AERIAL RADIOMETRIC SURVEY IN WEST CUMBRIA 1988.
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AERIAL RADIOMETRIC SURVEY IN WEST CUMBRIA: A preliminary survey of areas of restricted livestock movement in 1988.

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ABSTRACT

Details and results are presented of aerial radiometric measurements undertaken in summer 1988 over an area of restricted livestock movement in West Cumbria. The project was planned in June and July on the basis of discussions between MAFF and SURRC. The prototype aerial spectrometer developed at SURRC in March was used in a helicopter for three purposes. Firstly the sensitivity and spatial resolution attainable over variable and, in some places mountainous, terrain was confirmed, supporting the conclusions of earlier flight trials in Scotland. Secondly it was confirmed that ^{134}Cs could be detected semi-quantitatively within the survey area, providing insight into the origins of anthropogenic deposition of ^{137}Cs. Finally the distribution of both natural and anthropogenic gamma ray emitting radioactivity was determined within the survey zone.

The survey was conducted successfully in between 22nd August and 3rd September 1988. Despite unseasonably poor weather more than 1800 measurements were recorded from an area of over 45000 hectares. The detector performance and sensitivity was as expected, and it has been possible both to detect ^{134}Cs and to produce high resolution maps of the radioactivity within this area. A comparison of the results of other analyses of environmental materials from parts of the survey area, including a programme undertaken by MAFF in 1988, and the aerial results confirms the overall validity of the calibration method used.

Both ^{134}Cs and ^{137}Cs maps show considerable spatial variation throughout the survey zone and can be used to identify the areas of peak deposition due to Chernobyl. This basic information may be of use for devising and evaluating agronomic strategies to minimise the transfer of artificial nuclides through the food chain, and to help alleviate the problems experienced by farmers working in the restricted areas since the Chernobyl accident. The prototype detector and method used both show considerable potential for further development.

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1. INTRODUCTION

Project N611 was initiated to undertake a brief aerial radiometric survey of the area in West Cumbria which has remained under livestock movement restrictions since the Chernobyl accident in 1986. The study was in part a demonstration of an economical and promising method for mapping deposition, and in part to provide the first detailed map of the fallout pattern within this zone.

The aerial approach to measuring deposited radioactivity arises from the basic penetrated power of gamma radiation from terrestrial radionuclides. Whereas typical soils and rocks attenuate gamma radiation within some 20-30cm, the much lower density of air means that terrestrial gamma fluxes are detectable up to a few hundred metres from ground surfaces. Variations in radionuclide distribution lead to variations in the gamma radiation field which can be mapped out using a sensitive radiation detector in a low flying aircraft. The main advantages of this approach compared with methods based on collecting samples at ground level are the speed and economy with which thorough area surveys can be undertaken.

At the time of the Chernobyl accident there was no UK facility for aerial radiometric survey. Instead current knowledge of the UK deposition pattern is based on a combination of methods including laborious field measurements at ground level, laboratory analysis of environmental samples and inferences from meteorological evidence. This gives a necessarily incomplete picture.

The work undertaken by MAFF up to 1988 has been examined by parliamentary committee (HMSO,1988). The emphasis has been to record radioactivity levels in foods or in vegetation rather than to examine deposition per se. Areas of livestock movement restrictions have been defined by direct observations of contamination in carcasses and livestock rather than on the total inventory of activity in the soil.

The relationship between radionuclide deposition, measured in activity per unit area, and food contamination levels, in activity per unit mass, depends on complex environmental processes. Transfer through the food chain is the result of the physical and chemical form of the deposition, its weathering properties, the chemistry and ecology of soil and vegetation, and on the nature of local agronomy. Although the radiological safety and quality of foods depends on the combination of all these factors, direct measurements of deposition levels are highly relevant. They can target subsequent investigations to areas of greatest need, are directly relevant to external dose assessment, support identification of critical exposure paths, and have a bearing on devising strategies for dose limitation or minimising transfer to food.

The technique of aerial radiometric mapping is not new; nevertheless modern technology has had a dramatic impact on the potential. Originally applied to uranium and mineral exploration using gas filled detectors (Peirson & Franklin,1951,Stead,1950, Godby et al,1952) the practicability was first realised with the development of scintillation counters (Pringle et al,1953, Peirson & Pickup,1954) which, in a much developed form, remain the preferred detectors for this purpose today. Early British work included studies of total radiation mapping (Williams and Bisby,1960, Williams and Cambray,1960), appraisal of the use of helicopters in emergencies (Peirson and Crooks,1961) and an early environmental radiation surveys following the 1957 Windscale fire (Williams et al,1957, Chamberlain et al,1960). The method seems to have been largely neglected in the UK since this time.

Elsewhere methods to resolve different components of the gamma spectrum were developed over the following decades, firstly using single channel analysers and more recently with simple multichannel spectroscopy systems (Dickson et al,1981, Grasty, et al 1985). Applications include continuing interest in uranium prospection (Darnley,1973, Grasty,1975), prediction of meltwater floods (Kogan et al,1965, Peck et al,1971, Dahl & Ordegaard,1970, Grasty, 1973), estimation of atmospheric radon, and monitoring radiation exposure rates in the vicinity of US nuclear power stations (Burson et al,1972). A team of four aircraft was used in 1978 to search for radioactive debris from the Soviet Cosmos 954 satellite whose nuclear reactor broke up over Northern Canada (Bristow,1978, Grasty,1980).

Aerial survey was used successfully to determine the determine the distribution of Chernobyl fallout in Sweden (Linden and Mellander,1986). The exercise involved some 30000 line kilometres of flying in between 1st May and the 19th June 1986. Fallout maps were based on ^{134}Cs photons or on total radiation exposure rate, both of which were calibrated by comparison with measurements undertaken at ground level on areas identified from the air. Preliminary maps were reported to the Swedish population within two weeks of the accident. Readings were taken with a 50km line spacing over the whole country supplemented by 10km, 4km and 2km grids over selected areas of high deposition using a conventional 4 element geological detector. Levels of ^{137}Cs inferred from these flights to over 120 kBq/m^2, and in some places the combined count rate from the four detectors was too high for the electronics to process.

The work reported here was conducted using a prototype detector developed at SURRC, using University resources, in February 1988. Attempts to interest government departments in the method the previous year were unsuccessful. It is believed that there is very considerable scope for further instrumental development and methodological refinement to improve the sensitivity and speed of the survey. The present study therefore represents an extended trial application of a simple demonstration system.

Successful flight trials carried out in Scotland in February and March were followed in June by a request from MAFF to consider undertaking a preliminary survey of parts of West Cumbria later in the summer. This survey was carried out between 22nd August and 3rd September 1988 during which period a total of over 1800 readings were taken from an area of 45000 hectares.

2. THE DETECTOR AND SURVEY METHOD

2.1 The SURRC prototype detector

The detector used for this survey was based on a prototype built at SURRC in February 1988. The main detector element is a NaI crystal dimensions 11.5"x 4" made by the Quartz et Silice company some years ago and used originally by the Health Physics and Nuclear Medicine group in East Kilbride for whole body monitoring. The crystal is viewed by an array of 7 photomultipliers whose summed outputs develop scintillation pulses from gamma interactions in it. For aerial monitoring this unit has been mounted in a specially constructed enclosure to protect it from vibrations and thermal shock. It is powered from a battery driven 3.5 kV stabilised supply built into the housing and forms a compact and self contained unit which can be installed rapidly into many types of fixed or rotary wing aircraft.

The scintillation pulses are recorded in 1024 channels of an 8K multichannel analyser (Canberra series 10), thus forming a simple spectrometer capable of resolving different gamma ray components from 300 keV to 3 MeV. The energy resolution at 662 keV was 13-15% over the course of the study, in line with expectations for a detector of this geometry and age. Spectrometer and navigational data are logged from a portable computer. In the original flight trials in February and March this was a twin floppy disc laptop computer (Zenith Z181). For the Cumbrian survey a more powerful computer with hard disc (Locland 286) was used powered by a 250V AC sine wave inverter (Matchpower systems).

The flight trials in February and March (Sanderson et al,1988) confirmed that this system was capable of detecting ^{137}Cs in the presence of natural background components, although in its original and present forms we regard it as a demonstration system for continuing and future development. It is believed to be the only system of its type in the UK.

2.2 Detector Response and Survey Method

The gamma ray spectrum from 300 keV to 3 MeV comprises photopeaks, escape peaks and scattered radiation from natural and anthropogenic nuclides. The principal photopeaks of interest to this study are ^{208}Tl (2.615 MeV) from the thorium decay series, ^{214}Bi (1.76 MeV) from the uranium series, ^{40}K (1.46 MeV) and modern additions from ^{137}Cs (0.662 MeV) and ^{134}Cs (0.796 MeV). There are many other gamma ray lines from the natural series, and other possible environmental nuclides; those mentioned above however can be extracted from spectra observed in the environment. In transport between sources distributed on or in the ground and detectors above the ground surface, the radiation is attenuated and scattered both by soil or rocks and also in the air path beneath the detector.

The detector sensitivity and response are important to both the survey strategy and to a meaningful interpretation of the results. The development of a highly quantitative description of the response of hand-held, vehicular or airborne detectors to multi-nuclide, and possibly layered sources under varied topographic and environmental conditions is indeed a demanding task, and one which no doubt merits future attention. Nevertheless the main characteristics from a practical point of view can be determined from elementary gamma transport principles, and from semi-empirical analyses in the geophysics literature.

The dominant interaction between photons between 400 keV and 3 MeV and environmental media is due to the Compton effect for which mass absorption coefficients are not very strongly dependent on either atomic number or photon energy. The majority (ie 90%) of the radiation flux escaping from the ground originates from the top 20-30cm in rocks or dense mineral rich soils, or from the top 40-60 cm in a waterlogged organic medium. Attenuation in air is readily assessed from nuclear data (eg Storm and Israel,1970). Half depths for the photons under study in dry air can be shown to be 72m (137Cs at 662 keV), 82m (134Cs at 796 keV), 115m (40K at 1.46 MeV), 130m (214Bi at 1.76 MeV) and 158m (208Tl at 2.62 MeV), the attenuation with altitude being accompanied by a build of continuous Compton scattered radiation especially below 500 keV. Examples of environmental spectra taken in Cumbria are shown in the technical annexe.

Two other significant effects occur as a detector is raised above ground level. Firstly the solid angle subtended by the ground to the detector approaches 2 pi, as the influence of small topographic features is reduced. Secondly the area on the ground from which gamma rays can reach the detector increases rapidly. The circle of investigation depends largely on the anisotropy of the detector and the altitude (Duval et al,1971, Grasty et al,1979); for our prototype system it takes on a diameter of roughly 4-5 times altitude. Thus at 30m above ground the detector picks up radiation from an area diameter 120-150m, and at 100m from ground level it sees an area of roughly 500m diameter. At altitudes above 300m attenuation in air results in a much degraded spectrum.

Choice of survey altitude depends on the logistics of low flying in a particular area, and the spatial resolution required. For the Scottish feasibility studies and the Cumbrian surveys we have standardised on a nominal height of 100m. At this height each measurement comes from an area of 196350 m2, equivalent to measuring the mean activity of a source of 50000 tons. In balancing survey speed against sensitivity from this detector we have standardised on taking readings each 30s. The survey method therefore comprises flying along predetermined paths, generally parallel sweep-search grids, at speeds and spacings which determine the spatial resolution. Low altitude exemptions from

the CAA are needed to do this, and can be obtained fairly readily for work in rural areas. By logging a continuous sequence of 30 s spectrometer readings collated with altitude and navigational coordinates the variations in gamma ray flux and hence contamination level are recorded. Analysis of the data back on the ground can then be undertaken to quantify the environmental levels and to construct maps of the spatial variations.

The characteristics of aerial gamma spectrometry are very favourable for measuring radiocaesium. The depth range of investigation is closely matched to that used in conventional analysis of soil samples, and to the use of hand held monitors at ground level. The speed and efficiency of aerial monitoring greatly exceeds the alternative approaches to the extent that it is almost impossible to conceive of total survey of any significant area using ground based methods. Against this it should be noted that the sensitivity and discriminating power of the prototype system used in this study do not as yet match those achievable by laboratory based high-resolution gamma spectrometry. Although technical improvements in this regard can be envisaged in the future there will still be a place for follow up studies based on conventional methods.

3. SURVEY DETAILS.

3.1 The survey area

The survey was based in the part of West Cumbria still subject to livestock movement restrictions in 1988, and indicated in outline in figure 1. It is bounded by roads, rivers or lakes in all directions, forming a somewhat irregular shape. The requirements of the survey were to attempt to achieve a contiguous coverage with a spatial resolution of 500m over as much of this region as possible within the available time. A Bell Jet Ranger helicopter was chartered at short notice from Gleneagle helicopters in Edinburgh, and a temporary field base was set up at Wasdale Head between the 22nd August and the 3rd September. Fuel was transported to the field base by road.

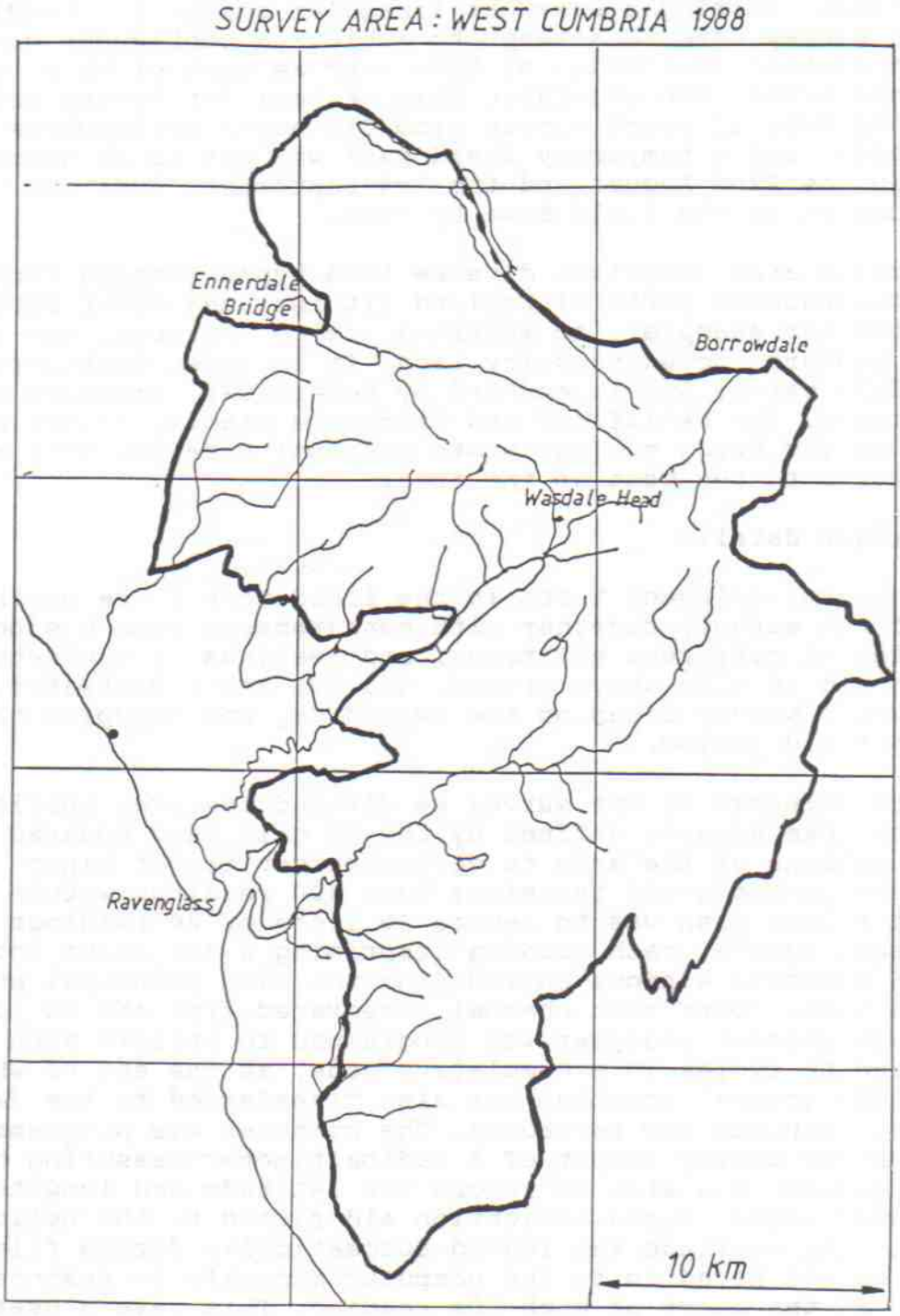
The survey area comprises diverse land types ranging from the most mountainous parts of England (it includes Great Gable and Sca Fell for example), to moorland, fells, forests, and some low lying pasture including dairy land. It includes Wastwater, Ennerdale water, and is bounded by Loweswater, Crummock water and Buttermere. The Sellafield and Windscale plants, Calder Hall reactors and Drigg nuclear waste disposal site are only a few kilometres to the west of the area.

3.2 Flight details

Preliminary equipment tests in the field took place on the first day of the survey, together with measurements over a single location at different altitudes, and readings of the detector background at 650m above ground, and 30m above Wastwater. The systematic survey began on the second day and occupied the rest of the field period.

For the purposes of the survey we divided the area initially into 10km by 10km squares defined by the OS grid, and squared off the rough outline of the area to define target flight lines. A complete square would therefore have 400 readings within it. The target flight plan was to record 20 lines of 20 readings each from each square, each reading comprising a 30s count integrated into 6 spectral windows surrounding the five principal photopeaks plus a total count rate channel integrated from 450 to 3000 keV. The multichannel analyser was programmed to perform such measurement cycles in a cumulative mode, at the end of which the full 1024 channel spectrum was also transferred to the data logging computer for recording. The computer was programmed to monitor the analog output of a radioaltimeter measuring height above ground, and also to record the latitude and longitude from a Navstar AD2000 Decca navigation aid fitted to the helicopter. Whereas the altitude was logged automatically during flight, the position was keyed in to the computer manually in response to a prompt at the start of each 30s reading. This gave a useful timing mark for pilot and navigator. Each data entry was labelled

FIGURE 1. OUTLINE OF THE SURVEY AREA : WEST CUMBRIA 1988



in the computer with the time of collection, the positions at the start and end of each measurement and the mid point. The potassium-40 photopeak at 1.46 MeV was monitored continuously to check the gain stability of the spectrometer, which was kept within about +-20 keV of the target throughout the survey.

To keep a track of navigation and to determine the accuracy of the Decca system, which was unknown in deep valleys, the pilot and navigator marked off each point on a 1:50000 OS map as it was recorded. A record of the actual tracks flown was thus produced. We observed that the Decca navigation system was accurate within its specification (+-30-50m) in the southern part of the grid (on OS sheet SD). Longitude in the northern areas (OS sheet NY) appeared to move systematically further west compared with the map, so that at Wasdale Head there was an error of approximately 100 m rising to 200-300m close to Lamplugh. We are inclined to attribute this effect to the distortions of the OS grid, but in any case felt that it was not necessary to correct for it given the survey resolution of 500m.

A system of data labelling was adopted whereby each 10km x 10km square was named by its 2 figure OS grid reference. For example the square with coordinate NY100100 as its bottom left hand corner was called NY11. All data recorded were given filenames derived from the square from which they were taken combined with an alphabetic code to differentiate between each line of measurements, a numerical code to define the data index number and a file extension to separate raw counts from full spectra. Examples would be that the file named NY11C0011.DAT would contain the 11th reading from line C of square NY11, and the corresponding spectrum would be placed in a file called NY11C001.SPC. These names were assigned automatically by the computer during flight.

Flights of up to 2-3 hours duration were made twice, and on occasions thrice per day subject to weather and pilot's permitted hours during the survey period. Despite Met Office predictions based on average wind and cloud base which led us to hope that more than 60% of daylight hours would be available for survey, the fortnight spent in Cumbria corresponded to a period of unseasonably poor weather. We were plagued by winds of over 50 knots, and cloud base beneath 2000 feet for much of the time, neither of which gave us access to some parts of the survey zone. The flight plans were adapted in such a manner as to collect data from contiguous blocks of the most mountainous terrain which could be surveyed safely on each day, saving the flat ground for days where low cloud base or high winds made these the only available areas. Some of the work was conducted in winds up to 35 knots. Under these circumstances we were quite pleased to return with a data set of over 1800 readings from an area of roughly 45000 hectares, although this still leaves a portion of the restricted area unsurveyed. Obviously the criteria which we used in deciding whether or not to fly in given conditions, while

balancing the expenditure of limited project funds against the quality of data expected, are quite different from those which would apply to the use of aerial radiometrics in an emergency. The helicopter was used for 36 hours in the course of this work. On the very last day we overflew a feature in the Esk valley (see section 5.3) at 30m altitude, partly to investigate an exceptionally high reading, and partly to test the predicted reduction of circle of investigation which could be achieved at this altitude for even higher resolution survey.

3.3 Preliminary data handling

At the end of each flight all data recorded on hard disc in the flight computer were copied onto 3.5" floppy discs and then taken to a data reduction computer kept in the hotel which served as our operations base. The data were transferred to the hard disc on this second computer, and immediately copied onto a duplicate floppy disc for backup purposes before undergoing any transformations. Both sets of floppy discs were kept in separate locations as a precaution against any data loss. This system of quadruple backup may seem excessively cautious, but we felt that it was warranted by the efforts taken to acquire the results. Production of backup data from a day's flying took up to 3 hours.

The first stage of data reduction comprised formation of summary files containing the main count data for each string of readings. Visual inspection of the summary files was used as the primary means of checking the data quality, and confirming the navigational entries. Quality assurance was applied at this stage by checking the full data files of any inconsistent data entries, to confirm the validity of the transmission from analyser to computer. Miskeyed navigational coordinates were corrected by interpolating the flight line in conjunction with the navigator's maps. We felt that it was important to do this during the field work period, although it kept us fully occupied when not in the air.

Summary files from each grid square were linked together to form area summaries at which stage the background count rates recorded at high altitude and over water (ie the detector and aircraft background) were subtracted to form a record of the net counts. The focus of all field based data reduction was to ensure the security and quality of the primary data archive, however we were also able to prepare a colour bit-mapped representation of the net count data which showed the relative positions of peak deposition by the end of the second week's survey. The picture revealed at this stage was remarkably similar to the deposition pattern produced in our final maps. Examples of each type of data file are shown in the technical annexe, together with a full set of spectra.

4. CALIBRATION

4.1 The calibration method

The relative deposition pattern can be readily observed simply by looking at the spatial variations of net count rate. Nevertheless calibration to equivalent deposition per unit area provides a far more useful, and easily interpreted, data set and was certainly one of the project aims.

There are three possible approaches to this problem. One is to calculate the detector response from first principles. As explained above this is a major undertaking, and was certainly beyond the scope of this project. While the primary spectral response of the detector can be evaluated for flat topography using fairly straightforward expressions, calculation of the scattered spectral response under realistic environmental conditions involves formidable Monte-Carlo simulation of the gamma transport. The excellent study by Lovborg & Kirkegaard (1975) illustrates the scale of the task, but still does not deal with anthropogenic nuclides, layered sources or undulating topography.

The second approach would be based on a set of individual large area (25m diameter) concrete calibration pads, preferably at the edge of a runway, individually doped with known concentrations of each nuclide of interest. This is analogous to the technique recommended by IAEA (1976) for calibrating spectrometers for uranium prospection. It is not practical for two reasons. There are no facilities of this type in the UK at present, although there are many elsewhere (Grasty,1976,1987, Lovborg,1983,1984). Furthermore although calibration pads for K,U and Th analysis have been prepared we do not believe that any have been made with deliberate additions of ^{137}Cs or ^{134}Cs.

The third approach is to base the calibration on a combination of spectral characteristics measured from laboratory sources, and data from selected ground samples analysed using high resolution gamma spectrometry. We believe that this composite approach is the most practical option in the short term in the UK, however it would be wrong to infer from this that the data cannot be interpreted without ground measurements or that this is the only way to tackle the problem.

The Swedish national survey (Linden and Mellander,1986), was calibrated approximately by direct regression analysis between counts from the ^{134}Cs energy band and a set of some 30 ground analyses from carefully chosen locations expressed as kBq/m^2. As far as we know this did not include an attempt to account for other spectral contributions to the energy window; perhaps this would have been an unnecessary refinement for an emergency survey. In our own work so far we have divide the calibration process into three stages. The first stage comprises pre-

processing to reduce the effects of spectral interference from channel to channel, and to make first order corrections for deviations from the nominal survey altitude. The second stage comprises an analysis of the relationship between pre-processed counts and ground data to determine the calibration equations. In the third stage these calibration equations are used to convert pre-processed counts to calibrated deposition levels.

The strengths of this overall approach are that it is adaptive to either extension of the pre-processing methods (which inevitably involve approximations and a priori interpretations), or to extension of the ground data. Providing the approach is followed rigorously the calibration of an individual reading should depend mainly on the quality of the field data and the absolute calibration of the ground measurements.

Our original Scottish ground based data set was used to produce a working conversion to kBq/m^2, although the pre-processing steps were extended as described below. It is this calibration which forms the basis of the maps presented here, which were prepared in September and October. The status of this calibration is described in section 4.5 below. Comparisons between deposition levels estimated from the aerial survey and other measurements by different methods are described in section 5.4.

4.2 Stripping Spectral Overlap

Although the photopeaks from gamma rays occur at extremely well defined energies, the effective energies for photopeak pulses from the detector are spread by its finite resolution. For this reason the counts due to each nuclide were recovered by integrating the pulse height spectra over set windows surrounding each peak. The windows used in this study were 570-768 keV (137 Cs), 708-861 keV (134 Cs), 1317-1623 keV (40 K), 1623-1908 keV (214 Bi) and 2337-2883 keV (208 Tl). The net count rates recorded in this way after subtraction of the measured detector include some spectral interferences from other nuclides. These are due to overlap of minor photopeaks from the individual gamma spectra of each nuclide, and to the build up of scattered radiation contributions to the lower energy regions. Where any single component dominates the spectrum, the signal within its main window should be a linear function of gamma intensity. This is not the general case however, and some form of spectral deconvolution is needed to separate components which vary independently of each other.

We have approached the general problem in a manner analogous to that used conventionally in geological aerial surveys, and in the analysis of spectra from whole body monitoring. Coefficients describing the fraction of each nuclide's contribution to every analysis window were determined experimentally at SURRC using a combination of pure radiation sources. 137-Cs and 134-Cs spectra were recorded using point sources and solutions, the high energy

part of the uranium series spectrum was approximated using a Ra-226 source, thorium series activity represented by an equilibrated thorium nitrate, and potassium recorded using a set of pure potassium salts. These experiments were performed to a high statistical precision (better than 0.5%) in March 1988, and repeated before the Cumbrian survey in August. The detector characteristics had not changed markedly over this period. Table 1 shows the coefficients determined.

Table 1. Fractional interferences determined using laboratory sources (August 1988).

Nuclide	Channel	1	2	3	4	5
137-Cs	1	1	0.18			
134-Cs	2	1.57	1	0.10		
40-K	3	0.229	0.17	1	0	
214-Bi (Ra)	4	3.17	1.13	1.04	1	0.09
208-Tl (Th)	5	2.63	1.63	0.62	0.36	1

There are a number of ways of applying these components to spectral deconvolution. The Health Physics group at SURRC have been using an iterative numerical method to deal with the general problem of spectral overlap in scintillation detectors for many years. Common practice in the aerial radiometric literature is to approximate the (3 channel:U,Th,K) system by the major (ie below diagonal) elements in which case the stripping procedure reduces to a set of simple linear equations. An extension of this latter approach to the 5 channel case was sufficient for our March feasibility study. In September this was extended to take the full mutual effect of the two caesium nuclides into account and to also account for the interaction between 214-Bi and 208-Tl, whose scattered radiation is a significant contributor to the lower energy channels. The resulting linear algorithm was used to calculate the stripped data used for the working calibration, as presented in the succeeding sections.

An alternative procedure was proposed at the end of December (Day,pers comm). In this case application of the inverse of the stripping matrix to the vector describing raw counts produces a transformed vector of stripped counts. We have investigated this approach also, which is readily programmed, and an accurate model. The absolute values of stripped counts in the first three channels change slightly (eg 10-20% for 137-Cs) compared with the procedure originally adopted, mainly due to redistribution of the Compton scattered contribution from 40-K to 137-Cs. Calibrated results are not very sensitive to such changes, since the

relationship between stripped counts and deposition per unit area is modified correspondingly. For example reading NY01C001 was originally calibrated to 21.7,4.8,161,7.6,11.6 kBq m^{-2} for channels 1-5 respectively. These values would become 21.3,4.7,163,7.6, and 11.6 kBq m^{-2} if the full matrix approach was applied. These differences are certainly insignificant in the context of the precision of the data.

The major sources of uncertainty in absolute values of stripped counts are due to the statistical limits of the raw counting data, and to the less readily quantified effects of approximating radiation fields in the environment by close coupled laboratory sources. The underlying assumption that the interferences are independent of altitude is itself an approximation. Further investigation of the relationship between laboratory and field spectra in different geometries would be valuable here. Fortunately the absolute values are of passing interest at this stage, since pre-processing operations are applied equally to all data including the calibration set.

4.3 The effect of altitude variations

Deviations from constant altitude are an inevitable feature of any flight under real field conditions, and do of course modulate the response of an aerial detector. The effects are small relative to measurement statistics for deviations of +-20m, which is achievable over slowly undulating terrain. However ground clearance fluctuations in mountainous terrain are inevitably greater than this, especially when imposing tight restraints on the ground speed and positioning of the aircraft. In a number of cases in the Cumbrian survey the altitude varied from less than 100 feet to over 1000 feet when for example just passing over a glaciated ridge in the landscape across the top of narrow ravine. Effects such as this produce easily detectable artefacts in the data set which we did not wish to generate spurious contour features in the mapping phase.

After investigating a number of possible procedures for correcting altitude variations we decided to filter the data before calibration using a set of linear equations deduced from regression analysis of count rates against altitude. At the present stage we do not have sufficient high precision altitude reference data to justify fitting a more physically meaningful correction model to each channel. Ultimately exponential integral functions are likely to be used.

The corrections have a minimal effect on measurements recorded close to the survey target height of 100m, but damp out the effects of gross deviations from these heights. For data recorded between 30 and 200m the residual effect of altitude variations is less than 20%. Table 2 gives the coefficients for the altitude corrections adopted. They are applied to the voltage reading (V) taken from the radioaltimeter in the helicopter and which is

approximately equivalent to 100 ft per volt. This reading is tabulated along with calibrated data in the technical annexe, which enables the importance of this correction to be judged in any individual reading.

Table 2. Linear altitude corrections

C' = C/ (a+b.V) where C' = altitude corrected count, C= stripped count , V= radioaltimeter signal

Channel	a	b
1	1.88	-0.26
2	1.62	-0.172
3	1.45	-0.135
4	1.215	-0.065
5	1.29	-0.087
6	1.48	-0.143

4.4 Conversion to deposition per unit area

The conversion of the data set to kBq/m^2 for channels 1 to 5 and to 2 pi gamma dose rate in mGy/a for the total flux channel (ch 6) was accomplished using our March 1988 working calibration determined in South West Scotland. The focus of this calibration was 137-Cs, and flights were deliberated planned to overfly 10 locations which had been surveyed from the ground and for which deposition levels ranged from below 5 kBq/m^2 to above 30 kBq/m2. The analyses were performed by Paul MacDonald at SURRC in 1987 using a combination of portable scintillation counter measurements in the field and accurate high resolution gamma spectrometry in the laboratory. The high resolution measurements were made using dried, homogenised soil cores analysed in a high precision cylindrical geometry on a 130 ml intrinsic Germanium detector. The detector calibration was derived from an absolute efficiency curve produced using multiple tracer standards loaded onto a soil matrix recovered from a sealed archaeological deposit and shown to be free from modern nuclides. Cross checks with IAEA reference materials have confirmed standards traceability at an international level. Deposition per unit area was calculated from the soil cores using bulk soil characteristics measured before analysis. Absolute accuracy for 137Cs and 134Cs and 40K is better than +-5%, for 214Bi and 208Tl it is between 5 and 10%.

The relationships between aerial and ground data for these sites have been investigated in detail both in March 1988 and, again having changed the stripping procedure in September 1988. For both Cs nuclides the range of absolute deposition is large

compared with measurement errors and the detector sensitivity can be estimated with reasonable precision using regression analysis. We have investigated various error structures including major axis regression and conclude that although both ground and aerial data have uncertainties the stochastic errors in the aerial data are the dominant source of variance. Regression with this as the dependent variable is thus appropriate. The correlation coefficients for 137Cs and 134Cs are 0.973 and 0.864 respectively indicating that most of the variation in the data sets are accounted for by the linear relationship between aerial count rates and deposition in kBq/m2. There are small but significant intercepts which have been retained. For the natural nuclides the range is small compared with the measurement precision resulting in lower correlation coefficients. In these cases we do not believe that regression lines form the basis for meaningful sensitivity determination and have instead calculated the mean ratio of deposition per unit count for these channels. The calibration equations shown below in table 3 apply to stripped data regardless of whether it has been corrected for altitude variations.

Table 3. Conversion between stripped counts and deposition.

D = a.C +b where D = deposition in kBq/m2, C= 30s stripped count

Channel	a	b
1	0.0106+-0.0003	3.5+-0.22
2	0.0201+-0.0017	-2.2+-0.48
3	0.28	-
4	0.55	-
5	0.55	-

The validity of this calibration depends on the vertical distribution of the activity in the environmental media being surveyed. The underlying assumption then is that the vertical distribution of nuclides in the Solway in March 1988, and overall environmental conditions are generally comparable with those in Cumbria 6 months later. Subject to this the calibration is traceable to international standards.

4.5 Error assessment and interpretation of results

We take the view that survey data should be used to construct regional deposition maps by image processing and surface fitting methods. Nevertheless there are also cases where the measured values in given locations are of interest in their own right, and in this context proper interpretation must be based on a general

understanding of the error structure of an individual result.

Aerial determinations like all radiation measurements are subject to stochastic variations due to counting statistics. In this case the propagation of Poisson errors through the stripping procedure must be taken into account. We have simulated the error structure and estimated these terms for the whole data set. The minimum detectable levels for both 137-Cs and 134-Cs are of the order of 2 kBq/m^2, precision depending both on the levels of the other nuclides forming the background count in any location and on the caesium reading. As a general guide most of the 137Cs results carry Poisson errors in the 5-15% region, 134-Cs is less well detected, mainly due to lower levels in the environment. Precision in this case is more like 10-25%. The precision of averaged data should of course improve with the reciprocal square root of the number of data points considered. When examining individual results with these levels of statistical uncertainty it should be remembered that a data set of 1800 measurements is sufficiently large for events with a low probability to express themselves. There should be several observations out to 6 sigma from any mean.

The accuracy of the calibrated data for these two nuclides is fairly well matched to their individual precision. For the majority of readings the uncertainties of altitude correction are not the error limiting term. In turning to unquantified perturbing factors the main effects which spring to mind are variations in the solid angle subtended to the detector by the ground, the effects of a variable water table, and variations in the vertical distribution of the nuclides. Significant increases in solid angle might be expected when flying along the bottom of a steep gulley only a few hundred metres wide, and similarly reduced solid angles would occur when flying along the lines of narrow glacial ridges. There certainly are locations like these in some parts of the survey zone, but our impression of the data set is that the effect is not as pronounced as might be feared. There is a need for a separate study of selected topographic features in conjunction with ground analyses to elucidate this effect more clearly. For most readings in the set it would be reasonable to expect overall accuracy to be at least comparable with the statistical precision of individual readings.

When interpreting the data set it must be born in mind that the precision of individual results is of the order of +-10-20% at least. The precision of area deposition estimates can be improved by spatial averaging, but this may not necessarily be matched by a corresponding accuracy. The readings are converted to activity per unit area on the basis of having an equivalent vertical distribution to that in the Solway Firth region in SW Scotland. Furthermore the overall levels are expressed relative to analyses from soil cores from this region. For comparison with other readings, they refer to the total deposition integrated over the full soil/rock core depth to at least 30 cm.

5.RESULTS

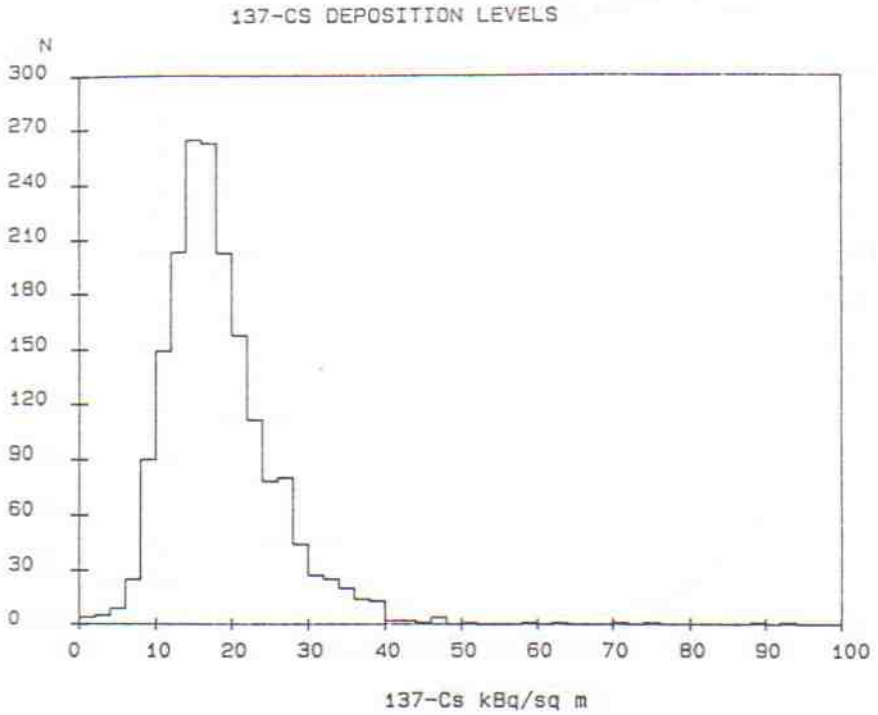
5.1 Overview of results

Figures 2 and 3 show the histograms of deposition level and measurement precision for the two caesium nuclides. As can be seen 137-Cs is detected with a modal value of roughly 15000 Bq/m^2. There are very few observations with levels below 5000 or above 50000 Bq/m^2, and the general indications are that little information has been lost beneath the minimum detectable level. There are slight hints of modalism in the histogram, for example there is a cluster of values in the 25000-30000 region and an edge at 40000. These readings have yet to be isolated to examine their common factor if any. Notable exceptions to this were two areas on the edge of the survey zone, which are discussed under 5.2 and 5.3 below.

134-Cs shows a long tailed distribution with a modal value of around 5000 Bq/m^2, and readings ranging up to 15000-20000 Bq/m^2. The half life of this nuclide is 2.08 years, and already the signs are that a significant number of readings have fallen below the minimum detectable level. The importance of 134-Cs from a diagnostic point of view is that it constituted roughly 60% of the 137-Cs deposited from the Chernobyl accident, whereas aged radiocaesium from weapons testing, or pollution from Sellafield is either free from or considerably depleted in this nuclide. The overall levels of 134-Cs appear to be broadly consistent with the aged Chernobyl ratio of 0.29 pertinent to the survey zone. Therefore the general conclusion from this survey is to confirm that the major part of the Cs activity has indeed arrived in 1986. The precision of individual 134-Cs readings makes it doubtful whether quantitative evaluation of the proportions of pre-and post Chernobyl caesium can be based on these data. However it may be noted that fallout levels from the atomic weapons testing period are expected to be below 5000 Bq m^{-2} , in all but the wettest parts of the UK, and we have encountered locations in Western Scotland where levels below this have been measured.

For comparison with the radiocaesium levels it might be helpful to note that natural potassium-40 levels vary up to several hundred kBq m^{-2}, although with only 11% of disintegrations producing a gamma ray the external radiation contribution is small. Similarly 214-Bi and 208-Tl have levels from 10-20 kBq m^{-2}.

FIGURE 2 137-CS OVERALL LEVELS



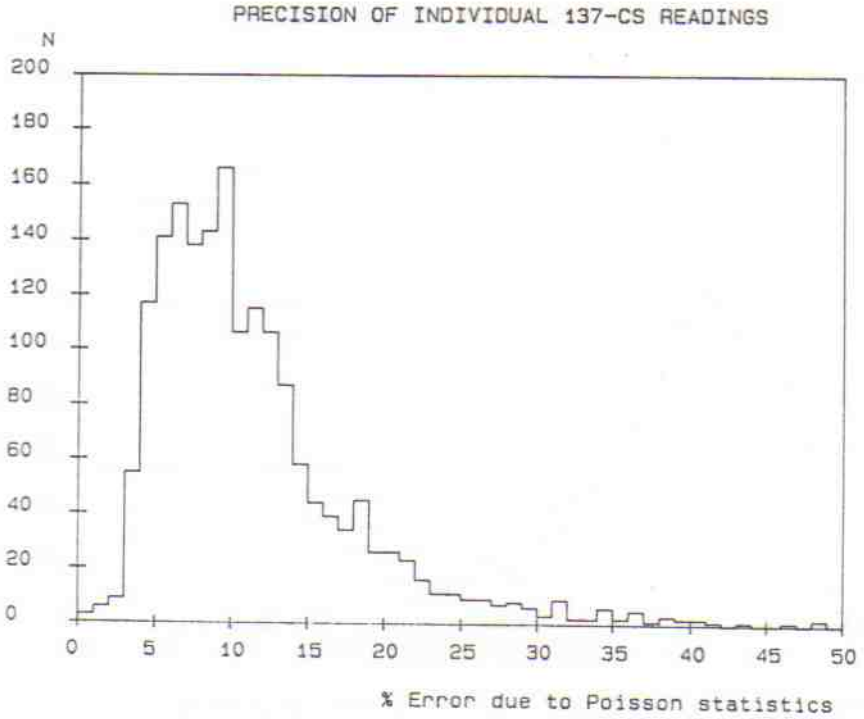
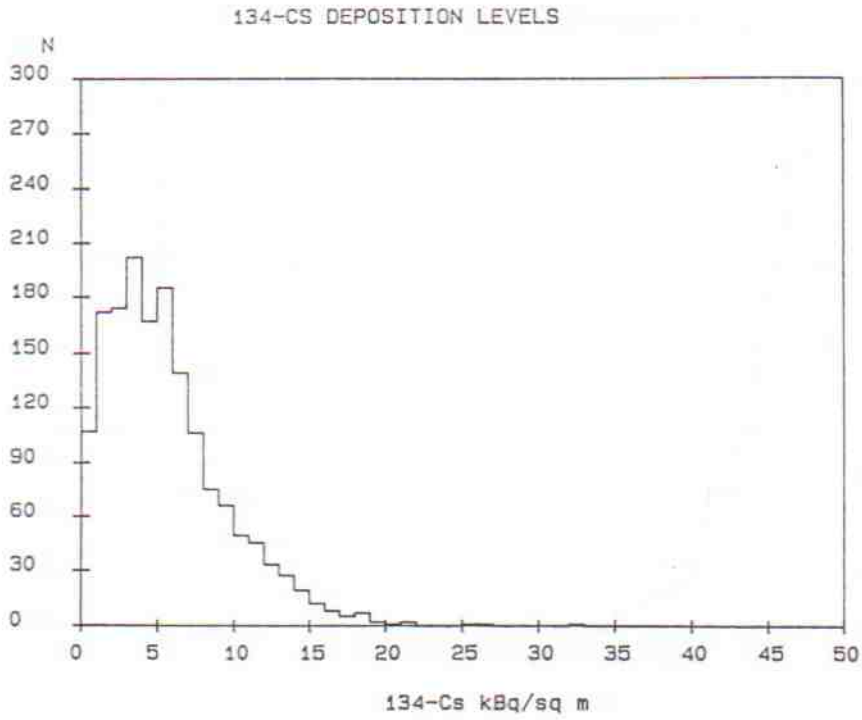
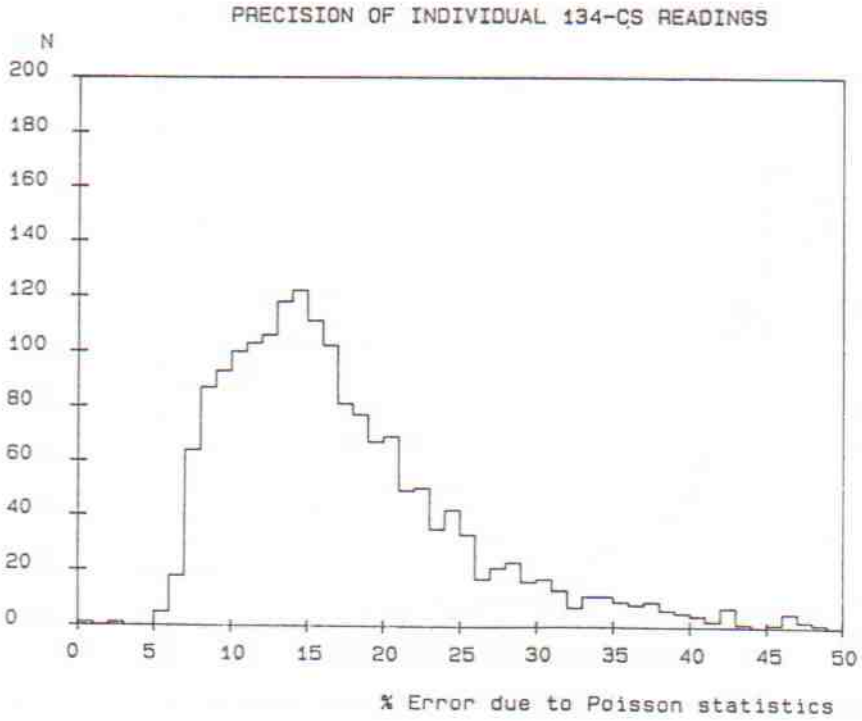


FIGURE 3 134-CS OVERALL LEVELS





5.2 Contour maps

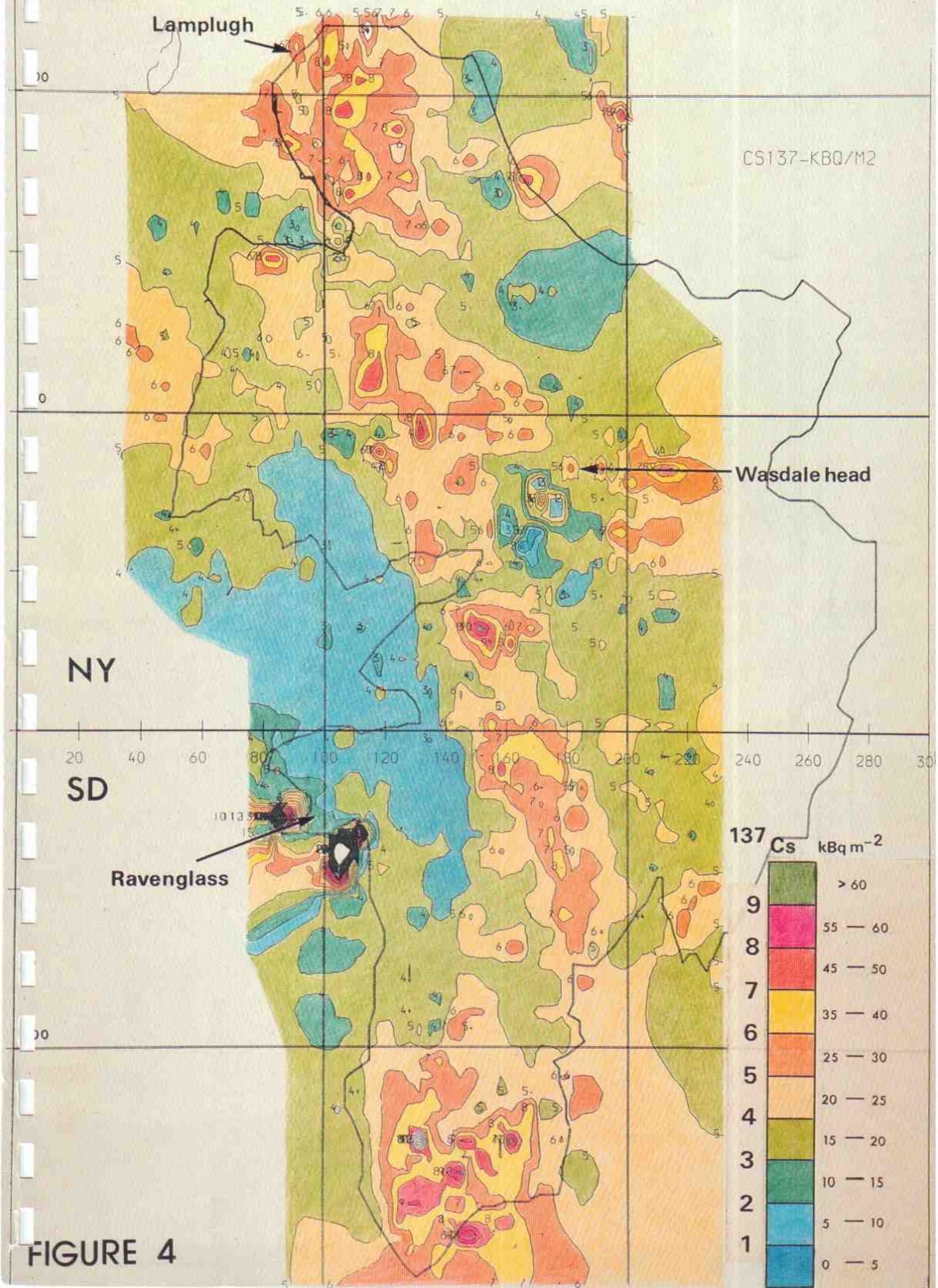
The spatial variations of the radiation fields are most revealing and are represented here by a series of contour maps produced using the Glasgow University mainframe computer. The calibrated data set was transferred and validated on this machine, and then used to produce a set of master maps on a scale of 1:50000. These included a set of maps indicating the positions and levels of the raw measurements, which was lodged with MAFF early in October 1988, and serves as a reference source for further studies.

Contouring was accomplished using a series of Ghost-80 routines called from fortran programs. The initial stage is to re-grid the data onto a perfect cartesian network based on interpolation of a two dimensional surface fitted to the points. This representation is then used to define the contours for computer mapping. With a data set of over 1800 points there is no question of not being able to interpolate the re-gridded surface in a meaningful manner. Comparison of the master charts of raw data and the contoured surfaces has confirmed that the contours bear a very reasonable relation to the data.

A reduced size set of contour maps has also been coloured up and provides a clear impression of the results. These maps are presented here in figures 4-9 for all channels. As a general rule the coloured areas are those for which the contours interpolate meaningful measurements. However there has been some artistic license here and some of the features outside the south-eastern boundary of the restricted area are extrapolations which still need to be surveyed to assess the levels. Used in conjunction with OS Landranger maps sheets 89 and 96, it should be easy to deduce the locations of features in these maps.

The main point about maps from aerial surveys is that they show where peak activity levels occur in a far more direct manner than tables of readings. Turning to the problem of Chernobyl fallout three features are immediately evident. Firstly peak levels of 137-Cs occur in a spine across the centre of the area and goes right to the edges of the survey zone. Secondly the 134-Cs map suggests that the central areas rather than the northern or southern extremities of this distribution are most likely to be dominated by Chernobyl caesium. Thirdly examination of the potassium-40 distribution shows evidence of severe potassium depletion in parts of the area of highest contamination. It is quite likely that the juxtaposition of these three strands of evidence has a direct bearing on the identification of critical areas for transfer of caesium to sheep.

A final comment here is that the survey has not reached the limits of the excess caesium distribution, which, regardless of its agronomic relevance, certainly extends beyond the restricted area.


Lamplugh
CS137-KBQ/M2
Wasdale head
NY
SD
20
40
60
80
100
120
140
160
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200
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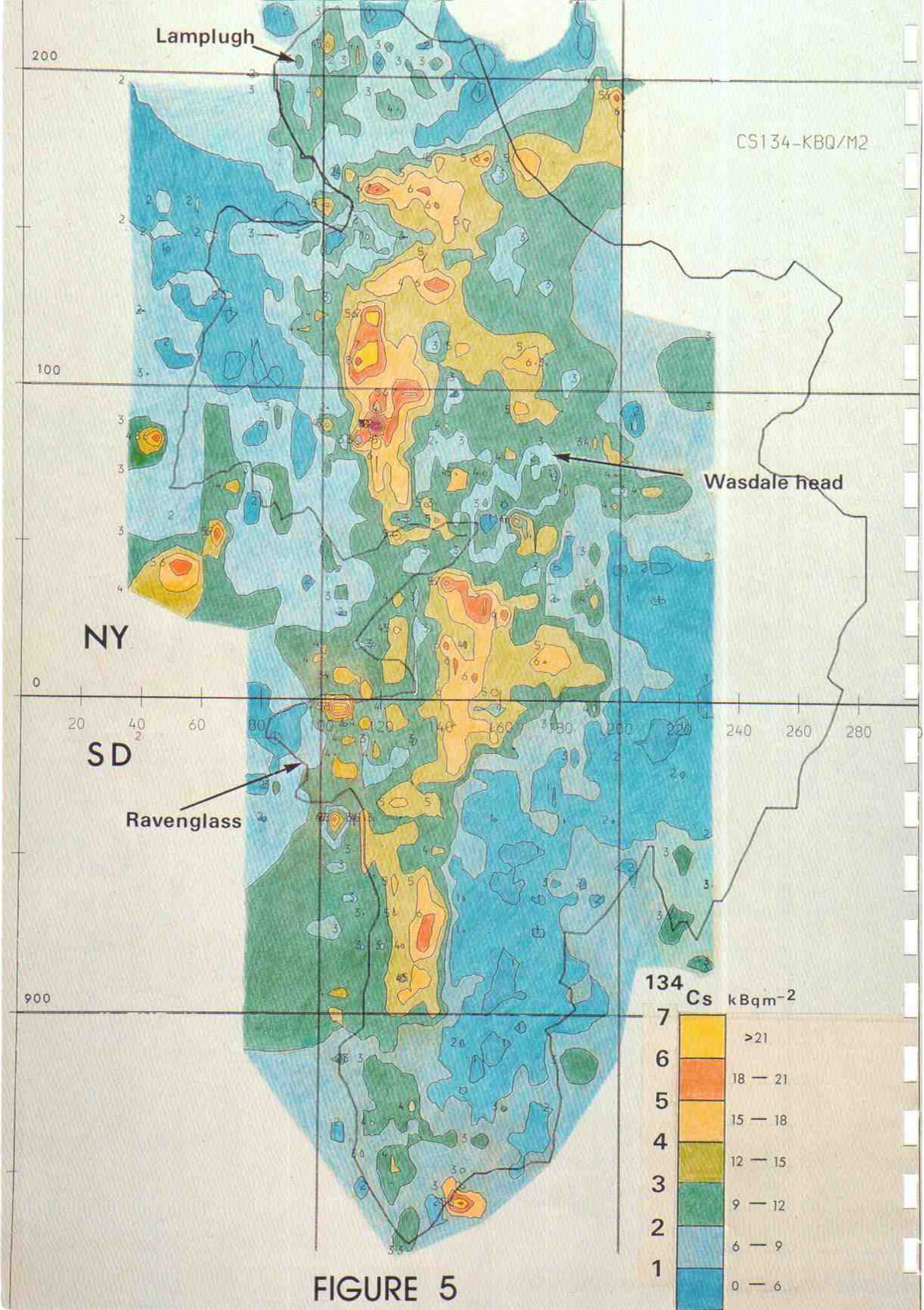
240
260
280
Ravenglass
137Cs kBq m-2
9
8
7
6
5
4
3
2
1
> 60
55 — 60
45 — 50
35 — 40
25 — 30
20 — 25
15 — 20
10 — 15
5 — 10
0 — 5

FIGURE 4


Lamplugh
CS134-KBQ/M2
Wasdale head
Ravenglass
NY
SD
200
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900
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100
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140
160
180
200
220
240
260
280
134 Cs kBqm-2
7
6
5
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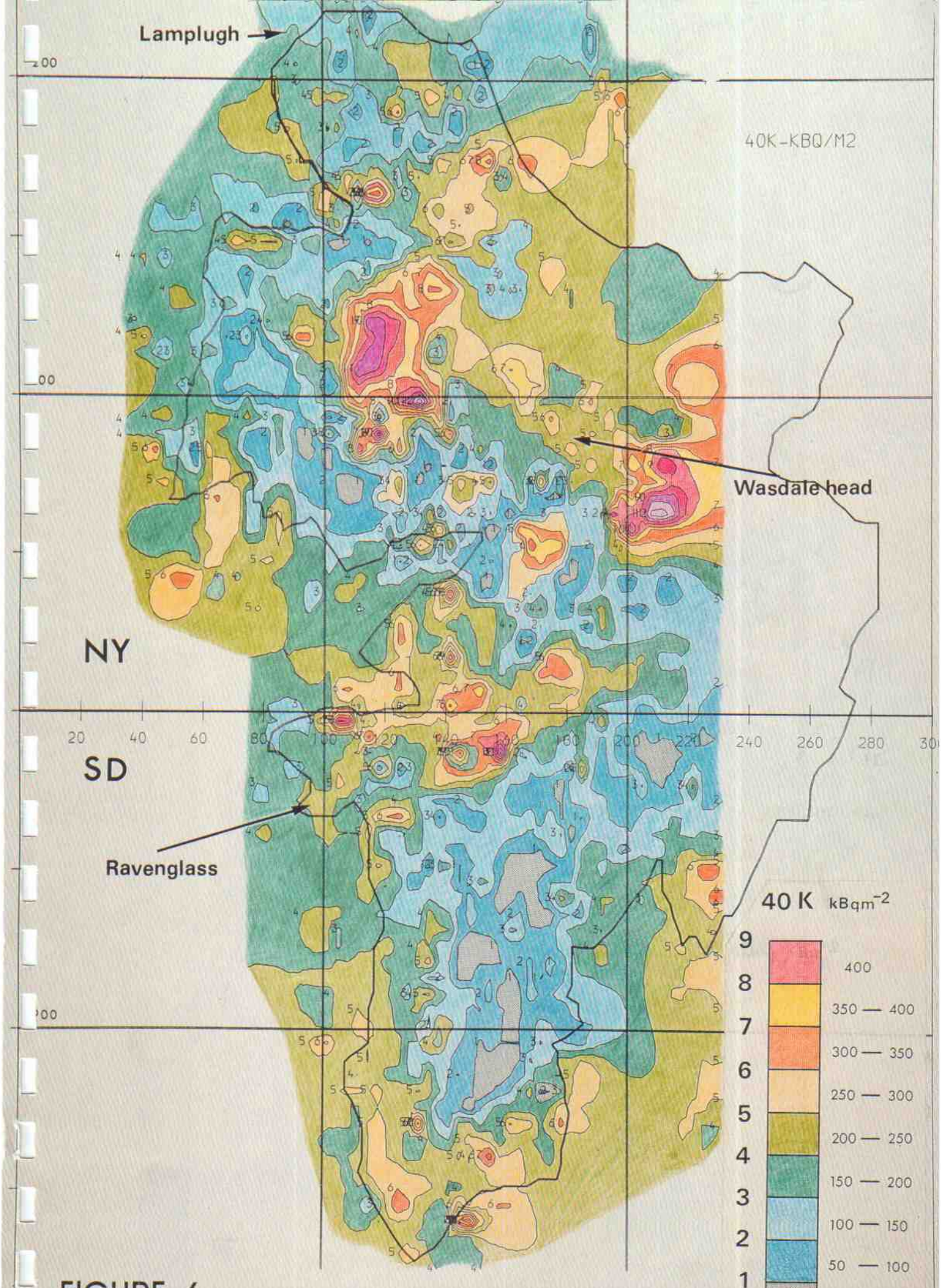
1
>21
18 — 21
15 — 18
12 — 15
9 — 12
6 — 9
0 — 6

FIGURE 5


Lamplugh
40K-KBQ/M2
Wasdale head
NY
SD
Ravenglass
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200
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240
260
280
300
40 K kBqm^{-2}
9
8
7
6
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4
3
2
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250 — 300
200 — 250
150 — 200
100 — 150
50 — 100

FIGURE 6

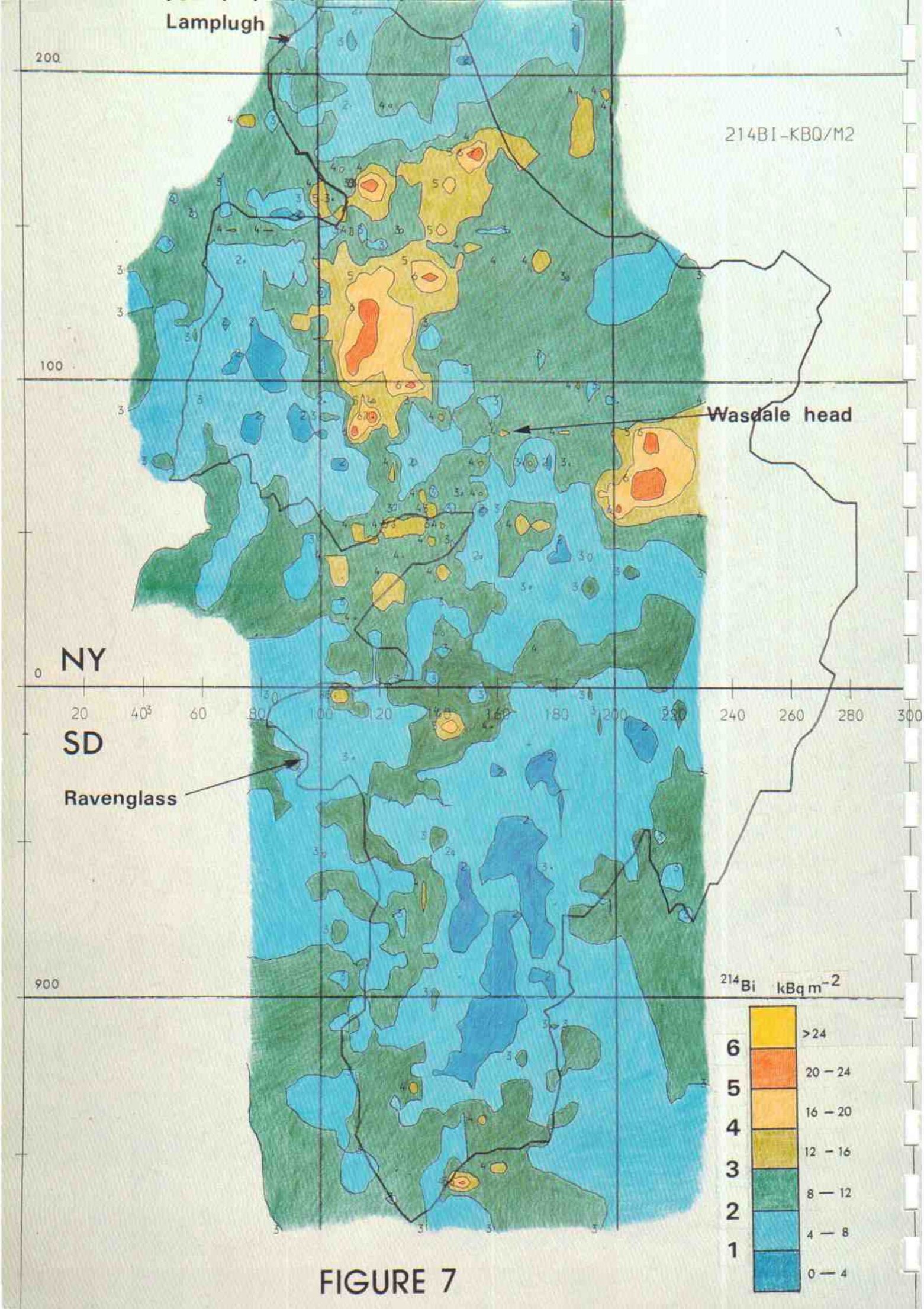
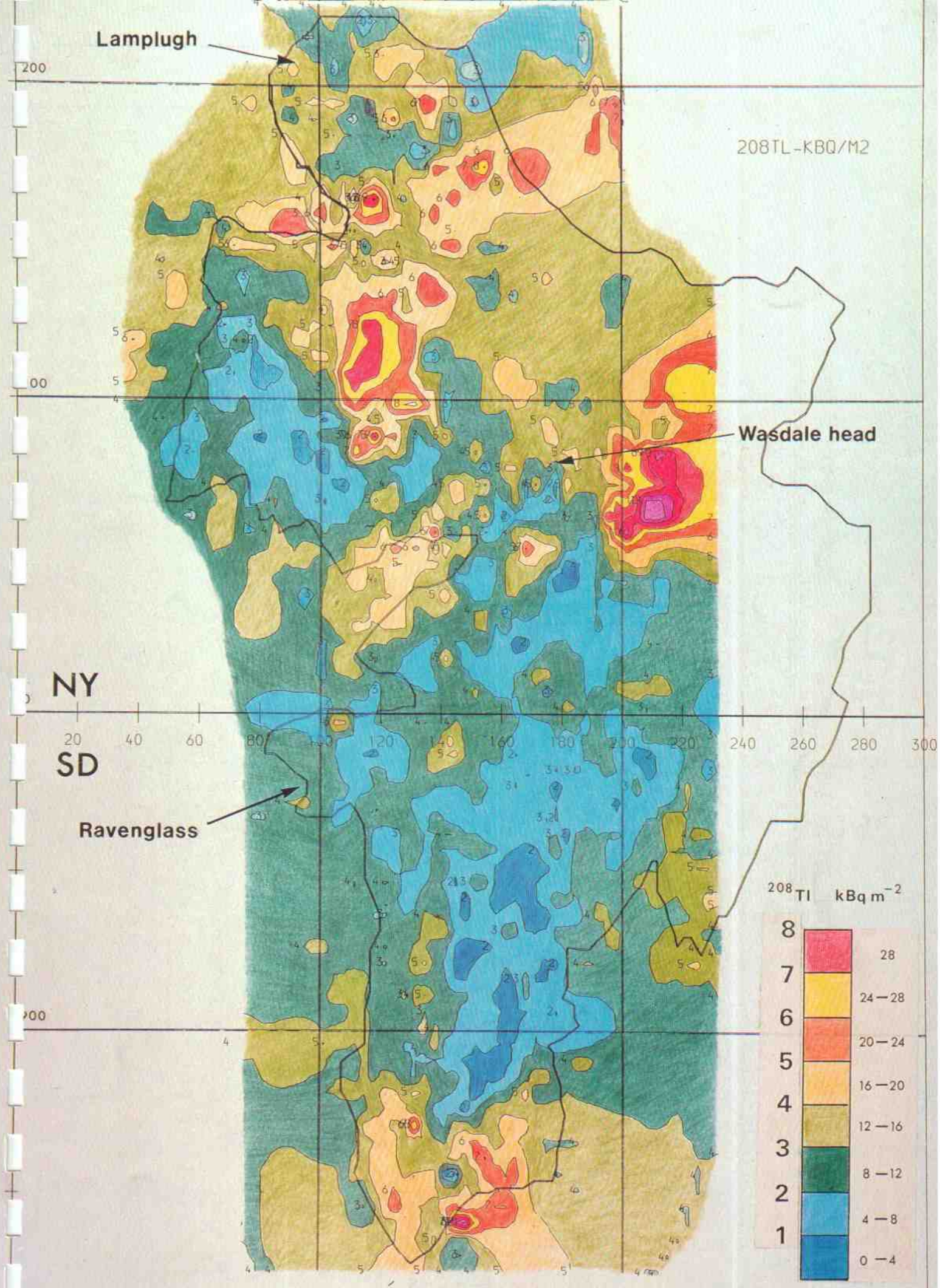

Lamplugh
200
214BI-KBQ/M2
100
Wasdale head
NY
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
SD
Ravenglass
900
214Bi kBq m-2
6
5
4
3
2
1
>24
20 – 24
16 – 20
12 – 16
8 — 12
4 — 8
0 — 4

FIGURE 7


Lamplugh
208TL-KBQ/M2
Wasdale head
NY
SD
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^{208}Tl kBq m^{-2}
8
7
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4
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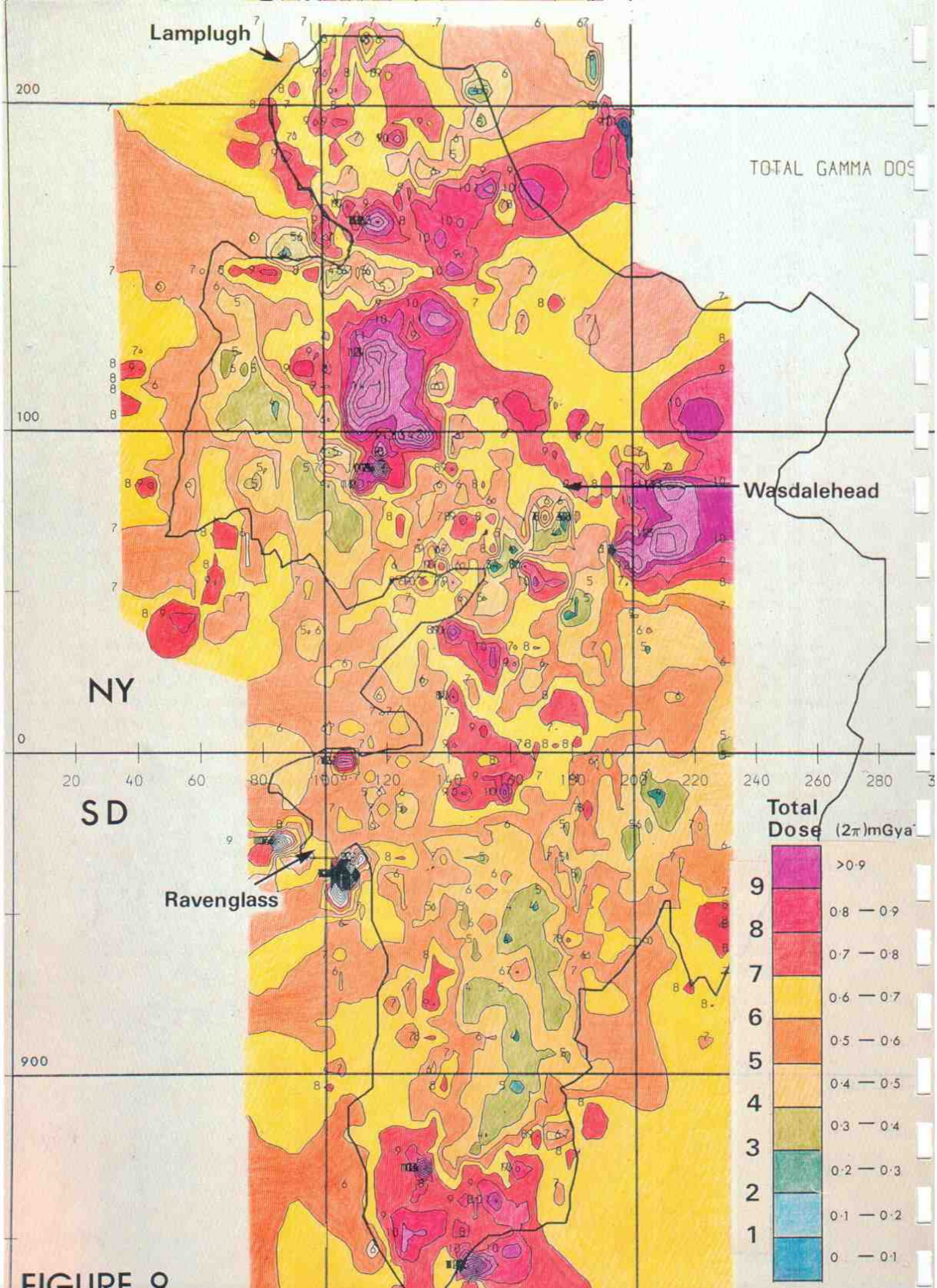
24 — 28
20 — 24
16 — 20
12 — 16
8 — 12
4 — 8
0 — 4

FIGURE 8


Lamplugh
TOTAL GAMMA DOS
Wasdalehead
NY
SD
Ravenglass
Total Dose (2π)mGya
>0·9
0·8 — 0·9
0·7 — 0·8
0·6 — 0·7
0·5 — 0·6
0·4 — 0·5
0·3 — 0·4
0·2 — 0·3
0·1 — 0·2
0 — 0·1
9
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7
6
5
4
3
2
1
200
100
0
900
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40
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100
120
140
160
180
200
220
240
260
280

FIGURE 8

5.3 Low altitude survey of the Muncaster feature

Two anomalous features can be seen close to Ravenglass in the 137-Cs plot. Levels of over 150000 Bq m^{-2} and 300000 Bq m^{-2} were encountered in a single transect over the Ravenglass estuary, and in a loop in the river Esk some 3.5 km inland close to Muncaster Bridge respectively. These features are both due to the reprocessing activities at Sellafield, and outwith the focus of this study. The contamination of the Ravenglass estuary is well documented and forms one of the critical exposure paths monitored routinely by BNFL (eg BNFL,1987).

However the inland feature at Muncaster was more problematic and occurs in an area to which the public has access. The aerial data from line SD19B produced a single reading with 5-10 times the usual background levels. Penetration of these elevated signals into surrounding readings was very slight. The possibility that this was a point source of radiation was investigated in view of the potential radiation hazard. On the final day three low altitude passes over the area (at 30m above ground) successfully located the feature, and together with a ground based follow up confirmed that it was a dispersed source of activity. The transects from the 30m sweeps (figure 10) provide clear evidence that flights at this low altitude are capable of resolving features of 100m dimensions. The spectrum from these transects (technical annexe p.52) shows the presence of ^{137}Cs without the ^{134}Cs peaks associated with Chernobyl fallout.

Subsequent enquiries confirmed that this feature is regularly assessed by MAFF, and was not a new discovery. The actinide content and chemical behaviour of samples from the general vicinity have also been studied in detail (Livens & Baxter,1988a,b).

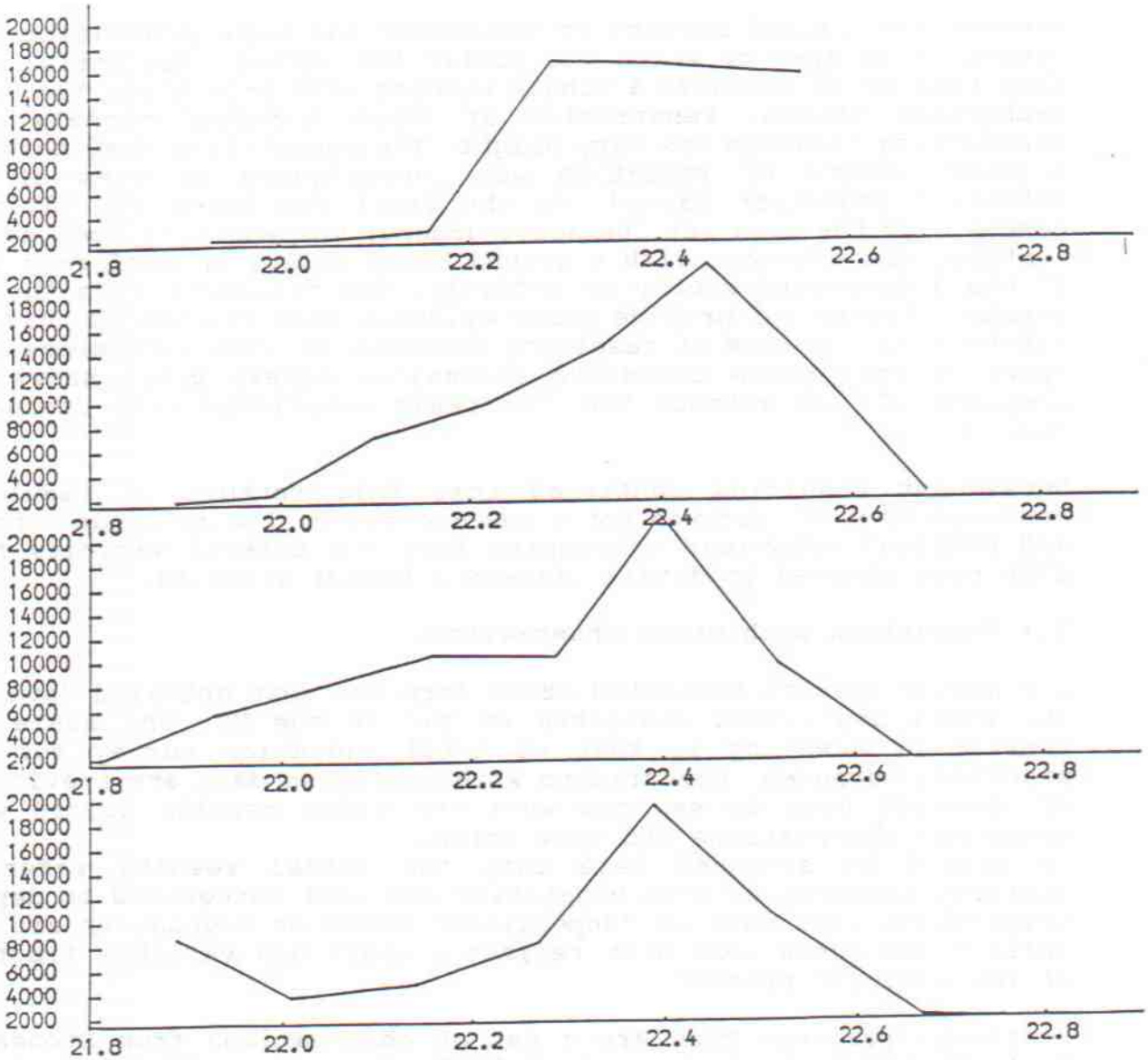
5.4 Comparison with other observations.

The survey results presented above form the most detailed data set for total deposition available so far in the UK. The scale and density of sampling is that of total radiation survey for all practical purposes. Comparisons with published data are inevitably of interest both to see how well the older results accord with these new observations and vice versa.
It should be stressed here that the aerial results refer to activity inventories from vegetation and soil integrated to depth. Comparisons with maps of "deposition" based on vegetation are not valid since these generally reflect a small and variable fraction of the activity present.

Pertinent readings here are a set of observations from Stoneside Hill, Corney Fell (Jackson et al,1987) which show 137-Cs levels of 30.3,48.3,18.5,and 19.6 kBq m^{-2}, integrated over a depth of 14cm at different periods from June 1986 to February 1987. Interestingly more than half the activity in the June 1987 sample

FIGURE 10. LOW ALTITUDE TRANSECTS IN THE ESK VALLEY.

The graphs show the variation of count rate with longitude (in minutes) in three complete passes across a distributed source. Data were recorded each 10s. The survey altitude was 30m.



was below a depth of 4cm, including a significant amount of 134-Cs. The Harwell results from 6 samples collected over the last two weeks of May 1986 (Cambray et al, 1987) show 137-Cs in Cumbria ranging from 11.5 to 14.5 kBq m^{-2}, accompanied by 134-Cs from 4 to 7 kBq m^{-2}. The assessment of Chernobyl deposition by NRPB and the Met Office (Clark and Smith,1988) includes unpublished data from BNFL ranging from 4 to 28.9 kBq m^{-2} 137-Cs from Chernobyl alone. Interestingly this analysis predicts that the survey area should be a minor western limb of a much larger feature whose maximum deposition area is well to the south and east. An unpublished SURRC analysis of a single soil sample taken for other purposes from Ennerdale Fell grid ref. NY063129 in 1987 (Hursthouse, pers comm) gives 32.2 and 7.5 kBq m^{-2} of 137-Cs and 134-Cs respectively. Readings obtained by MAFF before this survey include five soil analyses from Hesk Fell with 137-Cs levels ranging from 13.6 to 16.3 kBq m^{-2} accompanied by 4-5 kBq m^{-2} of 134-Cs (Coughtrey et al ,1988). These results are all in the same general order of magnitude as those from the aerial survey.

An opportunity for a more comprehensive comparison between methods also presented itself by recent MAFF fieldwork. Three areas within the survey zone each 3x3 km were studied using all-terrain vehicles to transport ground teams from point to point. These areas were on Corney Fell, Ennerdale Fell, and Ulpha Fell. A total of 225 measurements was made from each of the three squares comprising a scintillation counter reading in the field and the collection of soil and vegetation samples for analysis in the laboratory. The laboratory analyses consisted of measuring the two Cs nuclides in marinelli geometry without drying or homogenising the activity. The results from both soil and vegetation samples were expressed as activity concentrations in Bq kg^{-1}. This represents a massive undertaking from a logistic point of view and is probably again one of the most intensive mapping exercises of its type. Establishing the comparability of both data sets is therefore of interest.

The data sets were made available to us in mid November 1988, and a preliminary comparison has been undertaken. Two immediate problems present themselves. One is to match the spatial characteristics of the data sets. Clearly there is a mismatch of resolution in comparing samples from a fraction of a square metre with readings spatially smoothed over 200000 square metres. The second problem is that the ground analyses are expressed as concentrations whereas the aerial data refer to deposition per unit area. The usual way of relating the two scales is to record the product of bulk density and sample depth for the ground samples in kg m^{-2}, and to multiply the concentration data by this factor. However these parameters had not been measured in the MAFF data set. In experience at SURRC the uncertainties in estimating bulk soil properties are usually far larger than in measuring radionuclide concentrations by high resolution gamma spectrometry.

The approach taken in our preliminary analysis has been to split each of the three areas into 9 boxes of 1 km square, and to

calculate the mean values and standard deviations of the 134Cs/137Cs ratios, and of the absolute levels of 137Cs by both methods. Clearly there are far more ground based than aerial readings in each such box, this nevertheless provides a basic spatial unit for comparison. To achieve this the MAFF data were coded with OS grid references and put onto the Glasgow University mainframe computer. A search program was written to collate aerial and ground based measurements, and the resulting data used for statistical comparison.

In looking at the 134Cs/137Cs ratios first paired t tests were used to see whether there are significant differences between estimates by the different methods. The data for this comparison are shown in table 4.

There are really too few aerial readings in each 1 km box for meaningful variance estimates. By contrast the ratios based on soil or vegetation analyses are the averages of 25 readings each and are rather better estimated. None of the individual t tests showed significant differences between ground or aerial measurements based on single 1 km boxes. Taking the three areas individually, neither Corney nor Ennerdale Fell showed significant differences in isotopic ratio. There was a significant difference in Ulpha Fell, for which the aerial measurements produced a lower ratio than the ground based measurements. When all three areas are considered together there is no significant overall difference in ratio.

Dealing with the absolute values of 137-Cs is slightly trickier. In this case the soil samples only were considered. The missing variable of mass per unit area was substituted by a series of six values covering a range greater than the physical possibilities. Thus six hypothetical sets of soil data were generated corresponding to mass per unit area values of 50, 100, 150, 200, 300, and 400 kg m^{-2}. Similar t tests to those used for ratio comparison were carried out for means and standard deviations determined from each area as before. The mass per unit area values corresponding to the transition between significant overestimates and significant underestimates in the soil data were defined. As an adjunct to this approach a comparison of mean values was used to deduce the value of the missing variable which resulted in the best concordance. The results of these tests are that the closest band corresponding to the transition between over and underestimation is 200 kg m^{-2}. Significant differences occur in all areas for values moving to 150 or 300. The "best fit" values for this parameter are 214 (Corney), 171 (Ennerdale) and 215 (Ulpha). These values are very close to what would be expected. The MAFF project officers have confirmed that there are

Table 4. Comparison of 134Cs/137Cs ratios

Area	Box	134Cs/137Cs Vegetation	Soil	Aerial Data
Corney	1	0.351+-0.16	0.278+-0.26	0.86+-0.04
	2	0.242+-0.03	0.300+-0.11	0.08+-0.02
	3	0.286+-0.11	0.362+-0.19	0.08+-0.05
	4	0.287+-0.11	0.366+-0.22	0.78+-0.09
	5	0.248+-0.04	0.346+-0.20	0.10+-0.04
	6	0.238+-0.02	0.463+-0.25	0.08+-0.03
	7	0.338+-0.15	0.323+-0.20	0.69+-0.08
	8	0.279+-0.09	0.238+-0.13	0.16
	9	0.253+-0.04	0.292+-0.14	0.084+-0.06
	Overall	0.280+-0.03	0.329+-0.06	0.325+-0.3
Ennerdale	1	0.258+-0.03	0.232+-0.046	0.161+-0.012
	2	0.253+-0.02	0.358+-0.427	0.183+-0.04
	3	0.285+-0.106	0.271+-0.098	0.109+-0.047
	4	0.260+-0.057	0.272+-0.100	0.160+-0.018
	5	0.249+-0.017	0.282+-0.121	0.204+-0.03
	6	0.250+-0.024	0.244+-0.136	0.373+-0.282
	7	0.246+-0.026	0.221+-0.071	0.495+-0.156
	8	0.247+-0.016	0.261+-0.142	0.527+-0.053
	9	0.254+-0.038	0.318+-0.162	0.608+-0.065
	Overall	0.251+-0.02	0.265+-0.056	0.286+-0.186
Ulpha	1	0.266+-0.109	0.579+-0.241	0.041+-0.013
	2	0.299+-0.109	0.378+-0.339	0.078+-0.033
	3	0.332+-0.153	0.317+-0.194	0.121+-0.063
	4	0.235+-0.122	0.338+-0.164	0.052+-0.002
	5	0.292+-0.122	0.327+-0.226	0.106+-0.067
	6	0.332+-0.168	0.305+-0.156	0.131+-0.022
	7	0.252+-0.050	0.286+-0.170	0.056+-0.015
	8	0.276+-0.161	0.283+-0.152	0.071+-0.011
	9	0.370+-0.226	0.256+-0.134	0.177+-0.097
	Overall	0.341+-0.04	0.295+-0.09	0.093+-0.04

no reasons to expect the true value of mass per unit area to be outside the range of these estimates. It was notable that whereas the 134/137 ratio comparison showed greater variance in aerial data than ground data, the opposite was true when comparing the variance of absolute 137-Cs values. We are inclined to attribute this to the subsampling variance associated with the high resolution gamma spectrometry.

We have also analysed the correlation between estimates. Although the correlations are not very strong, it is both surprising and notable that the correlation between readings from vegetation and the aerial data is higher than between soil.

The comparison between these data sets is not a very powerful means of assessing the relationship between methods. This is because of the spatial mismatch of data points, the problem of scale and the fact that both methods are estimating the values of a surface which shows considerable spatial variation. Nevertheless there is evidence that the methods are compatible within their limitations; there is certainly no substantiation for a hypothesis that the aerial readings exaggerate 134-Cs. Also the 137-Cs readings from soil samples appear to be concordant with those recorded from the air.

6. CONCLUSIONS

The technique of aerial radiometrics, which has been neglected in the UK for over 25 years, has been used to measure the Chernobyl fallout pattern in West Cumbria. Despite the limitations of a prototype detector the levels of 137-Cs and 134-Cs have been mapped out along with natural radioactivity to an unprecedented level of detail. 1800 measurements over 45000 hectares were made in two weeks despite poor weather and mountainous terrain.

A comparison of the results of this survey and a ground based study of three 3 km squares confirms that the results are broadly compatible, supporting the general validity of the calibration of the aerial data. The overall levels of radiocaesium detected from the air are an order of magnitude higher than those found in vegetation in 1986.

With the exception of the two features described in section 5.3 the presence of 134-Cs confirms that the majority of the 137-Cs from the upland areas has originated from Chernobyl. The spatial distribution indicates clearly where peak deposition of 137-Cs has occurred, and shows how variable the Chernobyl fallout is on a local scale. Furthermore it is possible that the conjunction of these observations and the soil nutrient information from the potassium map has a bearing on the mobility and transfer of caesium through the food chain.

The 134-Cs from Chernobyl deposition will become progressively harder to detect from the air over the next 12-24 months, and this will effectively determine the additional sensitivity needed for future studies if the full national distribution is to be determined.

Areas for further work include using these data for a thorough external dose assessment, examining their predictive value for identifying areas of maximum transfer to livestock, completing and extending the survey, and continuing to develop the instrumentation and method.

The inherent feasibility of aerial survey has been clearly demonstrated in this study. The practical capabilities in terms of sensitivity and speed would be further improved by technical development which could be conducted in conjunction with continuing application work. There are many interesting and unexplored applications for this technique in studies of natural and anthropogenic radioactivity distributions in industrial, agronomic and environmental contexts which would justify further work.

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