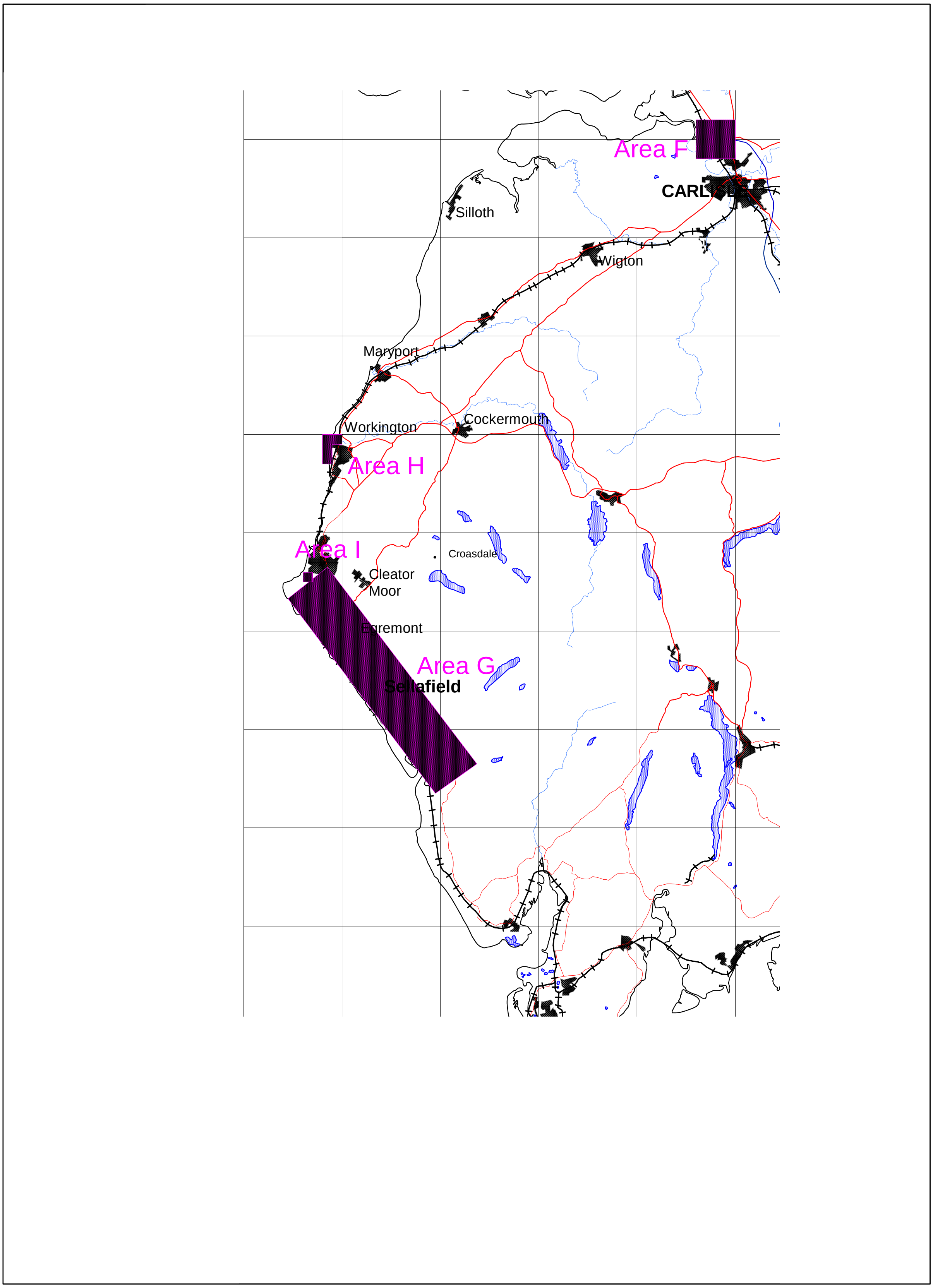

Figure 2.1: The areas surveyed in the current work

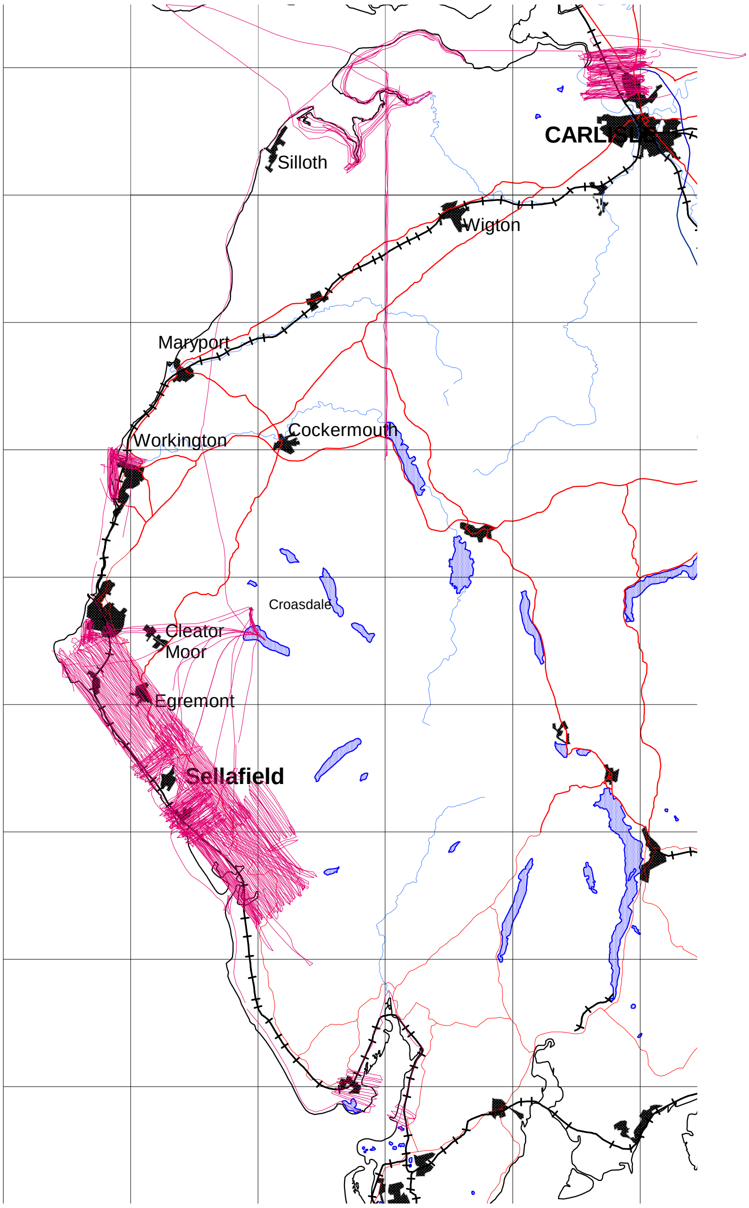

Figure 2.2: Flight lines recorded by the GPS systems

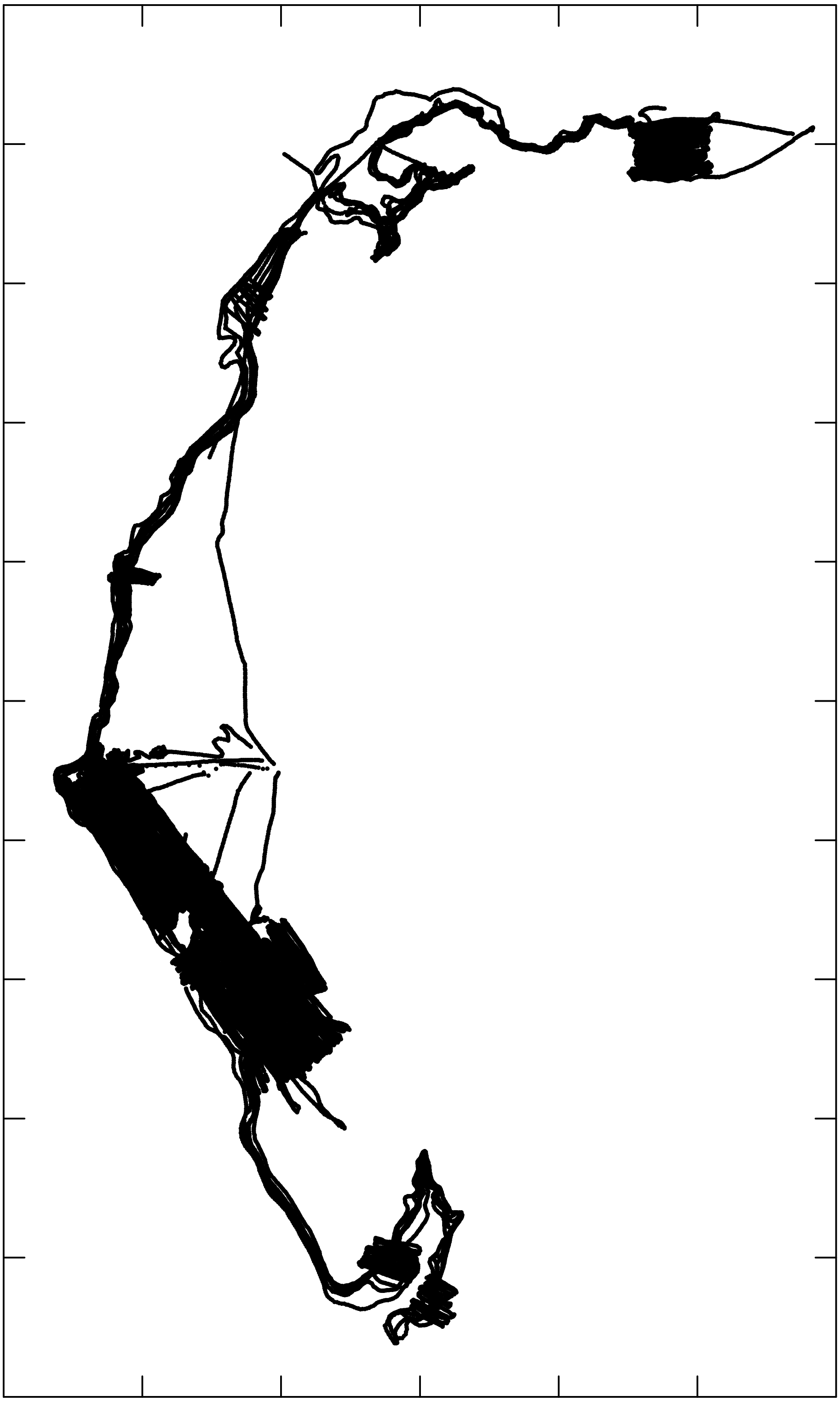

Figure 2.3: Locations of final summary data

3. RESULTS AND DISCUSSION

3.1 Sellafield Survey (Area G)

Much of the Sellafield area had been surveyed in 1990 (Sanderson *et al* 1990d) at 1 km line spacing with some additional survey flights of estuarine areas. The data presented here were recorded with much greater spatial resolution than the earlier data set.

3.1.1 ^{137}Cs Distribution

Figure 3.1 shows the ^{137}Cs distribution in the Sellafield area, which is plotted on a logarithmic scale for comparability with earlier reports, although fine details would be accentuated by the use of a linear scale.

There is a strong signal along the coast near the site, that was also present in the 1990 data. This feature appears to be centred on the area of the discharge pipeline, and may be due to contamination of the foreshore, direct shine from the site, possible exposure of part of the pipe line at low tide, or a combination of these effects. There is also activity on shingle and rock surfaces along the shoreline between Sellafield and St. Bees.

The dominant features near the site to the west, northwest and east are most probably associated with direct radiation projected off-site from facilities and materials stored on site. To the east of the site there are also strong signals due to ^{16}N and ^{41}Ar from the Calder Hall reactors.

There are very high levels of ^{137}Cs at the Drigg site, which clearly register the ISO storage compound within the site which also shows signals due to ^{60}Co, ^{214}Bi (uranium series) and ^{208}Tl (thorium series) and also containers of low-level waste material on railway sidings to the south east of the main storage area.

The activity observed on the salt marshes along the rivers Irt, Mite and Esk near Ravenglass are similar to the 1990 data. Quantitative comparisons of the activity will be made in the next stage of the project, although initial impressions are that the levels are similar after accounting for radioactive decay. Activity levels on the intertidal sediments appear to be slightly lower, possibly as a result of sediment mixing. There also appears to be enhanced activity above the normal intertidal limit of the Esk, possibly as a result of the transfer of marine sediments during recent flooding.

There are slightly elevated levels of ^{137}Cs near the Sellafield site and on uplands further from the site towards the north and east. This was also observed in the 1990 data, and attributed to aerial discharges from Sellafield, including the 1957 Windscale fire, with a contribution from deposition following the 1986 Chernobyl accident. There are also elevated levels of activity on the flanks of Muncaster Fell to the south east of Sellafield, with apparently less activity on the top of the fell.

A survey flight at lower speed and altitude conducted over woodland areas close to the Sellafield complex showed no evidence of contamination attributable to pigeon roosts, within the limits of detection of this technique.

3.1.2 ^{60}Co Distribution

Figure 3.2 shows the ^{60}Co activity distribution in the Sellafield area. The activity is given in count rates, altitude corrected to 100m ground clearance.

The strong signals near the Sellafield site are probably due to uncorrected interferences from ^{41}Ar (1295 keV) and direct shine, the data from the GMX detector should be able to identify any nuclide specific signals from this area.

There is a strong ^{60}Co signal from the Drigg ISO store, but there is no corresponding signal from the containers in the railway sidings.

The presence of ^{60}Co along the rivers Irt, Mite and Esk, with approximately 1-3 kBq m^{-2} surface equivalent activity, is probably the result of relatively recent discharges from Sellafield, since earlier releases would have decayed due to the fairly short half life of ^{60}Co (5.27 years).

There is also evidence of ^{60}Co contamination on Irton Pike and Muncaster Fell, at 1-2 kBq m^{-2} surface equivalent activity. However this correlates with enhanced ^{40}K signals and may be the result of poor stripping of interferences from ^{40}K. The data from the GMX detectors should confirm whether or not these ^{60}Co signals are due to genuine contamination. If ^{60}Co is indeed present in these localities, it would suggest that the associated ^{137}Cs is to a degree the result of recent airborne discharges from the Sellafield complex.

3.1.3 ^{40}K Distribution

Figure 3.3 shows the distribution of ^{40}K in the Sellafield area.

The signals near Sellafield are probably associated with direct radiation projected off site and, especially to the south east of the site, interferences from ^{41}Ar released from the Calder Hall reactors.

There is also a signal associated with the Drigg site.

The remaining enhanced ^{40}K levels appear to be associated with geological features (eg the uplands north of Gosforth and Muncaster Fell).

3.1.4 ^{214}Bi Distribution

Figure 3.4 shows the distribution of ^{214}Bi, a decay product in the uranium series, in the Sellafield area.

The feature to the east of the Sellafield site is probably associated with direct radiation from the site and interference from ^{16}N released from the Calder Hall reactors.

There is a feature at Drigg, probably associated with materials stored in the ISO compound.

There are a number of signals associated with non-nuclear sites, including the Albright and Wilson site at Whitehaven (described in section 3.4) and two sites at Cleator Moor and Frizington noted during transit flights into and out of the survey area (described in section 3.6) with enhanced ^{214}Bi levels but no enhancement in ^{208}Tl. A further feature near Eskmeals shows enhanced levels of both ^{214}Bi and ^{208}Tl.

Other enhanced levels of ^{214}Bi, the upland areas north and east of Gosforth and the area around Egremont, are most likely due to geological features.

3.1.5 ^{208}Tl Distribution

Figure 3.5 shows the distribution of ^{208}Tl, a decay product in the thorium series, in the Sellafield area.

The strong signal to the east and south east of Sellafield is probably associated with direct radiation from the site and interference from ^{16}N released from the Calder Hall reactors.

There is a highly localised signal in the ISO storage compound at Drigg.

The strong signal near Eskmeals is spatially correlated to a signal in the ^{214}Bi channel, indicting the presence of material of natural origin but with larger activity than the local geology. The exact nature of the material giving rise to this signal has yet to be established.

3.1.6 γ-ray Dose Rate

Figure 3.6 shows the γ-ray dose rate in the Sellafield area.

The enhanced dose rate on the coastal side of the site near the discharge pipeline corresponds to enhanced ^{137}Cs activity levels, and to a lesser extent enhanced ^{214}Bi and ^{208}Tl activity. This has been attributed to either direct radiation from the site, contamination of the foreshore or possible exposure of part of the pipeline at low tide. Further along the coast towards St. Bees there is a slightly elevated dose rate corresponding to ^{137}Cs activity observed on shingle and rock surfaces on the foreshore.

The elevated dose rate to the south east of Sellafield corresponds to signals in all the nuclide specific channels, and is probably associated with direct radiation from the site and ^{16}N and ^{41}Ar releases from the Calder Hall reactors.

There is also a high dose rate at Drigg, associated with high activity in all the nuclide specific channels at the ISO storage compound with more widespread signals due to ^{137}Cs and ^{60}Co. A more localised feature to the south east of the main compound corresponds to enhanced ^{137}Cs activity associated with containers in railway sidings. These signals are due to contained radioactivity within the Drigg site, or the contained packages being delivered to it. They do not, therefore, represent environmental contamination.

High dose rates are also observed along the saltmarshes of the rivers Irt, Mite and Esk corresponding to the high ^{137}Cs, and to a lesser extent ^{60}Co, contamination in these estuarine environments.

Enhanced dose rates are also observed on the upland areas with ^{137}Cs deposition (eg Muncaster Fell and the uplands north east of Gosforth).

The feature near Eskmeals with enhanced ^{214}Bi and ^{208}Tl is associated with an enhanced dose rate, although the other sites with anomalous ^{214}Bi signals do not dominate the overall γ-dose rates of their environments.

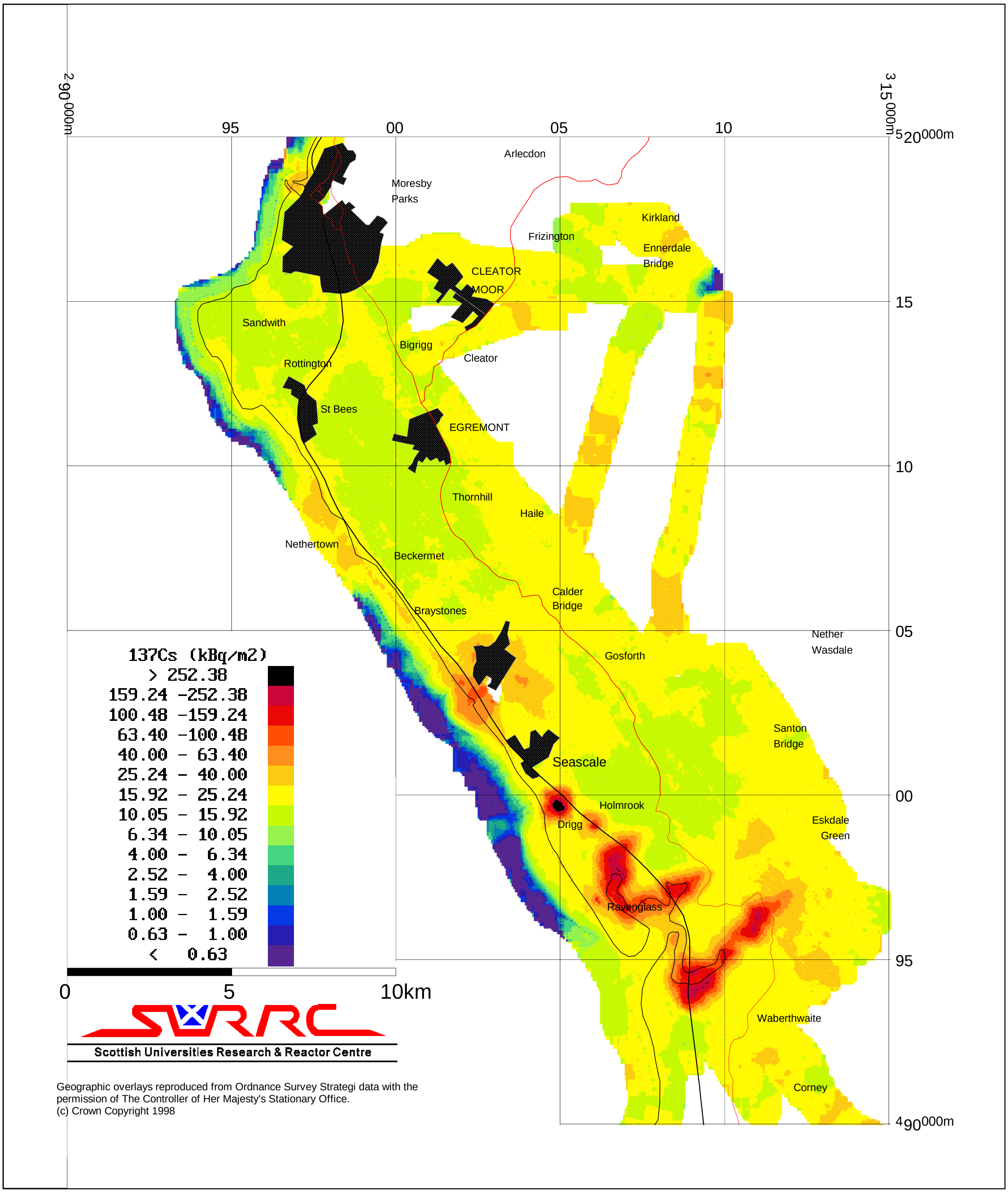

Figure 3.1: ^{137}Cs distribution in the Sellafield area

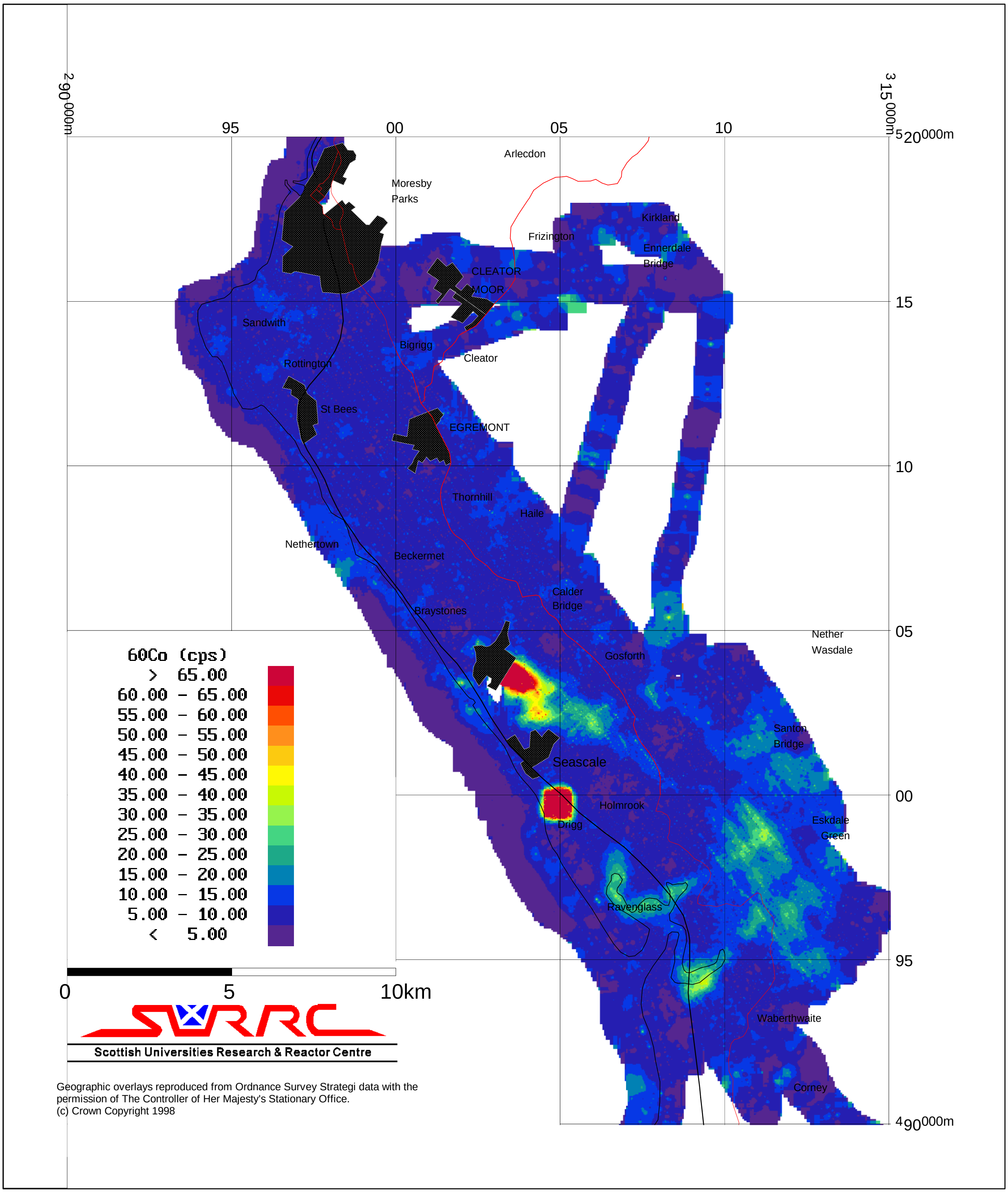

Figure 3.2: ^{60}Co distribution in the Sellafield area

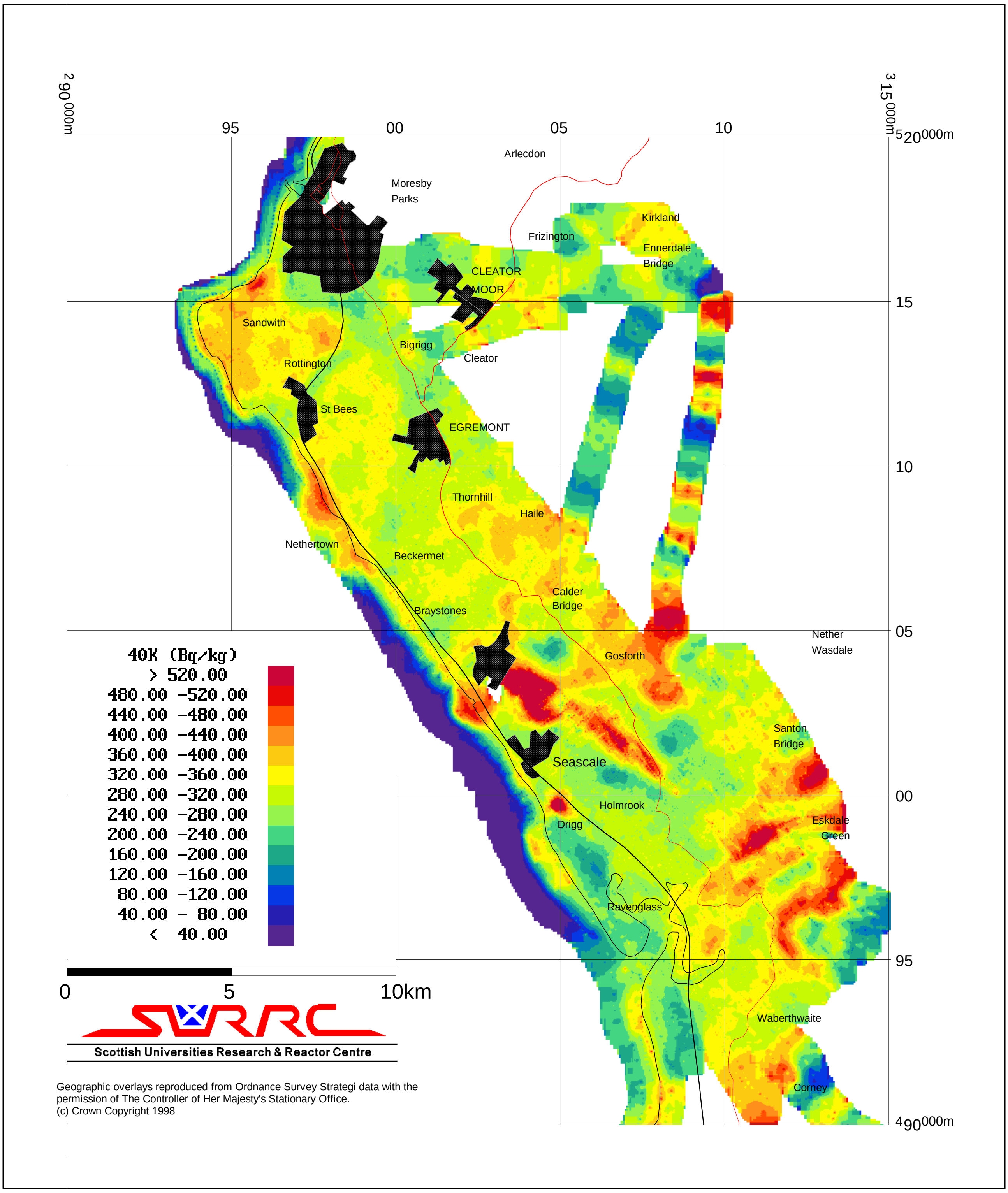

Figure 3.3: ^{40}K distribution in the Sellafield area

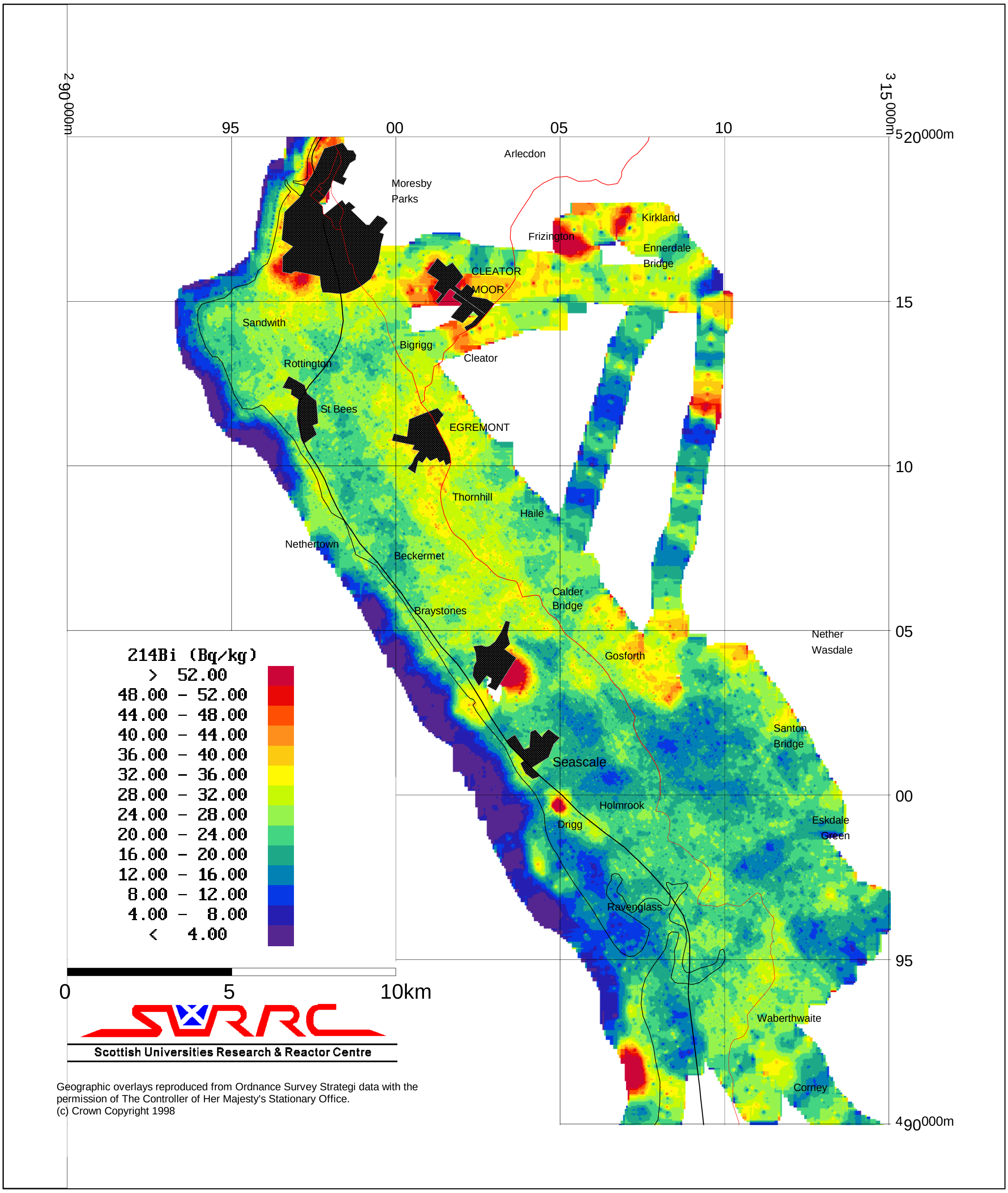

Figure 3.4: ^{214}Bi distribution in the Sellafield area

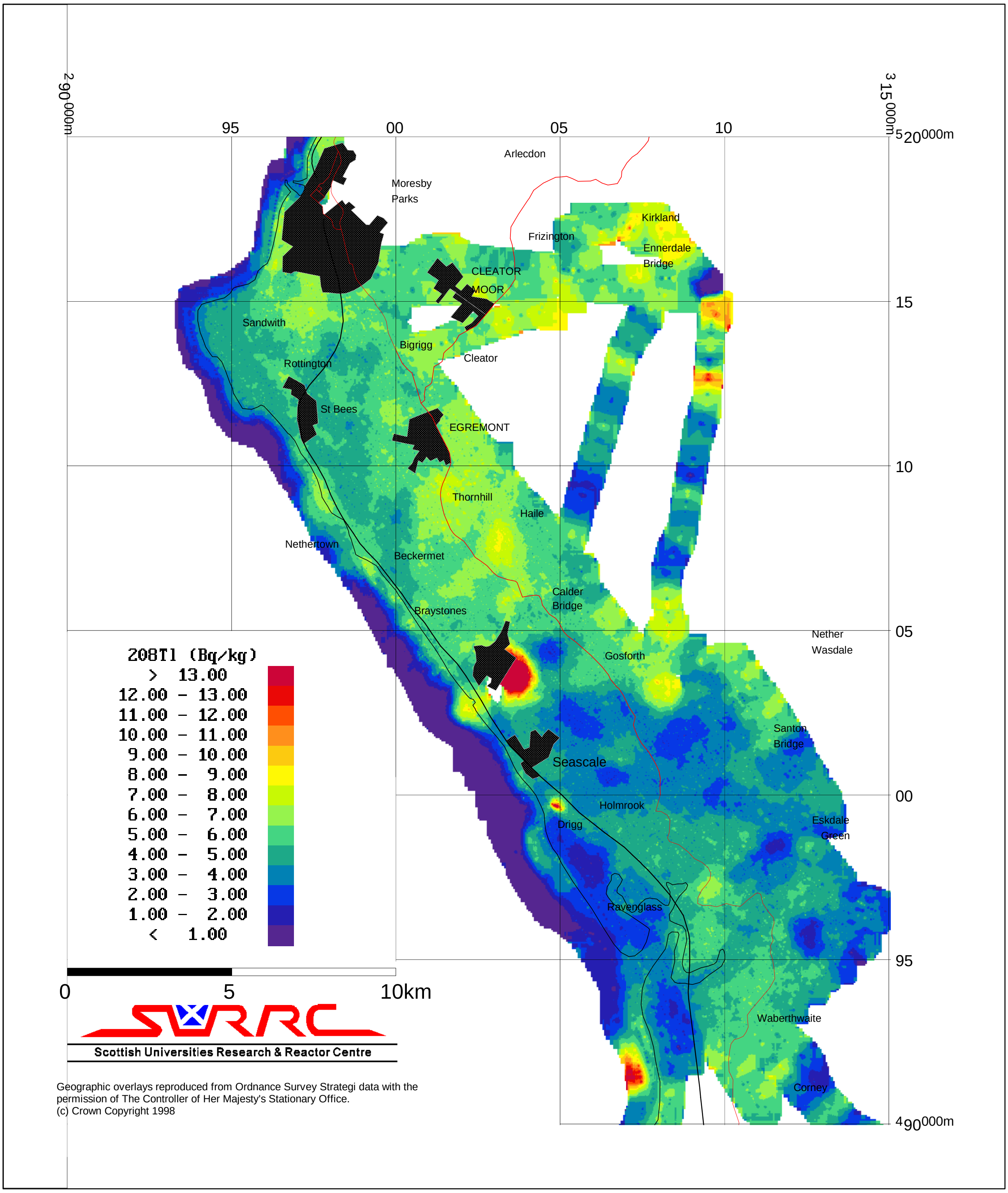

Figure 3.5: ^{208}Tl distribution in the Sellafield area

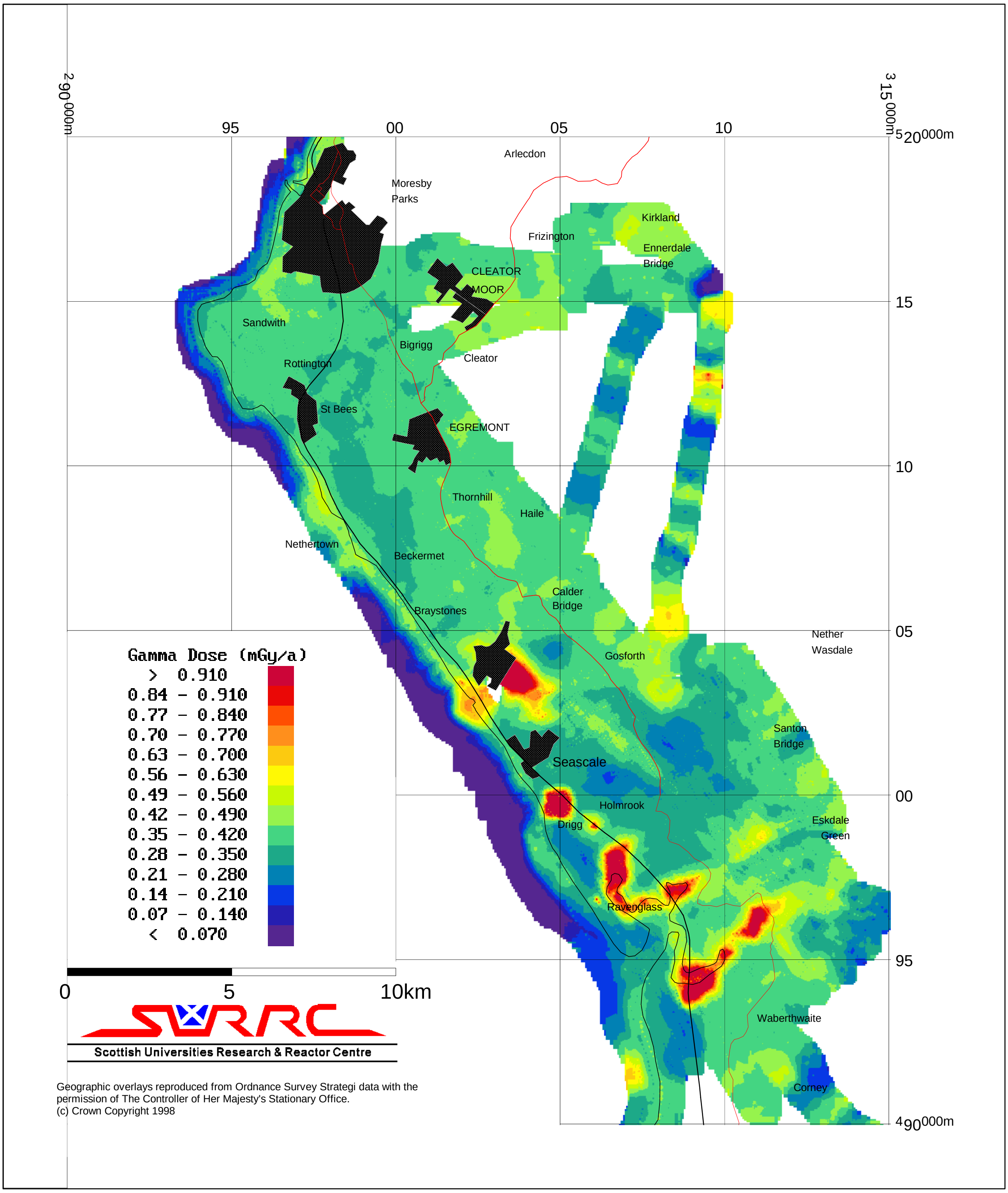

Figure 3.6: γ-ray dose rate in the Sellafield area

3.2 Coastline Survey (Area E)

Sections of the Cumbrian coastline have been surveyed on previous occasions, including the Sellafield area in 1990 (Sanderson *et al* 1990d) at 1km linespacing, the Duddon Estuary in 1993 (Sanderson *et al* 1993c) at 300m linespacing, the inner Solway in 1992 (Sanderson *et al* 1992) at 500m linespacing and again in 1999, along with Moricambe Bay (Sanderson *et al* 2000), at 250m linespacing. The data presented here were recorded in a series of lines approximately 100 m apart parallel to the coast at low tide. In most cases, one line was flown over the sea, another over the land with the remaining lines over the beaches, mud flats and salt marshes exposed at low tide.

3.2.1 ^{137}Cs Distribution

Figure 3.7 shows the ^{137}Cs distribution for the Cumbrian coastline, including the Sellafield survey. In addition to the features noted in the Sellafield area, the most significant enhanced levels of ^{137}Cs activity are on salt marshes in the inner Solway, around Moricambe Bay, and the Duddon Estuary. These features have all been observed previously, although in Moricambe Bay there appears to be some activity above the normal intertidal limit, which may be due to sediment transport during recent flooding, similar to the Esk. A comparison with the 1999 data set would confirm whether there is additional activity above the intertidal limit, and make an estimate of how much additional activity there is.

3.2.2 ^{60}Co Distribution

Figure 3.8 shows the ^{60}Co distribution for the Cumbrian coastline. In addition to the features noted in the Sellafield area, there are slight levels of activity observed on the salt marshes of the Duddon Estuary, and slight hints of activity on the inner Solway near Port Carlisle although in this case it does not appear to be on a salt marsh nor is it associated with particularly high ^{137}Cs activity. There is a small feature behind Silloth, which also registers in the ^{208}Tl channel, the origin of which is at present unknown. Further examination of the data from the GMX detector may be of use in clarifying the low level ^{60}Co distribution.

3.2.3 ^{40}K Distribution

Figure 3.9 shows the ^{40}K distribution for the Cumbrian coastline. Outside the Sellafield area the ^{40}K activity is generally quite low, except for the shingle beach south of Eskmeals.

3.2.4 ^{214}Bi Distribution

Figure 3.10 shows the ^{214}Bi distribution for the Cumbrian coastline. In addition to the features noted in the Sellafield area, some anomalous ^{214}Bi levels were noted at Millom and Askam in Furness (described in section 3.6). There are also elevated ^{214}Bi levels, without any corresponding elevation in the levels of ^{208}Tl, along the coast between Whitehaven and Maryport. More detailed study of the data would be needed to determine the origin of these signals.

3.2.5 ^{208}Tl Distribution

Figure 3.11 shows the ^{208}Tl distribution for the Cumbrian coastline. The only significant feature, in addition to those noted in the Sellafield area, is just to the east of Silloth corresponding to a strong ^{60}Co signal. The origin of this signal has yet to be determined.

3.2.6 γ-ray Dose Rate

Figure 3.12 shows the γ-ray dose rate along the Cumbrian coastline. The highest dose rates outside the immediate vicinity of Sellafield and Drigg correspond to the areas of high ^{137}Cs activity in the salt marshes, especially on the Duddon estuary with lower dose rates from the salt marshes of Moricambe Bay and the inner Solway. The shingle beach south of Eskmeals which shows elevated ^{40}K activity is a minor dose-rate feature, there are also highly localised features to the north of Workington and associated with the ^{60}Co and ^{208}Tl signal just east of Silloth.

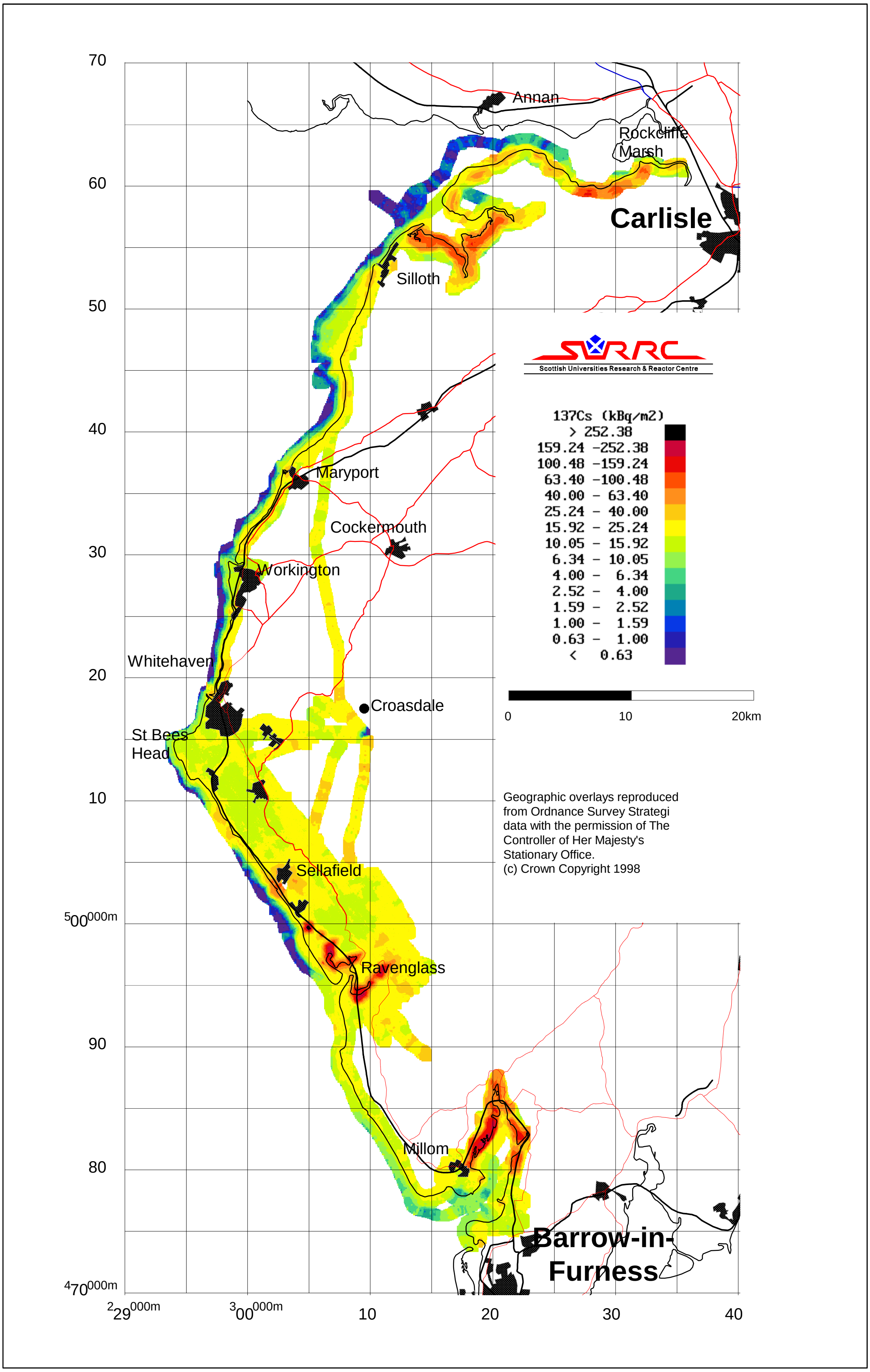

Figure 3.7: ^{137}Cs distribution for the coastline survey

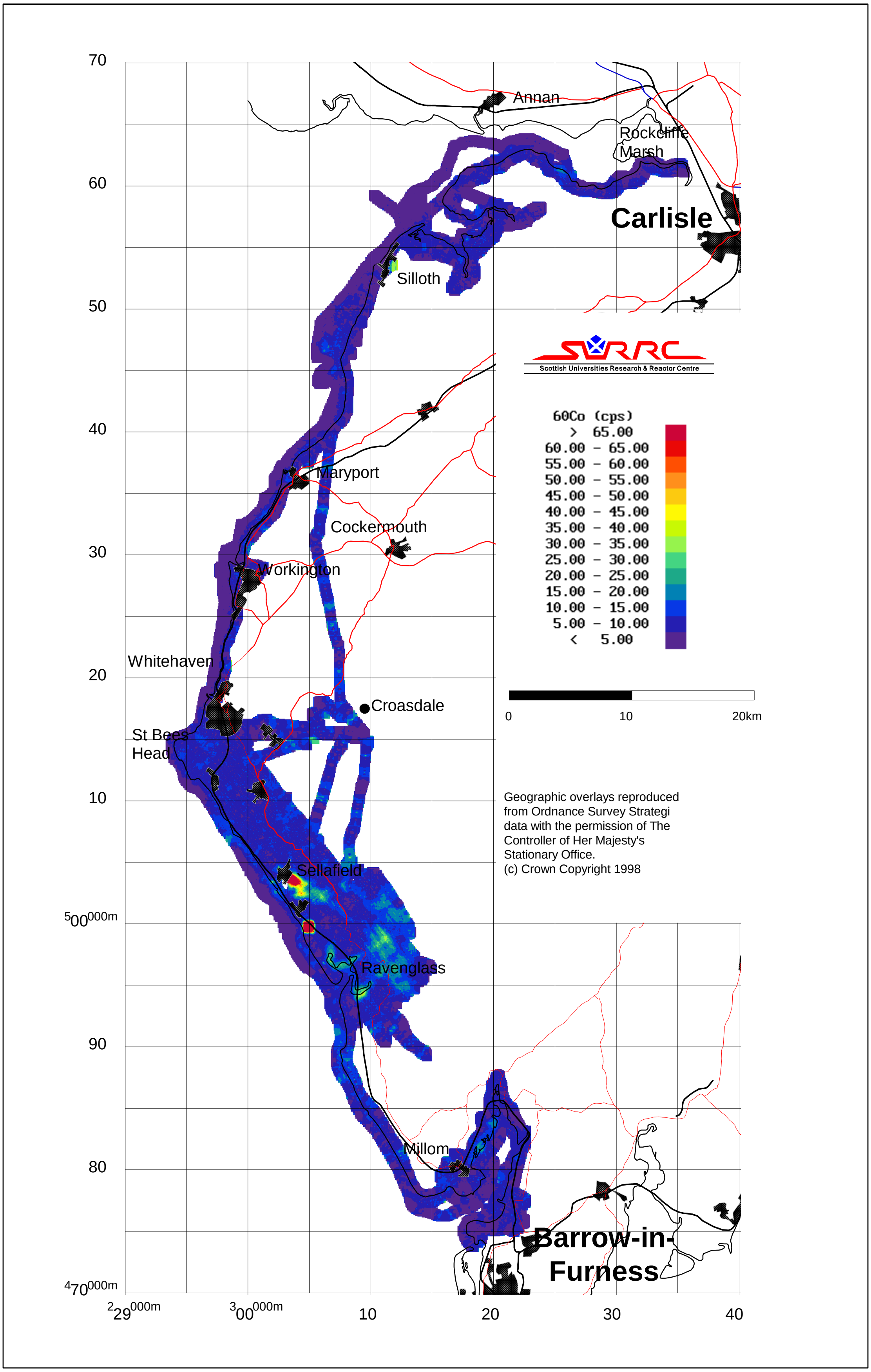

Figure 3.8: ^{60}Co distribution for the coastline survey

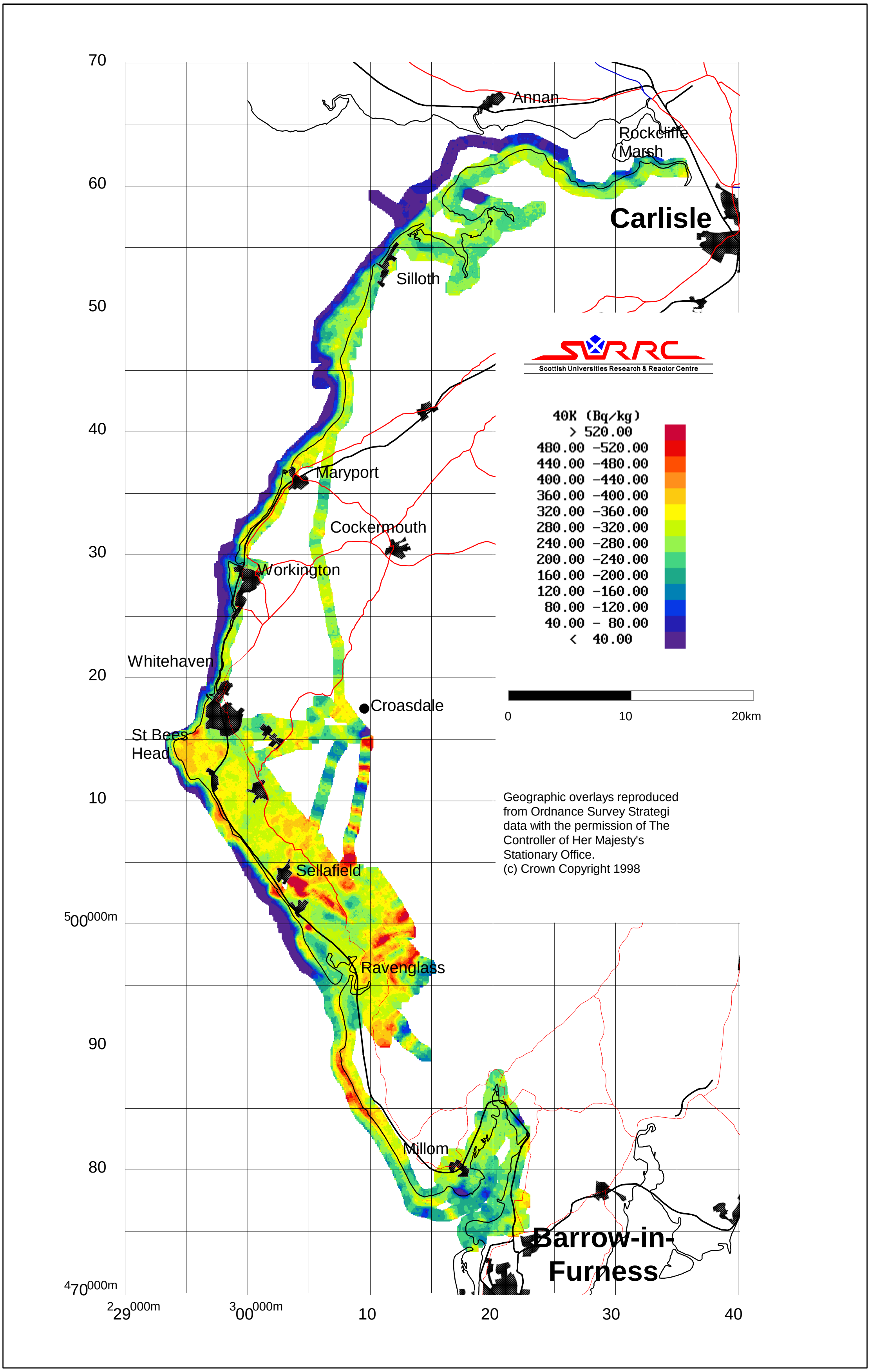

Figure 3.9: ^{40}K distribution for the coastline survey

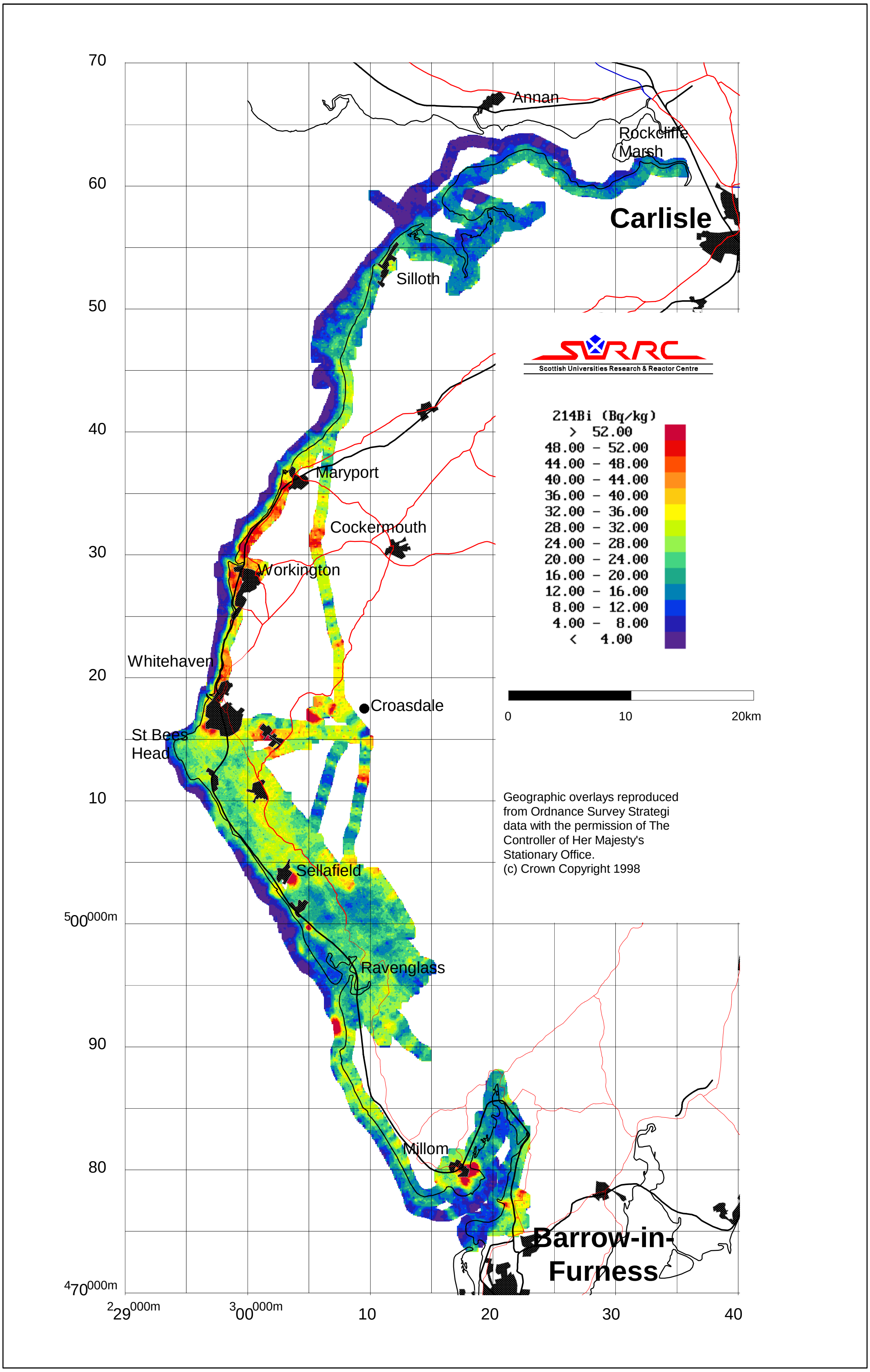

Figure 3.10: ^{214}Bi distribution for the coastline survey

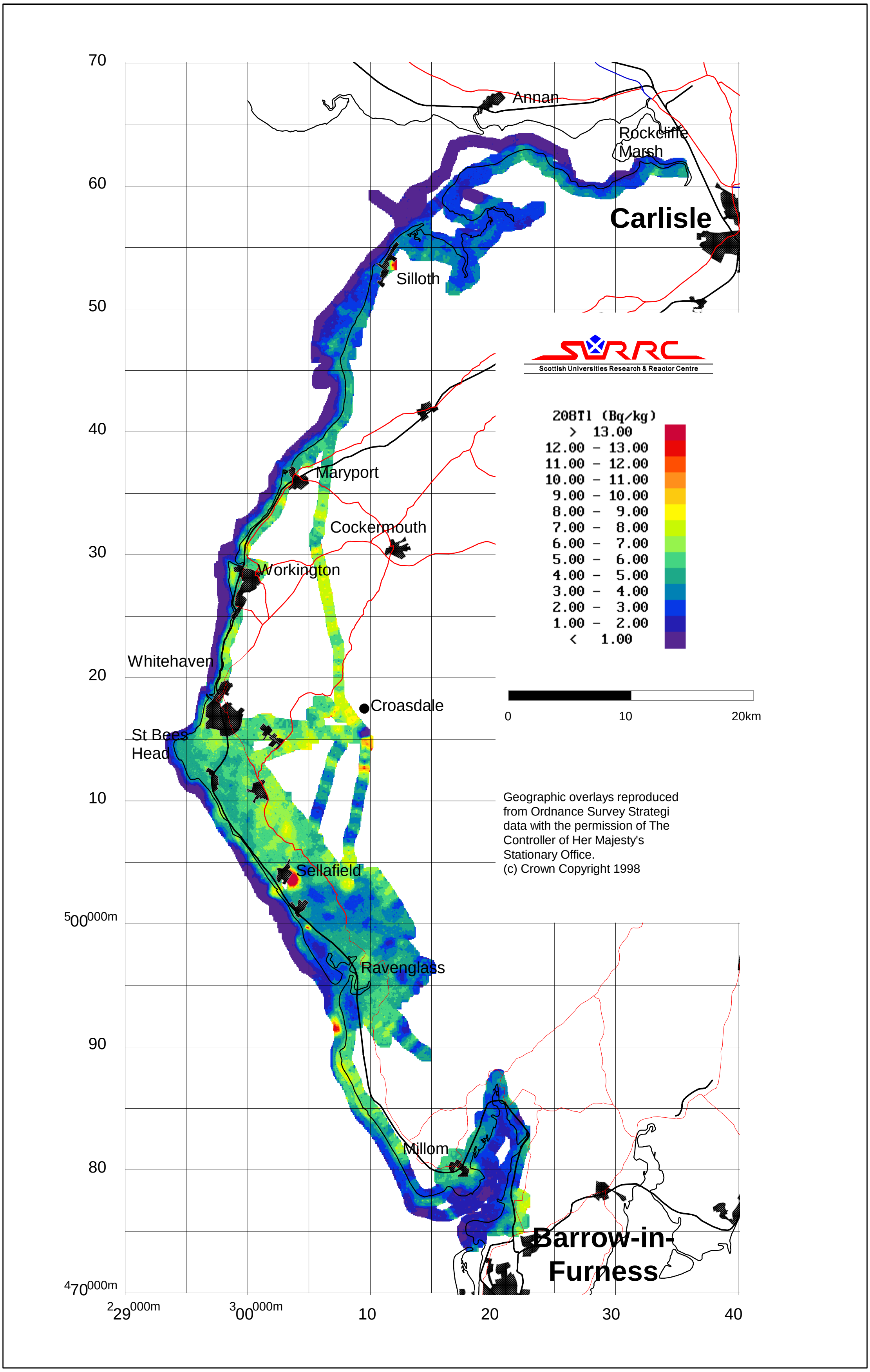

Figure 3.11: ^{208}Tl distribution for the coastline survey

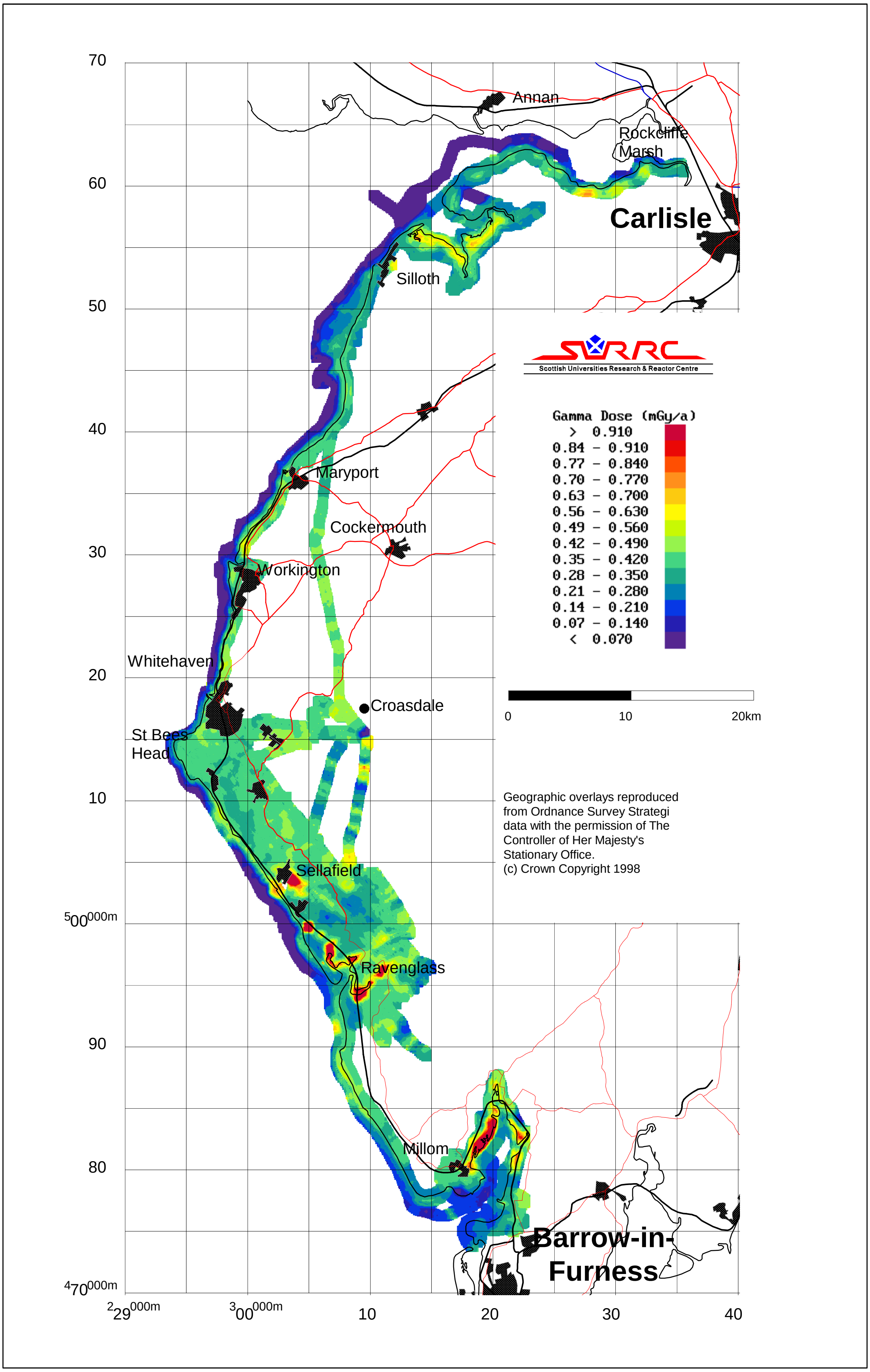

Figure 3.12: γ-ray dose rate for the coastline survey

3.3 RAF Carlisle Survey (Area F)

The former RAF Carlisle site had been contaminated by radium, but has been decontaminated. The primary purpose of the survey of this area was to confirm that no further contamination remained on the site, within the detection limits of the survey. The area was covered in the 1999 survey (Sanderson *et al* 2000) at 250m line spacing.

3.3.1 ^{137}Cs Distribution

Figure 3.13 shows the distribution of ^{137}Cs in the vicinity of RAF Carlisle, with the only feature being contamination along the River Eden

3.3.2 ^{40}K Distribution

Figure 3.14 shows the distribution of ^{40}K in the vicinity of RAF Carlisle.

3.3.3 ^{214}Bi Distribution

Figure 3.15 shows the distribution of ^{214}Bi in the vicinity of RAF Carlisle. There is enhanced activity on the railway sidings to the west of the main railway line, with no corresponding enhancement in the ^{208}Tl channel indicating that some waste industrial material is present. It seems likely that this anomaly results from the use of industrial slag as the hard core for the construction of the sidings

3.3.4 ^{208}Tl Distribution

Figure 3.16 shows the distribution of ^{208}Tl in the vicinity of RAF Carlisle.

3.3.5 γ-ray Dose Rate

Figure 3.17 shows the γ-ray dose rate in the vicinity of RAF Carlisle, the largest contribution being from the railway sidings.

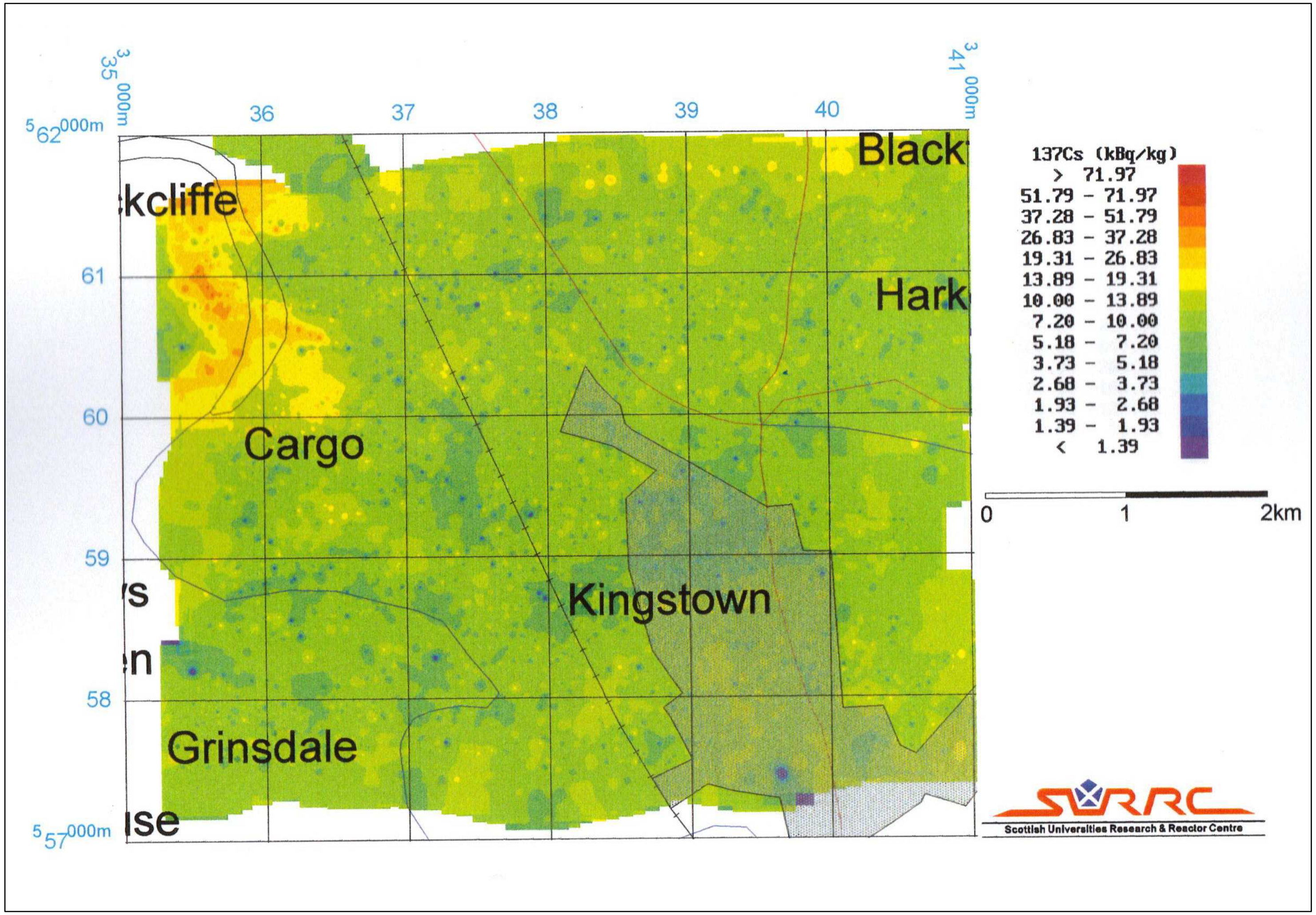

Figure 3.13: ^{137}Cs distribution in the RAF Carlisle area

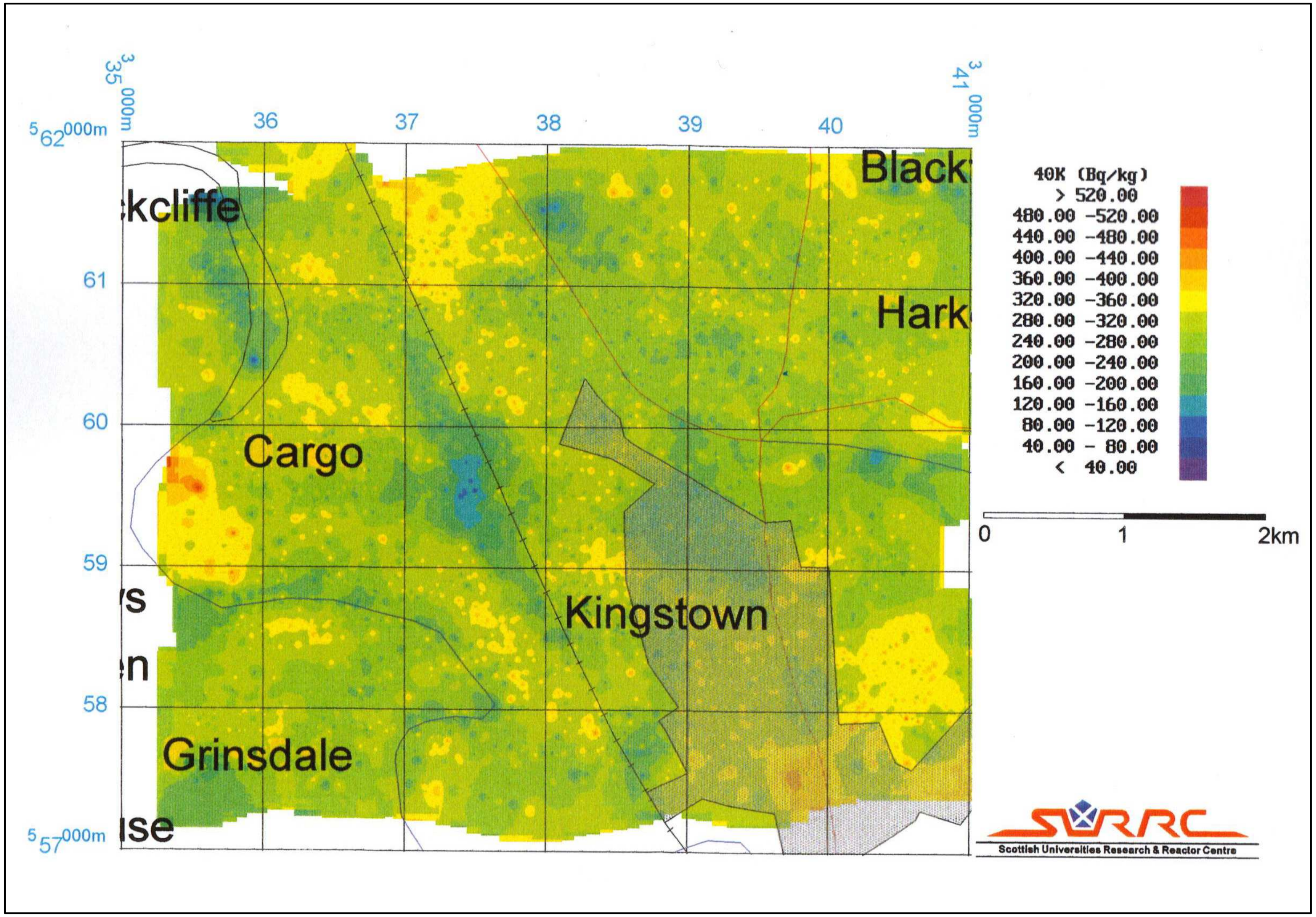

Figure 3.14: ^{40}K distribution in the RAF Carlisle area

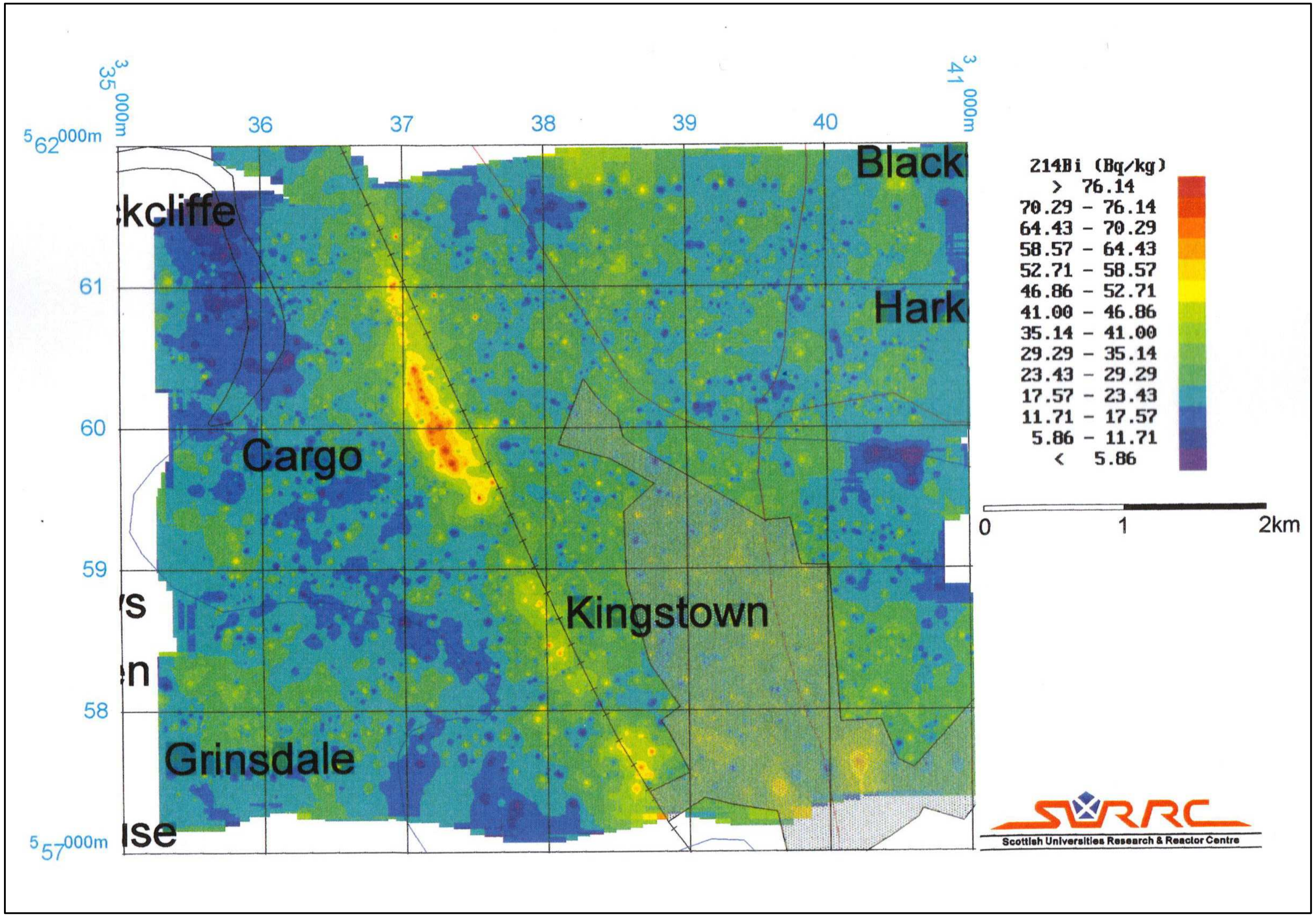

Figure 3.15: ^{214}Bi distribution in the RAF Carlisle area

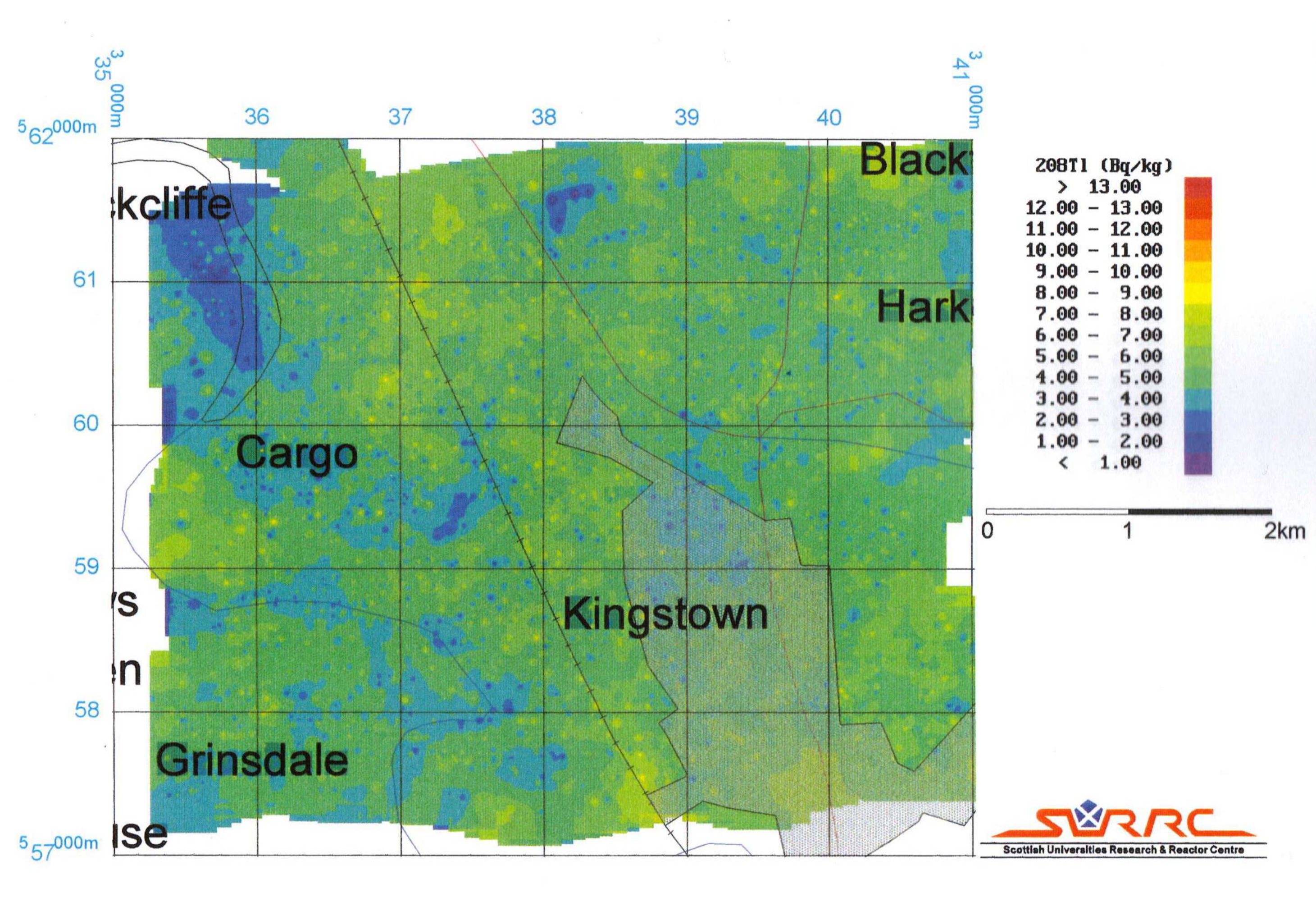

Figure 3.16: ^{208}Tl distribution in the RAF Carlisle area

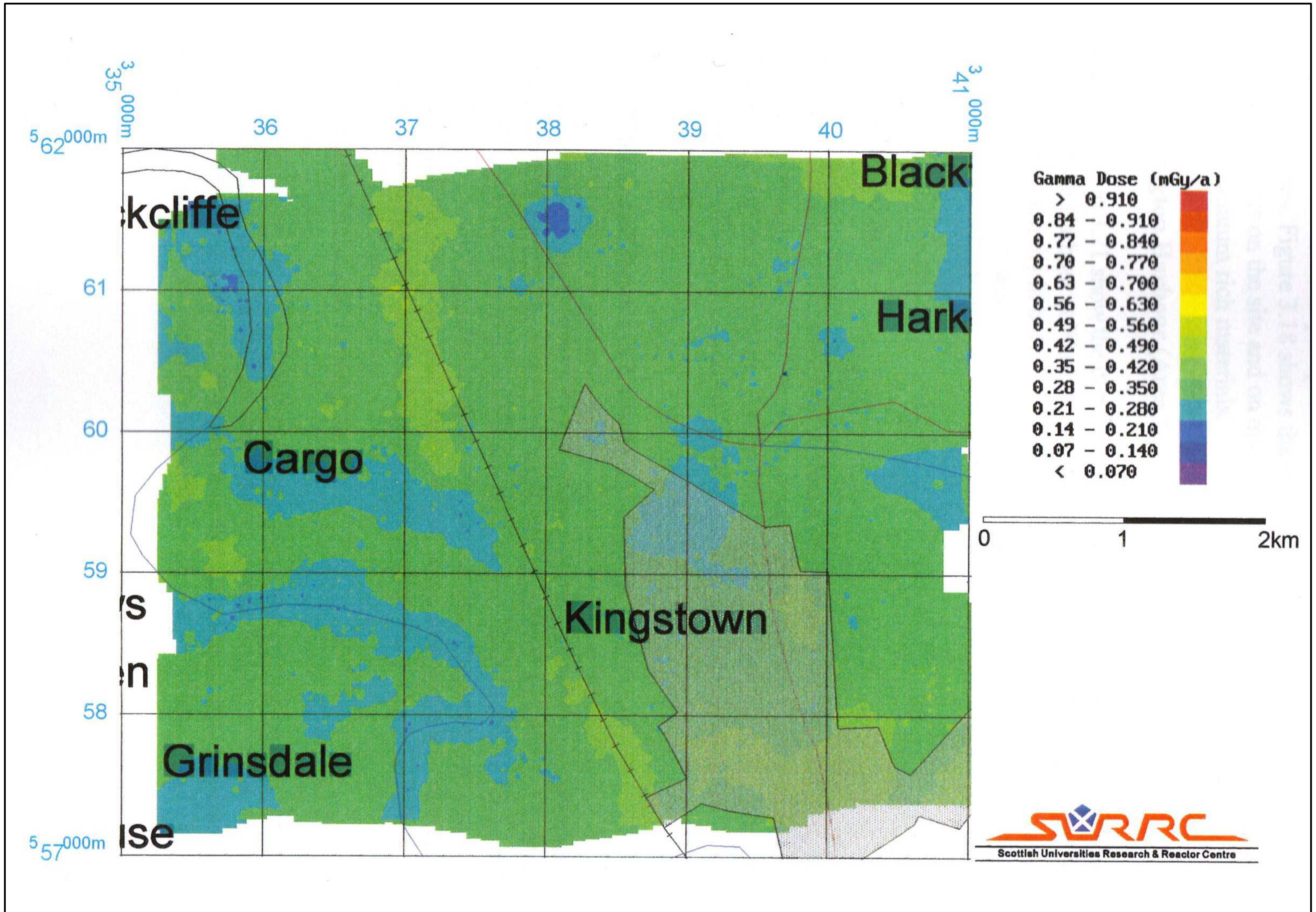

Figure 3.17: γ-ray dose rate in the RAF Carlisle area

3.4 Albright and Wilson Plant (Area I)

The Albright and Wilson plant situated to the south of Whitehaven is a chemical plant with a history of production of phosphate based fertilisers from raw materials enhanced in uranium series isotopes. Figure 3.18 shows the distribution of ^{214}Bi in the vicinity of the plant, showing enhanced levels on the site and on open ground to the east of the site, presumably as a result of processing uranium rich materials.

3.5 Workington Harbour (Area H)

Figures 3.19 to 3.21 show the distribution of ^{214}Bi and ^{208}Tl activity and the γ-ray dose rate in the vicinity of the Harbour at Workington and the steel works to the south of the harbour. Enhanced natural series activity in both the U and Th series is evident at a disused quarry between the steel works and the coast, and at a point near the wind farm to the north of town. There is an additional feature in the ^{208}Tl distribution within the town of Workington. The γ-ray dose is dominated by these features.

3.6 Additional Sites

During the course of the survey some sites with anomalous ^{214}Bi activities, in addition to those originally tasked to be studied, were noted. Short survey flights were conducted to better characterize the sites at Millom, Askam in Furness, Frizington and Cleator Moor. Some further investigations of the nature and any potential radiological or environmental impact of these site may be appropriate.

3.6.1 Millom and Askam in Furness

Figure 3.22 shows the ^{214}Bi activity at Millom and Askam in Furness, with three features evident. These features are associated with industrial waste material in a disused quarry south of Millom (SD177792), a large heap of similar material east of Millom (SD183805) and another heap at Askam Pier (SD807773). In the later case, part of the heap has been used for a recent housing development. In situ γ-ray measurements and some samples were collected from the Millom sites, but have yet to be analysed.

3.6.2 Cleator Moor and Frizington

Figure 3.23 shows the ^{214}Bi activity at Cleator Moor and Frizington. The features at Cleator Moor were only observed from data recorded during transit flights, whereas a short additional flight was undertaken to the east of Frizington to better define those features. During that flight, it was found that one of these features is associated with a waste dump.

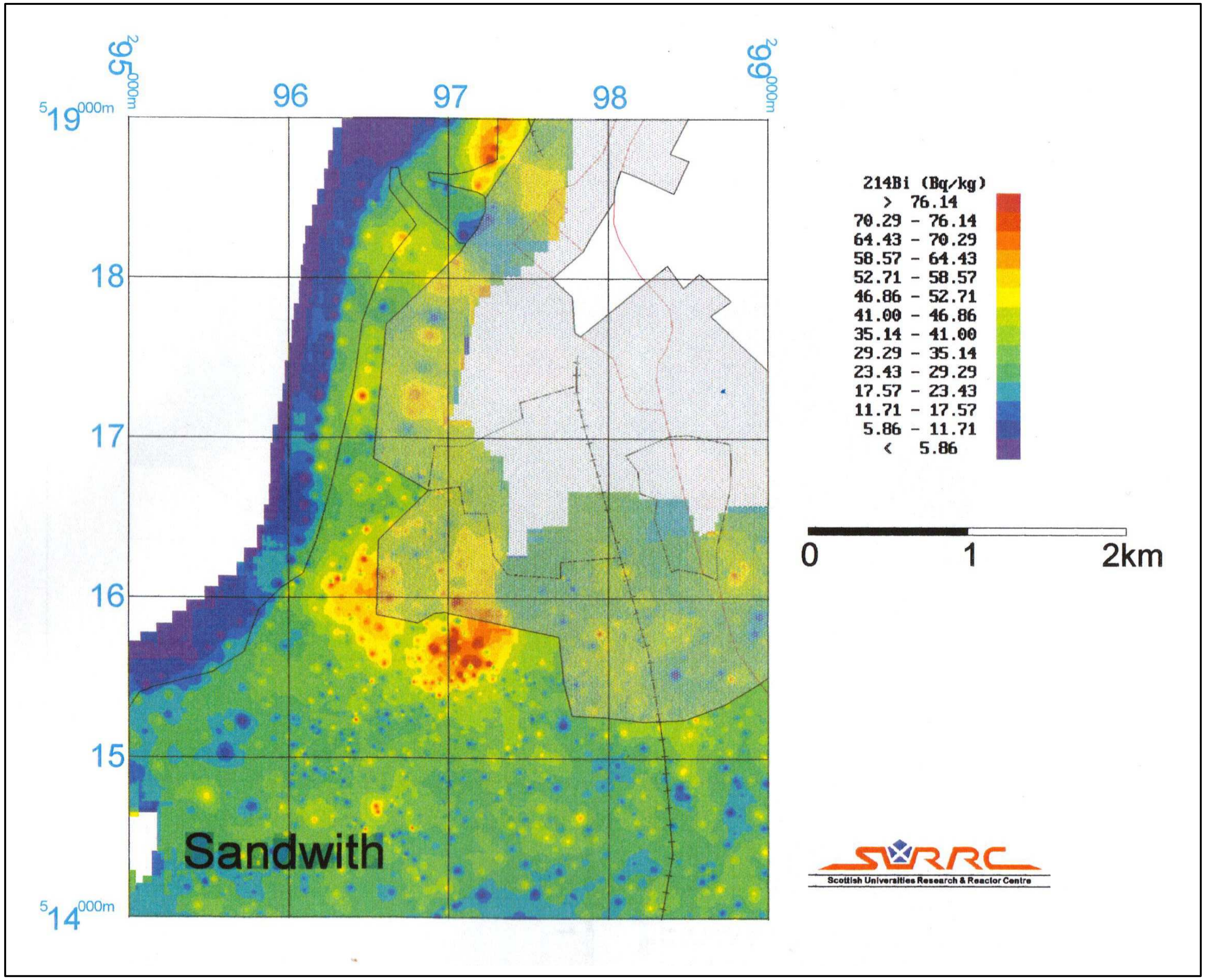

Figure 3.18: ^{214}Bi distribution in the vicinity of the Albright and Wilson plant, Whitehaven

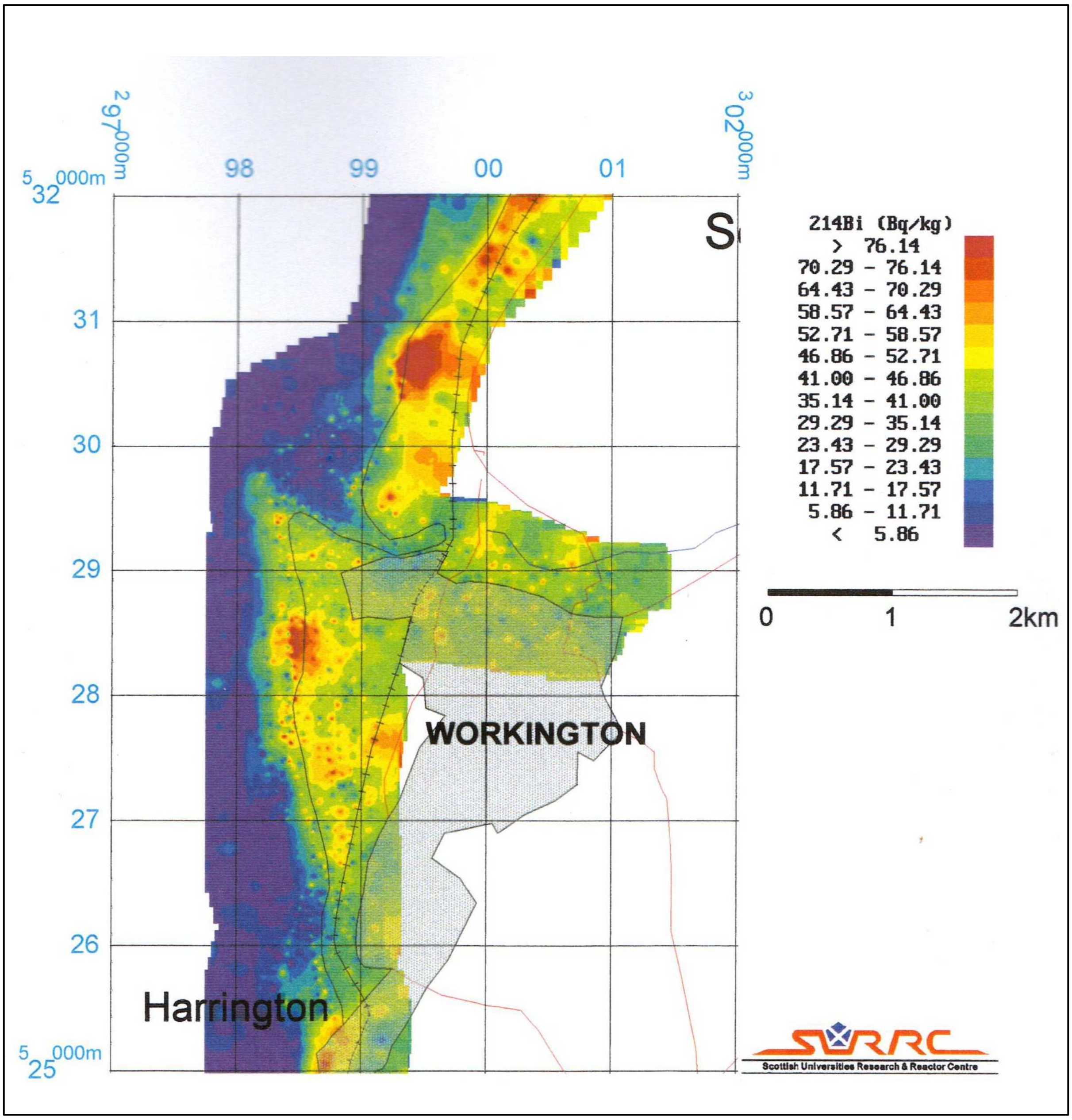

Figure 3.19: ^{214}Bi distribution in the Workington Harbour area

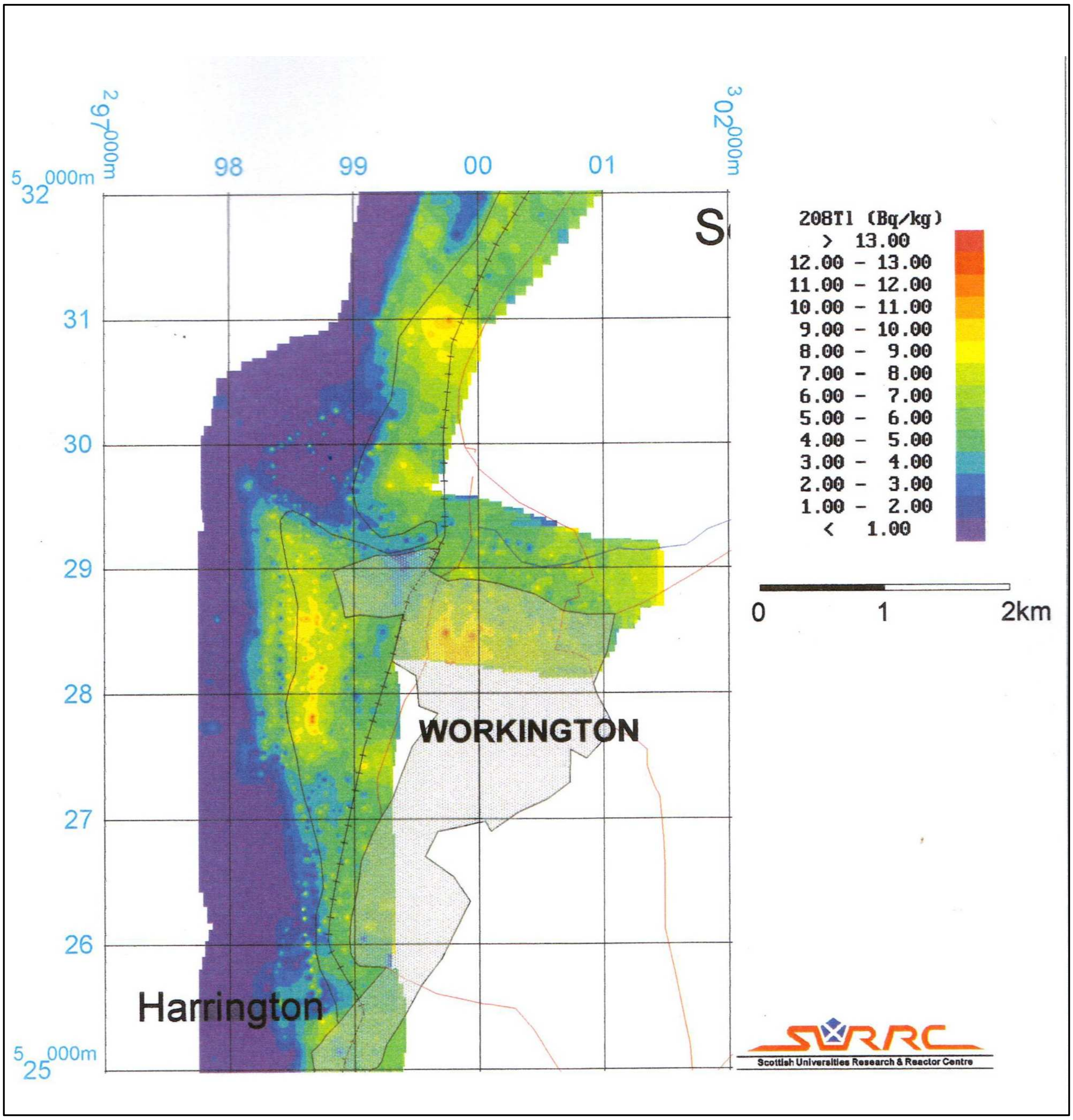

Figure 3.20: ^{208}Tl distribution in the Workington Harbour area

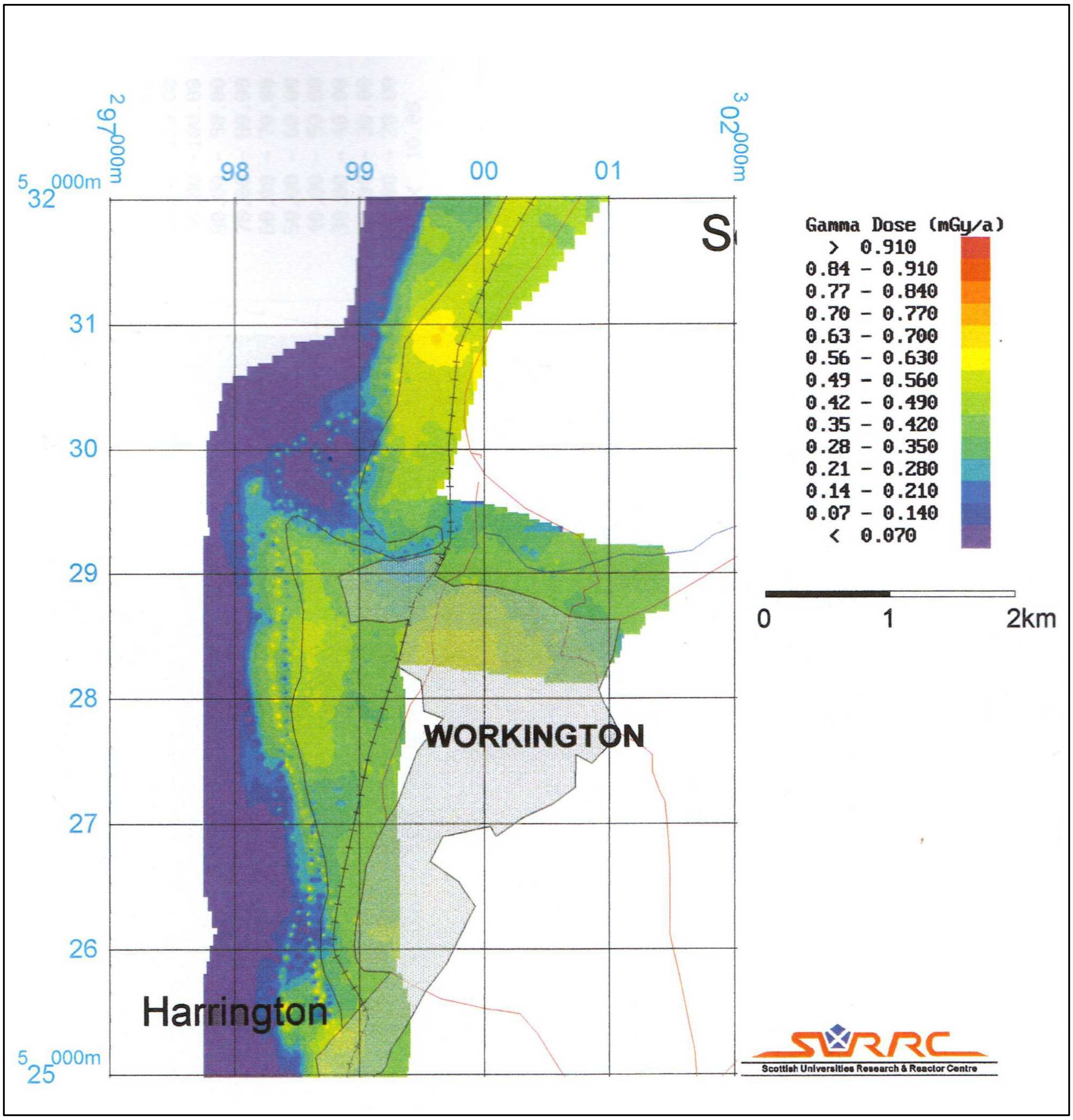

Figure 3.21: γ-ray dose rate in the Workington Harbour area

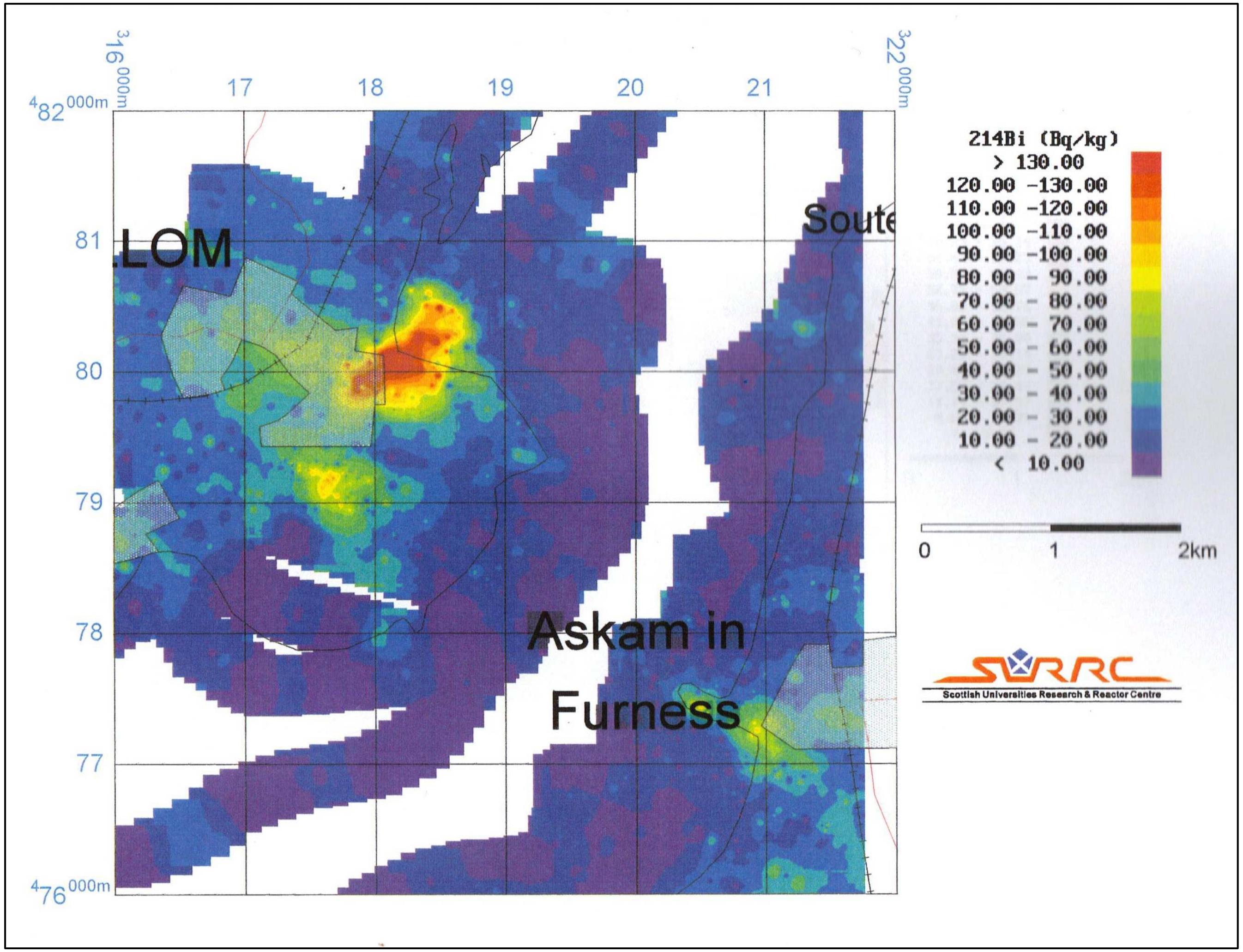

Figure 3.22: ^{214}Bi anomalies at Millom and Askam in Furness

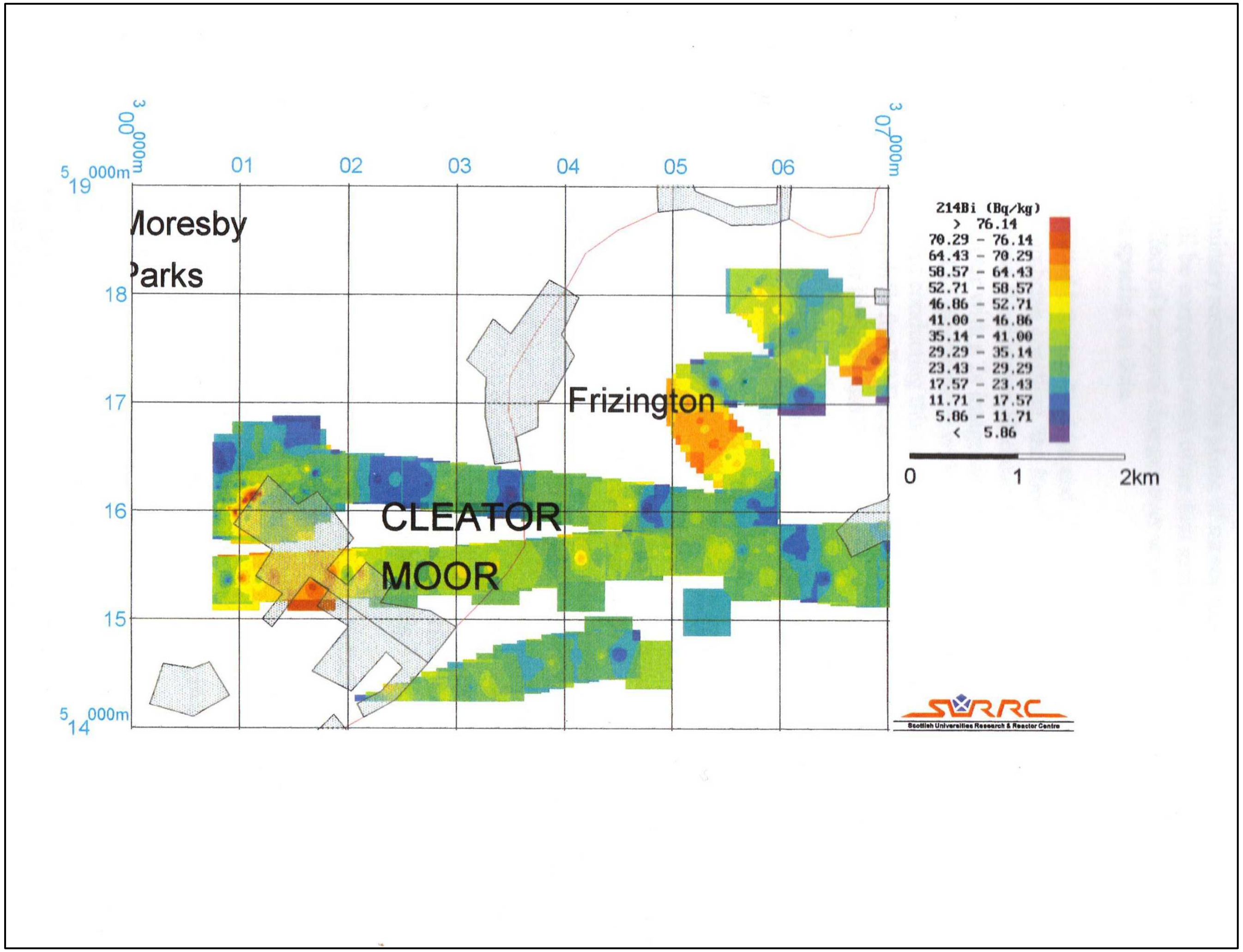

Figure 3.23: ^{214}Bi anomalies at Cleator Moor and Frizington

4. CONCLUSIONS

An Airborne Gamma Spectrometry (AGS) survey of parts of West Cumbria and North West England has been conducted as part of a project investigating spatial and temporal aspects of AGS. The preliminary 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 and reproducibility.

The survey conducted between the 14th and 22nd March 2000 covered a 25×5km region around Sellafield, the Cumbrian coastline, the former RAF Carlisle site, the Albright & Wilson plant near Whitehaven and Workington Harbour. In total some 47000 spectra were recorded from the NaI(Tl) spectrometer with a 2s integration time, and 23500 spectra from a 50% efficiency Ge semiconductor (GMX) spectrometer with a 4s integration time. A total of approximately 38 hours flight time was spent conducting this survey; 19h for the Sellafield vicinity (area G), 10h for the coastline (area E), 4.5h for RAF Carlisle (area F), 2.5h for the Albright and Wilson plant and Workington Harbour (areas H and I) and transfer of the aircraft from Cumbernauld airport.

The data recorded have been used to map the distribution of ^{137}Cs, ^{60}Co, ^{40}K, ^{214}Bi, ^{208}Tl and the γ-ray dose rate within the survey areas.

At present, the ^{137}Cs activity has been calibrated to the activity and mass depth distribution on the Caerlaverock Merse measured from cores collected in April 1999 for the first phase of survey (Sanderson *et al* 2000). Working maps calibrated in this manner are comparable with the 1999 survey data. However, the potential effects of variations in mass depth distribution within the survey area considered should be considered when interpreting quantitative estimates of activity per unit area. The survey has largely shown the previously observed distribution of ^{137}Cs on the estuarine salt marshes of the rivers Irt, Mite and Esk (Sanderson *et al* 1990d), the Duddon Estuary (Sanderson *et al* 1993c), Moricambe Bay and Burgh Marsh (Sanderson *et al* 1992, 2000) as a result of historic marine discharges from Sellafield. It was noted that the ^{137}Cs activity extended beyond the normal inter-tidal limit of the river estuaries, possibly as a result of deposition of intertidal sediment following recent floods.

Previously observed ^{137}Cs signals along the beach near Sellafield (Sanderson *et al* 1990d) have been confirmed, and with the higher spatial resolution of this survey better localised. There is a strong signal on the beach near the discharge pipeline that may be due to contamination of the foreshore, direct radiation projected off site or possible exposure of part of the pipeline at low tide. Further work would be needed to identify the source of this signal. Further along the beach towards St. Bees there is evidence of contamination of shingle and rock surfaces.

^{137}Cs activity was also observed on upland areas near Gosforth and Muncaster Fell, again this had been observed previously (Sanderson *et al* 1990d) and attributed to aerial discharges from Sellafield including the 1957 Windscale fire, with contributions as a result of the 1986 Chernobyl accident. It was noted that the activity appears to be concentrated on the flanks rather than the top of Muncaster Fell, which may be a consequence of deposition from atmospheric sources.

There is no evidence of contamination of woodland areas, within the detection limits of this technique, attributable to the roosts of pigeons.

There is evidence of more recent discharges of ^{60}Co in the saltmarshes of the rivers Irt, Mite and Esk, as well as on upland areas of Irton Pike and Muncaster Fell, although in these upland areas there are also elevated ^{40}K levels, and the apparent ^{60}Co distribution in these areas may reflect interferences from ^{40}K. Further work, including analysis of the GMX spectra, will be needed to confirm these upland signals.

A survey of the former RAF Carlisle site has shown no evidence of residual radium contamination above the limit of detection of this technique. There is, however, an anomalous ^{214}Bi signal associated with the railway line, which it is assumed results from the use of industrial waste material in the construction of the line.

Anomalies in the uranium series ^{214}Bi activity distribution were also observed associated with non-nuclear sites. These sites include the Albright and Wilson plant near Whitehaven, and the steel works just south of Workington. In addition, some further sites were identified during the course of the survey associated with industrial slag material:

- Two features were observed near Millom, one associated with industrial wastes in a disused quarry to the south of the town (SD177792) and the other with a larger area of industrial wastes to the east of the town (SD183805).
- Another similar area of industrial wastes was identified near the pier at Askam in Furness (SD807773), on part of which a housing estate has recently been built.
- A few features were observed near Cleator Moor and Frizington from transit flight data, a short additional flight over the latter found that it was associated with a small waste dump.

Some further investigation into the nature of these sites, and any potential environmental or radiological impact, may be advisable.

The data sets generated in this survey provide an abundant resource to define the radiological contexts of the survey areas, and to provide a means of measuring changes to the environment. Further analysis of the data will take place at later stages of the project. However, this report and the similarities between many of the features observed here and the earlier 1990 survey of the Sellafield area, confirm the value of radiometrics in defining the radiation environment of nuclear sites.

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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)	105-136
2	^{60}Co (1172 keV)	175-210
3	^{40}K (1461 keV)	221-267
4	^{214}Bi (1764 keV)	267-311
5	^{208}Tl (2615 keV)	378-461
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	0.00483	0	0	0
^{60}Co	0.510	1	0.521	0.0366	0.0236
^{40}K	0.674	0.485	1	0	0
^{214}Bi	3.365	1.515	0.955	1	0.0747
^{208}Tl	2.532	0.687	0.622	0.454	1

Table A.2: Stripping ratios measures 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 checks