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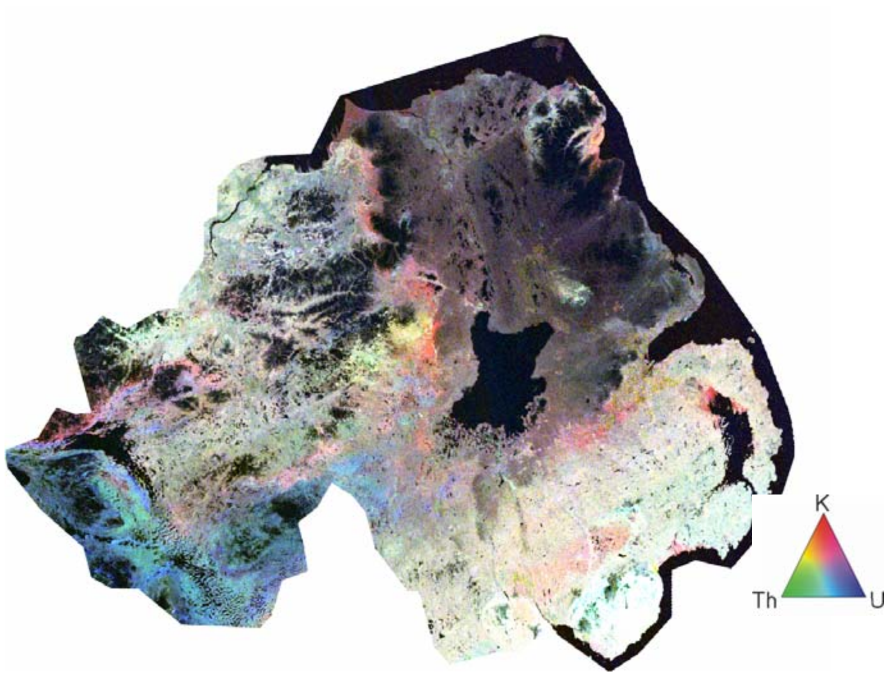
A preliminary interpretation of Tellus airborne radiometric data

Geological Survey of Northern Ireland

Commissioned Report CR/07/061 N



BRITISH GEOLOGICAL SURVEY

GEOLOGICAL SURVEY OF NORTHERN IRELAND

COMMISSIONED REPORT CR/07/061 N

A preliminary interpretation of Tellus airborne radiometric data

D G Jones and C Scheib

Contributors

R. J. Cuss and B. G. Rawlins

Keywords

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Front cover

Ternary image of the Tellus airborne dataset showing relative proportions of K (red), U (blue) and Th (green).

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British Geological Survey offices

Keyworth, Nottingham NG12 5GG

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☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

☎ 028-9038 8462 Fax 028-9038 8461

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff, CF15 7NE

☎ 029–2052 1962 Fax 029–2052 1963

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

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Summary

An airborne geophysical survey of the whole of Northern Ireland was flown by the Geological Survey of Northern Ireland in 2005 and 2006 as part of the Tellus project funded by the Department of Enterprise, Trade and Investment of Northern Ireland and by the Rural Development Programme through the Northern Ireland Programme for Building Sustainable Prosperity. Magnetic, electromagnetic and radiometric data were acquired at 200 m line spacing and a flying height of 56 m (240 m over built-up areas) using the Joint Airborne Capability of the British Geological Survey and the Geological Survey of Finland. In total, 82,000 line-km of data were acquired. The radiometric data were collected as full 256 channel gamma-ray spectra every 1 s or approximately 70 m of ground coverage. The Tellus project also included a baseline geochemical survey of Northern Ireland for which 22,000 samples, of soils, stream sediments and stream waters, were collected.

A preliminary assessment of the radiometric data has been carried out to illustrate the type of features present in the dataset, at both regional and local scales, and provide pointers to possible areas of future research. At the scale of the whole of Northern Ireland the data reflect the major solid geological subdivisions; the Lower Palaeozoic greywackes and Palaeogene intrusives of the SE have relatively high K, U and Th contents. In contrast the Palaeogene basalts in the NE have much lower radioelement concentrations, although Palaeogene rhyolites, and inliers of Palaeozoic and Precambrian rocks in this area, have higher values. Surrounding the basalts to the south and west, the Triassic sedimentary rocks have moderate K, eU and eTh levels. The more heterogeneous geology of the western part of Northern Ireland is reflected in the radiometric data with juxtaposed areas of relatively high and low radioelement content. Formation boundaries within the basement and Upper Palaeozoic rocks, sometimes faulted, are clear in places as ENE-WSW and NE-SE-trending features.

Regional effects of superficial deposits and soil overlying the solid rocks are also readily apparent. River valleys form distinctive features with the water or wet sediments having an attenuating effect, whilst compositional difference between alluvial deposits and the surrounding terrain can also provide a marked contrast. Low radioactivity resulting from peat cover is very clear, as are higher zones where glacial tills are derived from areas of relatively radioelement-rich geology. Drumlin fields produce very distinctive patterns in the radiometric images, especially in the SW and NE.

At a more local scale greater detail is apparent in the solid geology and the effect of superficial deposits overlying the solid rock becomes more apparent. Features are enhanced by plotting subsets of the data. This improves the contrast and brings out compositional differences in the glacial deposits resulting from their derivation and transport direction. Variations within the solid geology are also enhanced. Human influence is also clear both in the urban environment and as wastes produced from power generation and those deposited in landfill sites or associated with mineral extraction. Towns have a distinctive speckled appearance that is the result of greater variability due to increased statistical noise arising from the higher flying height and correction of the data, compared to the lower altitude of 56 m. Added to this may be a contrast resulting from differences in radioelement content between the built environment and surrounding rural areas.

Data for ^{137}Cs show well-defined banding of higher values along NNW-SSE and WNW-ESE orientations. This pattern is consistent with deposition by rainfall intercepting the contaminant plume following the Chernobyl nuclear accident. It probably also reflects longer term rainfall and consequent deposition of nuclear weapons fallout. It is controlled, in part, by topography and aspect. The bands extend into the Irish Republic and are clearly not related to single flight lines, groups of lines flown together or blocks of data. Similar linear features are seen, or predicted, in

data from other parts of the UK and France but are probably more pronounced in the Tellus data owing to the close line spacing (200m). Concentrations of ^{137}Cs are in line with previously published values, allowing for decay of ^{137}Cs post-Chernobyl and earlier fallout. Laboratory analysis of ^{137}Cs in soil samples from the Tellus geochemical survey, and from ground to air comparison work, correlated well with the airborne ^{137}Cs measurements, giving confidence in the airborne results.

The data have the potential to be used in a wide range of applications, for example geological and soil mapping, mineral exploration, radon potential mapping and environmental studies as well as providing a baseline against which future measurements can be assessed.

1 Introduction

An airborne geophysical survey of the whole of Northern Ireland was flown in the summers of 2005 and 2006 as part of the Tellus project funded by the Northern Ireland Department of Enterprise Trade and Investment and by the Rural Development Programme through the Northern Ireland Programme for Building Sustainable Prosperity (www.tellus.detini.gov.uk). The aircraft (a De Havilland Twin Otter) carried magnetic, electromagnetic and radiometric sensors. It is operated as a joint venture between the British Geological Survey (BGS) and the Geological Survey of Finland (GTK). Survey lines were spaced 200 m apart and orientated NNW or SSE (165 and 345º), with tie-lines 2000 m apart, and at right angles to the flight line directions, acquired only in the early part of the survey. The tie lines cover only the westerly blocks A and B. The flying height was 56 m above ground (185') in rural areas rising to 240 m over urban areas and as necessary to safely clear obstacles.

Radiometric data were collected with an Exploranium GR820 256 channel gamma spectrometer system comprising 32 L of downward looking NaI(Tl) detectors and 8 L of upward looking detectors. Data were collected every second (approximately 70 m flight line distance). Fuller details of the geophysical and navigational equipment and data processing can be found in Beamish *et al*., (2007).

The spectrometer collects information on naturally-occurring potassium (K), uranium (eU) and thorium (eTh), and man-made radionuclides (mainly ^{137}Cs) in the ground surface. As uranium and thorium are measured indirectly from their radioactive decay products the values are referred to as equivalent uranium and thorium, designated eU and eTh. The gamma radiation measured comes from a shallow surface layer of no more than about 30 cm in rock, although this will increase for low density unconsolidated materials perhaps to a maximum of a few metres in dry peat. The ground area or footprint from which most of the contribution of radioactivity to each 1 s measurement comes has the form of an ellipse, elongated in the flight direction. For example, at 56 m altitude 75 % of the measured radiation will come from a width of about 150 m, extending to around 220 m along the flight line (Pitkin and Duval, 1980), although this varies with detector characteristics such as shape and the type of processing applied to the data (Billings *et al*., 2003; Grasty *et al*., 1979; Grasty *et al*., 1982; Kellogg, 1982). Within that ellipse the greatest contribution will, in general, come from directly beneath the aircraft and falls off exponentially with lateral distance from the flight line.

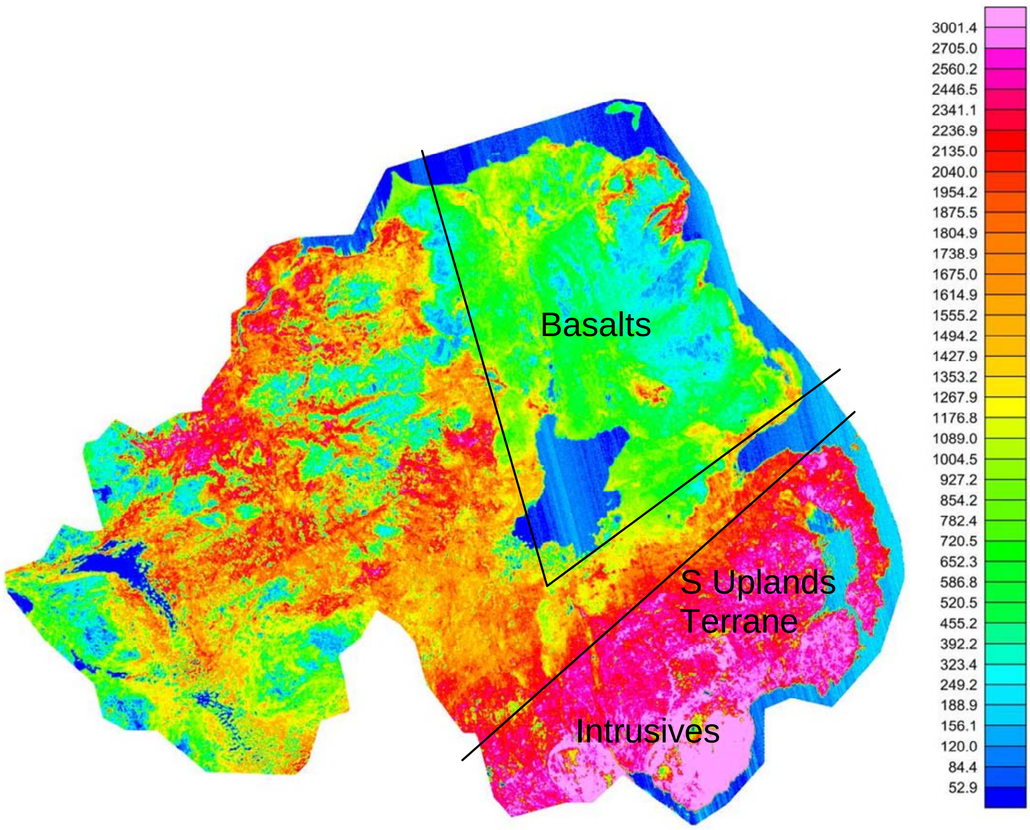
This report presents a preliminary overview interpretation of the airborne radiometric data. It is designed to show examples of the types of feature that can be identified in the data. This is intended to be merely an illustration of uses of the radiometric data. It does not set out to cover all possible aspects but should be a guide to use of this dataset. These applications may well be enhanced by combining the radiometric and other Tellus datasets, but that has not been attempted here.

2 Results and interpretation: natural radioactivity

2.1 ALL OF NORTHERN IRELAND

2.1.1 Solid Geology

The broad scale relationships between the radiometric data and regional solid geology (digital version of Geological Survey of Northern Ireland, 1997) are clearly apparent (Figures 1-3). The



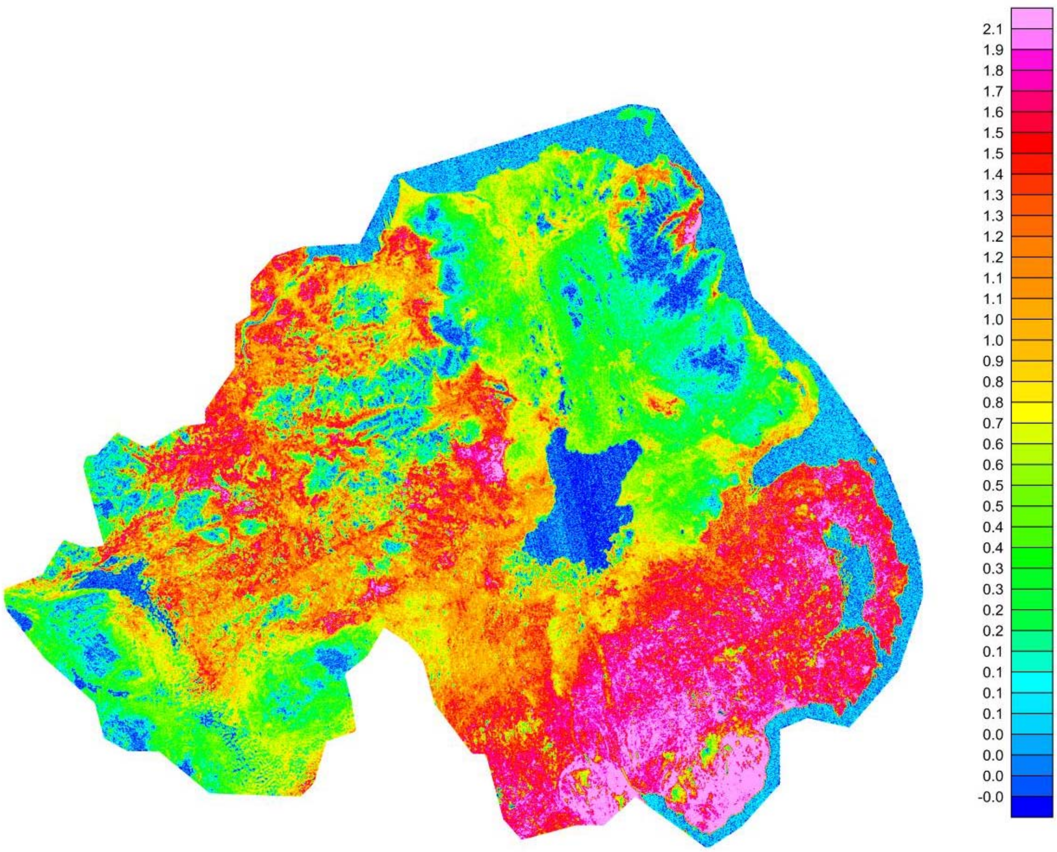


Figure 1a, b. Total count (cps) and K (%) images of the entire Tellus radiometric dataset

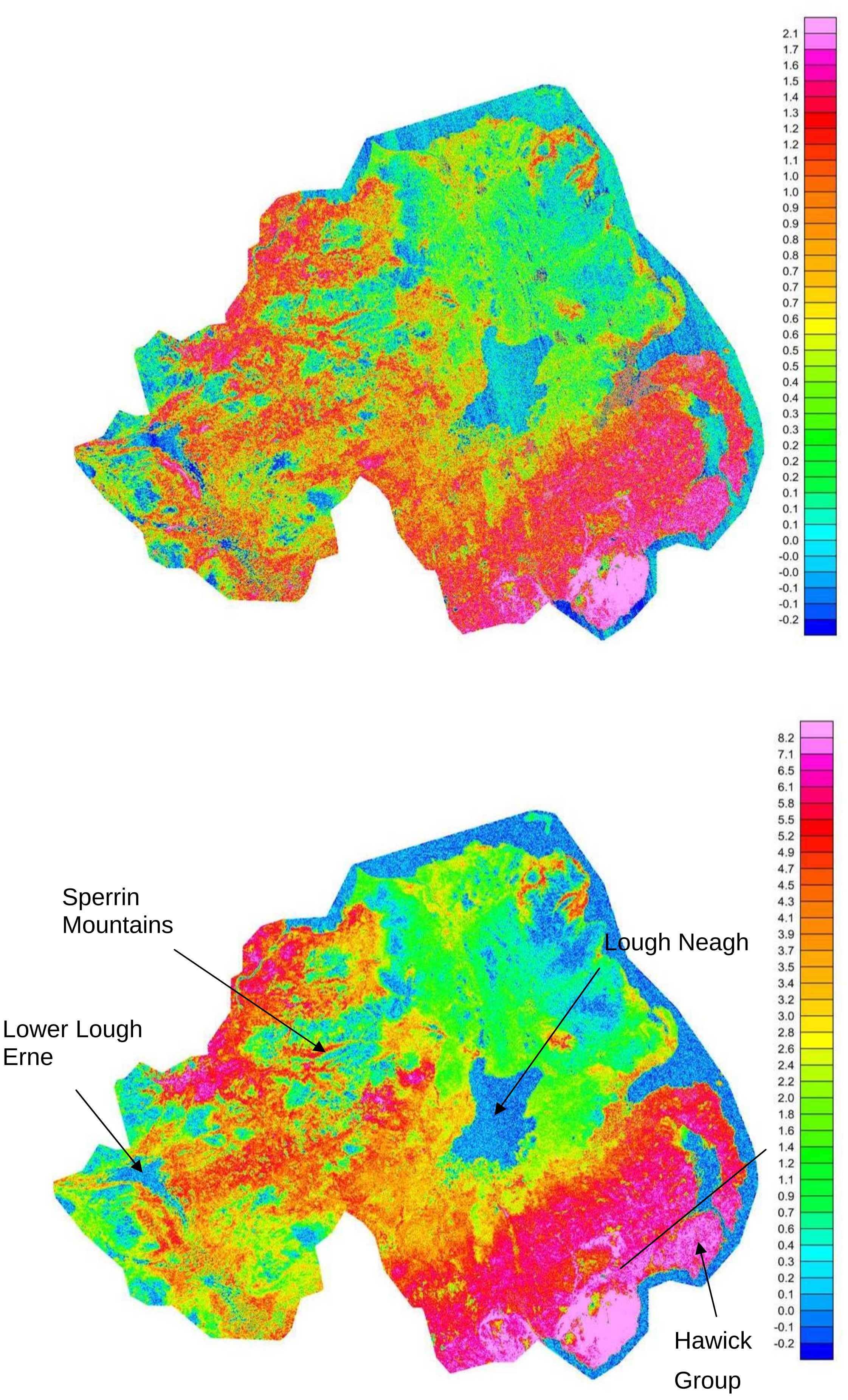


Fig 1 c, d. eU and eTh (ppm) images of the entire Tellus radiometric dataset

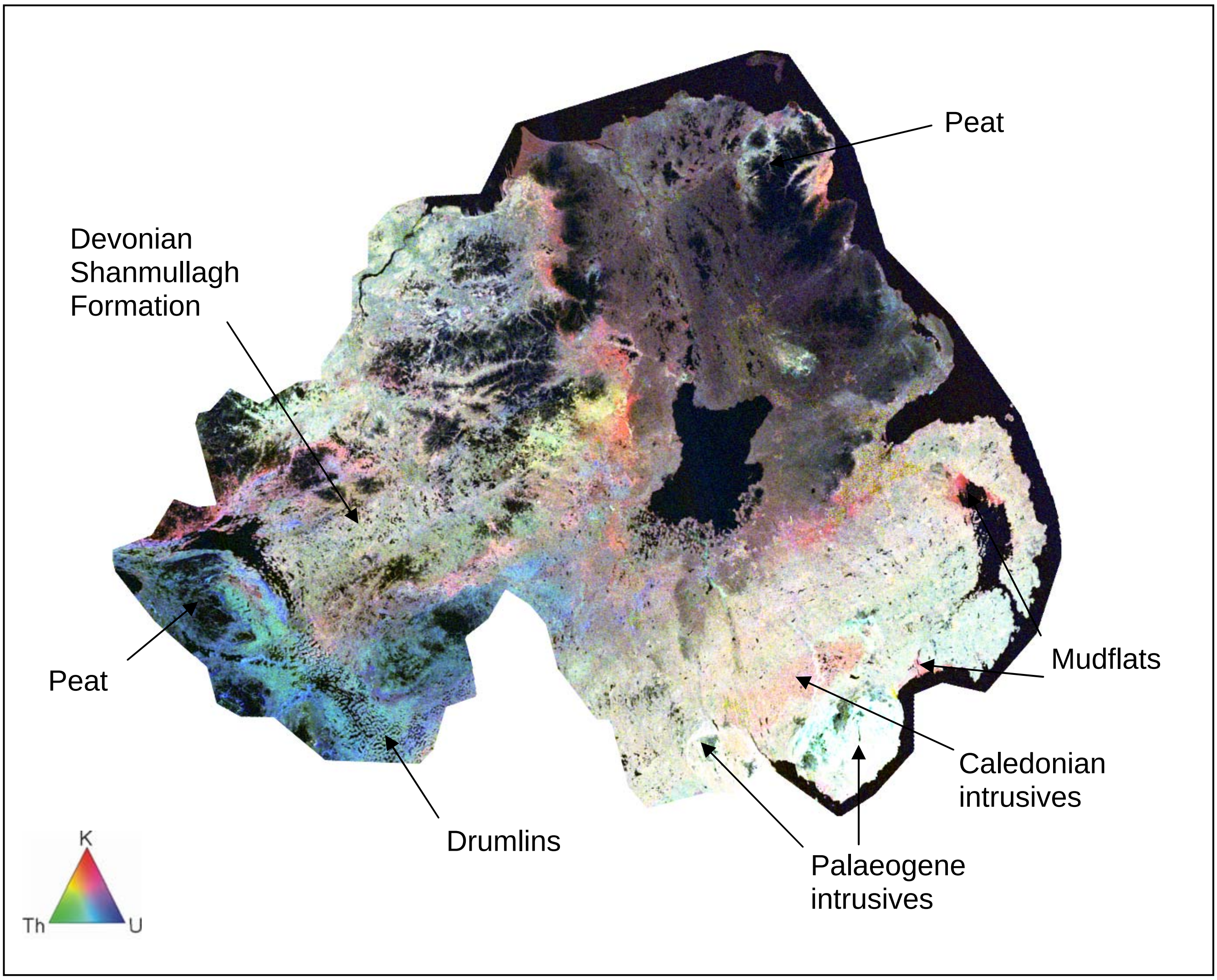


Figure 2. Ternary image of the entire Tellus radiometric dataset

Lower Palaeozoic rocks in the SE of Northern Ireland (Southern Uplands Terrane) form a block of ground with higher values for total count and all three radioelements. There is a general rise to the south and SE reflecting the highest concentrations in the acid intrusives of the Newry, Mourne Mountains and Slieve Gullion complexes, as well as generally higher levels in the Hawick Group relative to the Gala Group and older Lower Palaeozoic formations. There is a major contrast between the SE and the NE of Northern Ireland where the Palaeogene basalts (Cooper, 2004) and overlying sediments (mostly the Lough Neagh Group) have much lower concentrations of K, eU and eTh. Within this generally low radioelement area are much higher values associated with parts of the Proterozoic and Palaeozoic sequence in the inlier in the extreme NE and a small area of rhyolites NE of Lough Neagh. The SE and NW fringes around the basaltic outcrop have moderate K, eU and eTh levels corresponding to the Triassic Sherwood Sandstone Group and parts of the overlying Mercia Mudstone Group.

The more heterogeneous geology of the western part of Northern Ireland (Figure 3) (Mitchell, 2004a) is reflected in the radiometric data with juxtaposed areas of relatively high and low radioelement content. The NW of this area has generally higher K, eU and eTh on the upper Dalradian psammites and semipelites (Cooper and Johnston, 2004a) of the Southern Highland Group (Londonderry, Ballykelly and Claudy formations) as well as the overlying Tournaisian Barony Glen Formation (Mitchell, 2004b). The Dalradian, Dart, Glenelly and Mullarghcarn

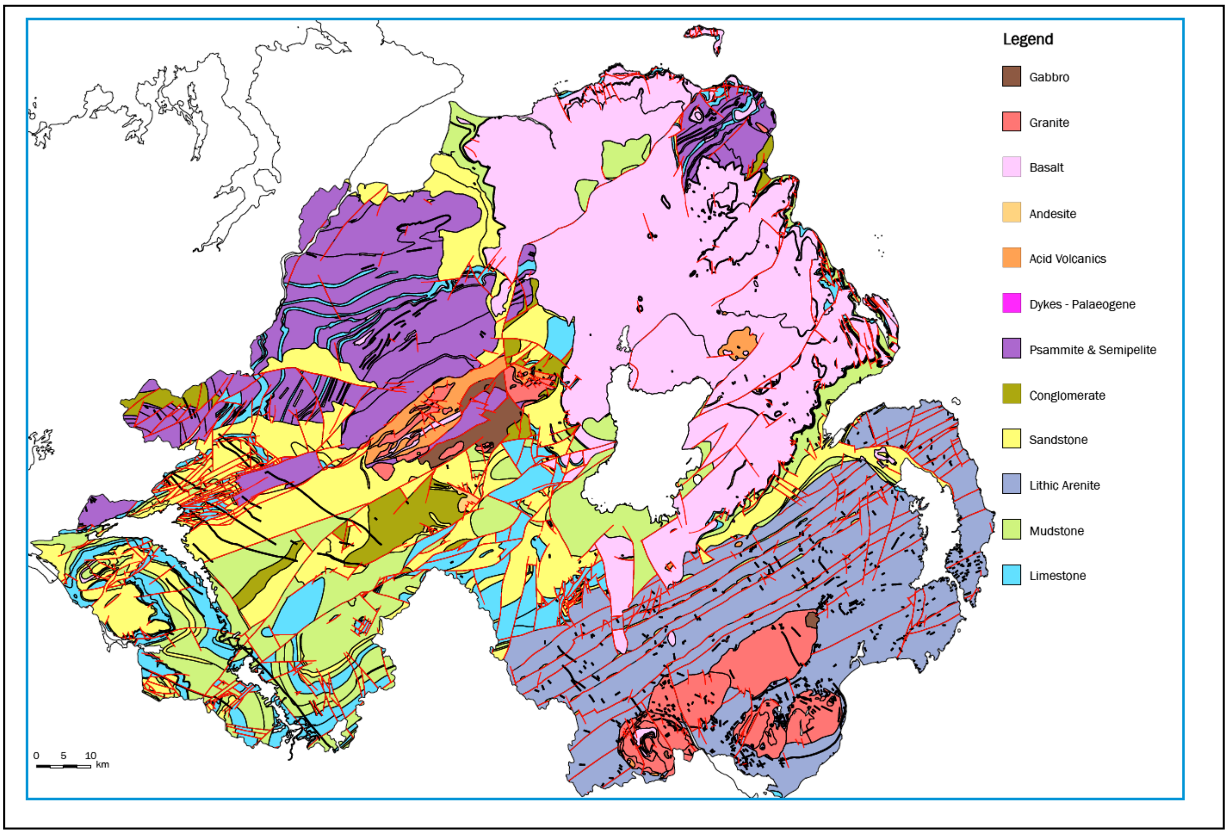


Figure 3. Simplified solid geology map

formations, of the Sperrin Mountains (Cooper and Johnston, 2004a), tend to have generally low values for K, eU and eTh. The patterns of highs and lows do not fit closely everywhere with the regionally mapped (1: 250 000 scale) solid boundaries because of the influence of the overlying superficial deposits and soil (Figures 4 and 5). However, certain features do reflect the regional solid geology.

There are ENE-WSW and NE-SE highs that match boundaries in the basement and upper Palaeozoic rocks; the former mirror formations within the Dalradian Central Highlands Terrane, the latter, clearest on the total count, K and ternary images, pick out the faulted margins of the Devonian Shanmullagh Formation (Figure 6) (Mitchell, 2004c). There is also a sub-parallel feature just to the south, extending from the southern tip of Lower Lough Erne, within the Namurian Ballinamallard Mudstone Formation (Mitchell, 2004b). This appears to truncate a more northerly-trending linear on the line of the Tempo-Sixmilecross fault (Figure 6).

Further south another NE-SW boundary is very clear in the K data and follows part of the trace of the Clogher Valley fault, although the southern end of the fault, towards Upper Lough Erne is not apparent.

The Caledonian intrusives in the Midland Valley Terrane (Cooper and Johnston, 2004b) are not, in general, well defined in the radiometric data (Figure 7); the more basic rocks of the Tyrone volcanic province in places show higher radioelement concentrations than the granitic rocks. The Slieve Gallion Granite and parts of the Pomeroy, Carrickmore and Beragh granites and the Laght Hill Tonalite do show higher values but the data suggest the influence of superficial cover of a different composition to the bedrock.

To the south of Lower Lough Erne, arcuate patterns are seen in the radiometric data (Figures1, 2 and 6), slightly more strongly developed for eU and eTh than for K. These mirror the outcrop patterns as they parallel the western side of the lough. The strongest response being from the lower Carboniferous BallyShannon Limestone (Mitchell, 2004b).

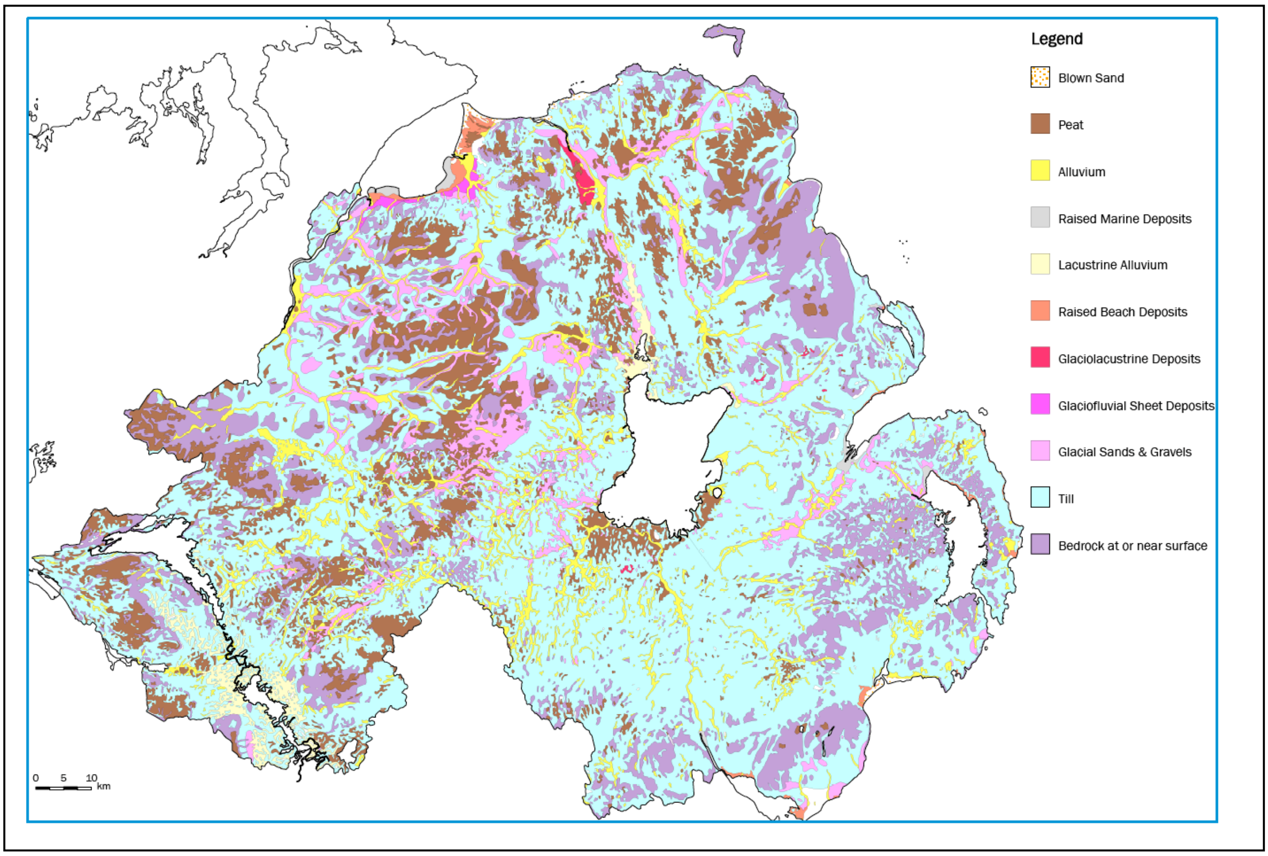


Figure 4. Simplified superficial geology map

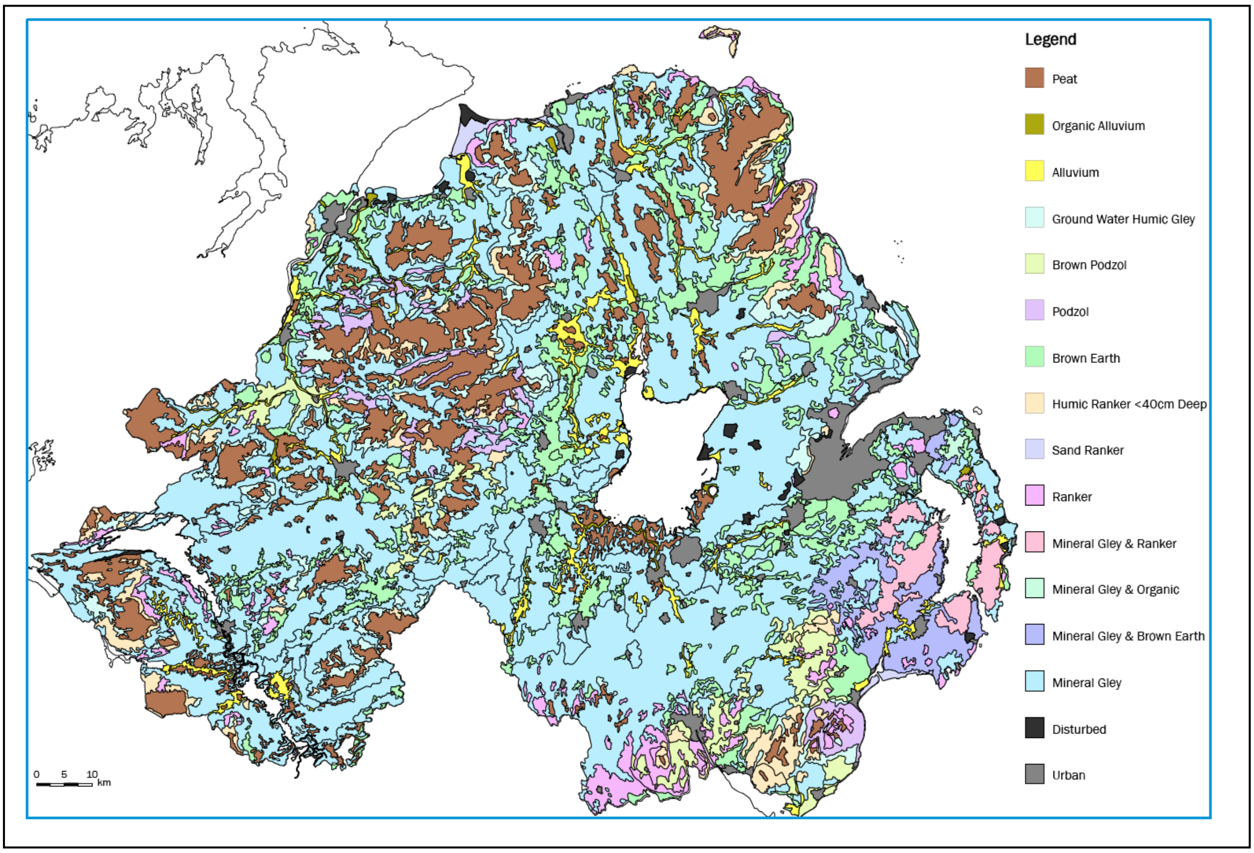


Figure 5. Simplified soils map (courtesy of Northern Ireland Department of Agriculture and Rural Development)

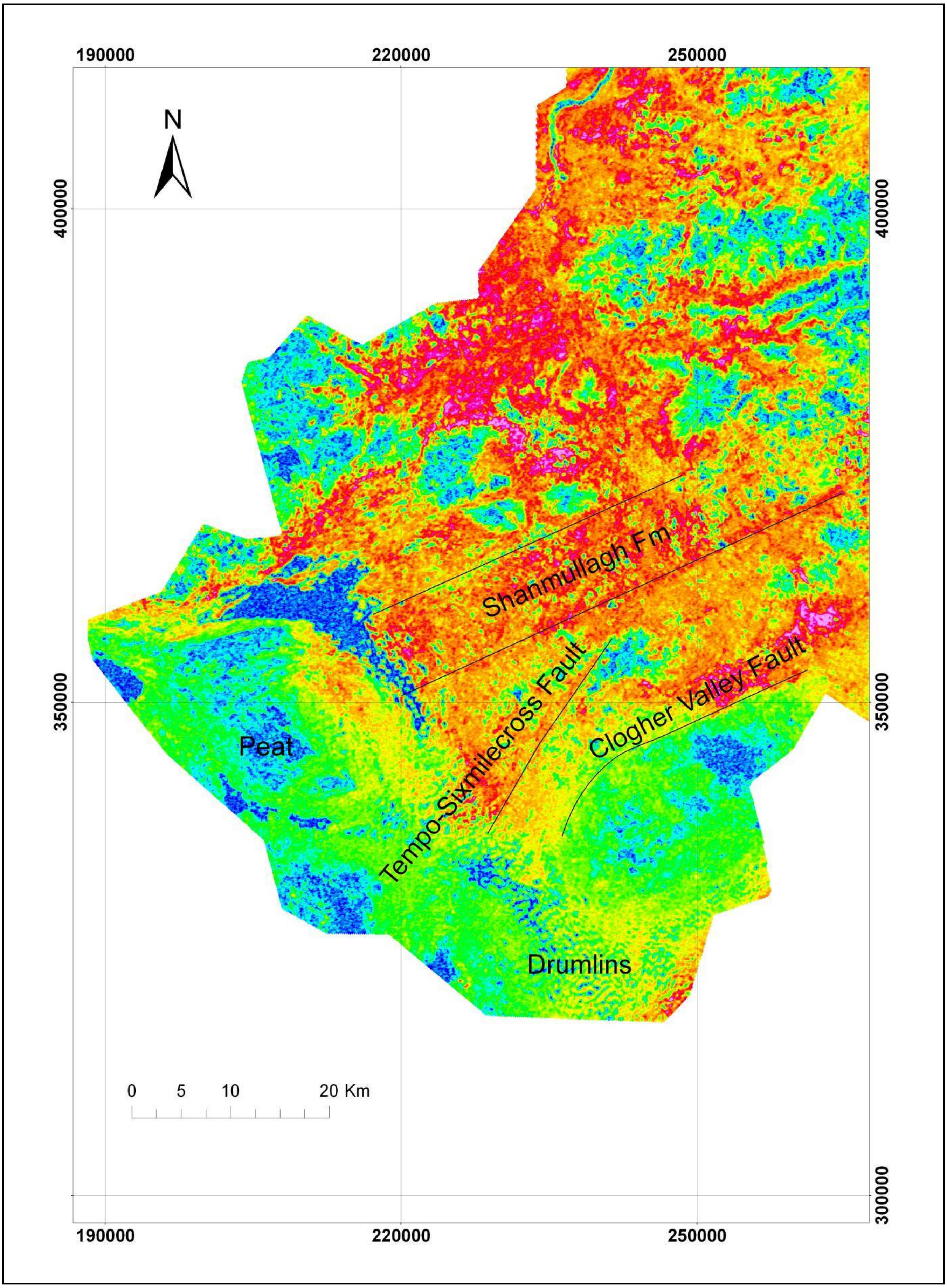
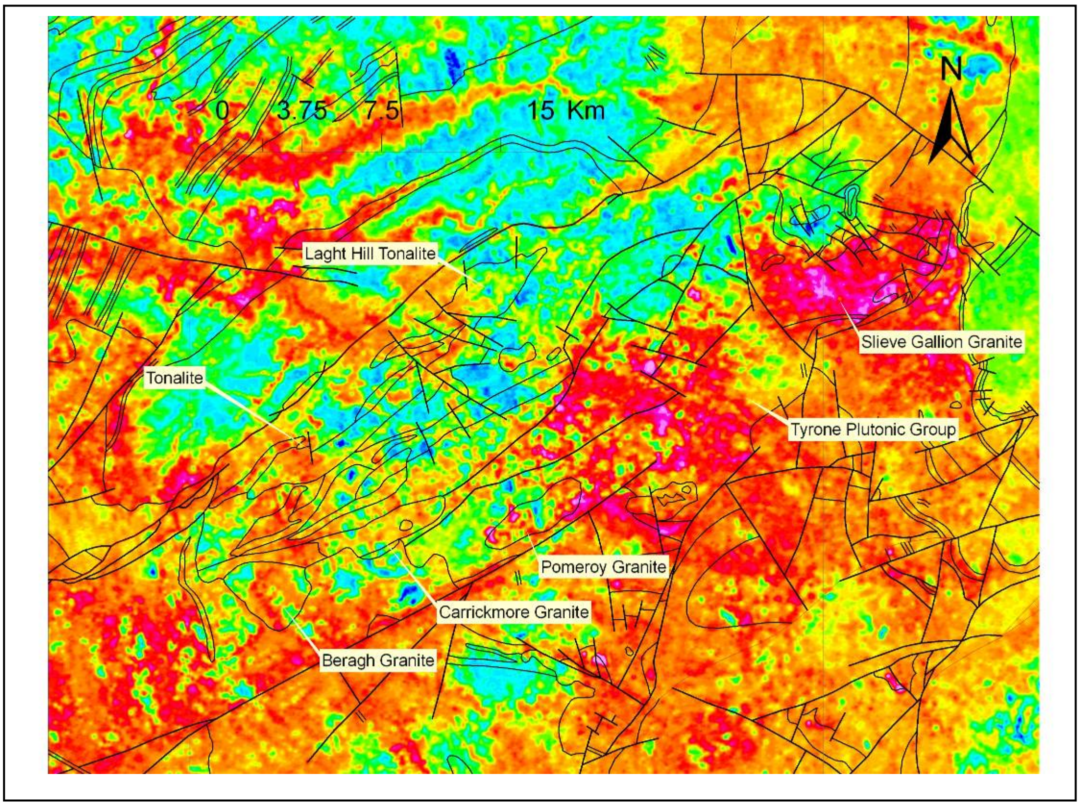


Figure 6. K (%) image of the SW of Northern Ireland (colour scale as in Figure 1b)



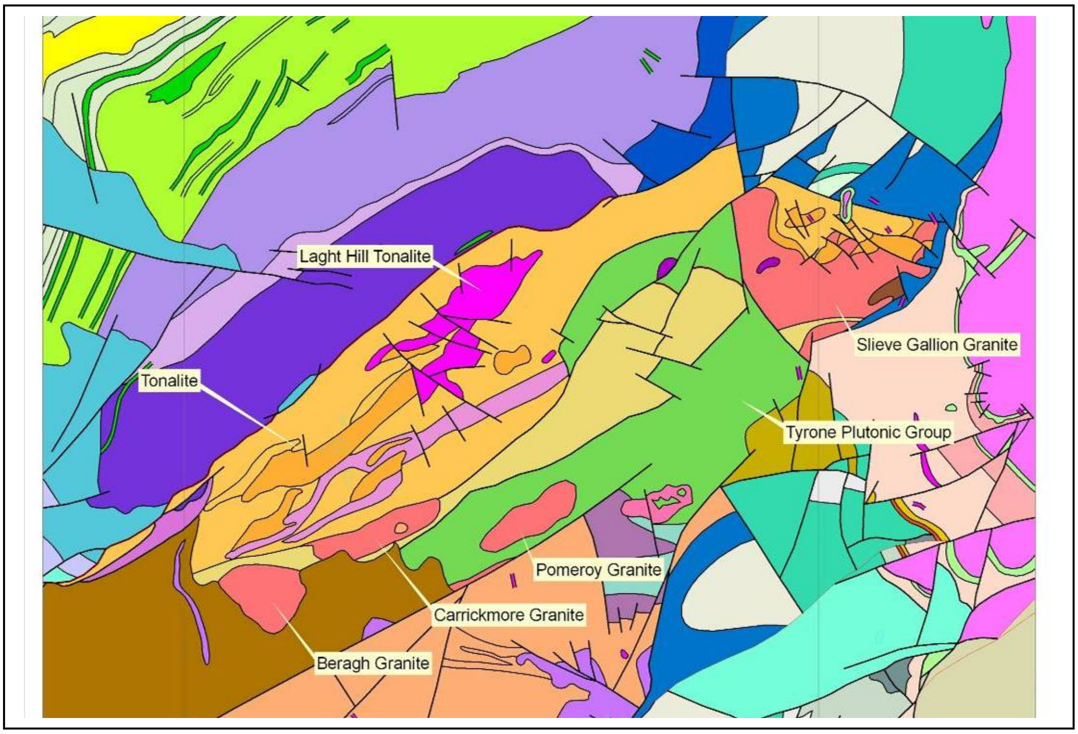


Figure 7. Total count (cps) image (colour scale as in Figure 1a) of the Tyrone Igneous Complex with solid geology of same area below. The Slieve Gallion granite stands out with high total count, other acid intrusives are masked by lower activity superficial deposits. The basic intrusives of the Tyrone Complex are covered by higher activity diamicton (till).

The remaining Carboniferous rocks in the extreme SW of Northern Ireland have rather low K, but more variable eU and eTh.

2.1.2 Superficial geology

Although the broad patterns in the airborne radiometric data reflect major elements of the solid geology, both regional and more local features clearly result from the overlay of superficial deposits (Geological Survey of Northern Ireland, 1991) and soil (Figures 4 and 5) where these mask the signatures of the underlying rocks. One of the more obvious features is related to the drainage network where there is a dual effect; the water itself and the associated wet sediments attenuate the gamma ray signal reaching the airborne detectors, whilst the alluvium and other deposits may also have different radioelement contents to the geology they overlay. There are many examples at the regional scale.

The northern end of the River Foyle (Figure 8) cuts a lower activity swathe through the Dalradian rocks, wide enough near its mouth to show a water response and with alluvium further south that has relatively low K, eU and eTh contents. More commonly the alluvium, and associated glacial sands and gravels that fill the valleys have a relatively high radioelement contents compared to rocks they blanket. There are many examples of this, perhaps the most striking being Glenelly River and the Owenkillew River and Owenreagh River draining the Sperrin Mountains (Figures 9-12). The former, in particular has higher K, eU and eTh associated not only with the main valley but most of the tributary streams.

There are other clear examples of contrast between the valley deposits and their surroundings where rivers drain westwards off the older rocks onto the basalts and the stream course can be seen as a meandering line of higher radioelement values. An excellent example of this is the Clady River and its tributaries the Grillagh and Knockoneill rivers to the north and NW of Lough Neagh (Figure 13), but other river valleys in this area also have similar characteristics. Higher K, eU and eTh also occur along valleys in the NE Antrim inlier, a clear example being the Glendun River.

Drainage-related radiometric features with lower radioelement contents occur on the Southern Uplands Terrane (Figure 14), both for streams flowing to the north, such as the Cusher river and its tributaries and the Ballybay River (although the low area is partly due to basalt in this case), and those draining to the south, including the Newry River, and those flowing NE into Strangford Lough including the Quoile River.

The other type of superficial deposit that has a major impact on the pattern of the radiometric data is peat. In general this has very low concentrations of K, eU and eTh and many areas are clearly defined on the images. There are several areas around Lower Lough Erne, to the NW and N of the lake and to the SW and S between the Lough and the border with the Republic (Figures 1, 2 and 6). Another major area is the Sperrin Mountains, where the contrast between the lower radioelement contents of the peat-covered uplands and the more radioactive alluvium and glacial deposits is particularly striking (Figures 9-12). The peat is, however, sufficiently low in K, eU and eTh to even be readily apparent on the basalts (Figures 1, 2, 13 and 15), which are the least radioactive of the major rock types. The largest expanses are close to the NE coast, where they cover the highest ground (Figure 15). The extent of peat on the simplified soil map and the 1: 250 000 Quaternary geological maps differ in detail (Figures 4 and 5) and the radiometric signature in some areas fits better with the Quaternary map and in others matches more closely to the soil map.

The gamma ray signal for natural radioisotopes in rocks comes almost entirely from the top 35 cm (IAEA, 2003). A small amount of low activity cover can have a marked effect on the signal. Soil moisture also can have a significant impact with a 10% increase causing a similar drop in

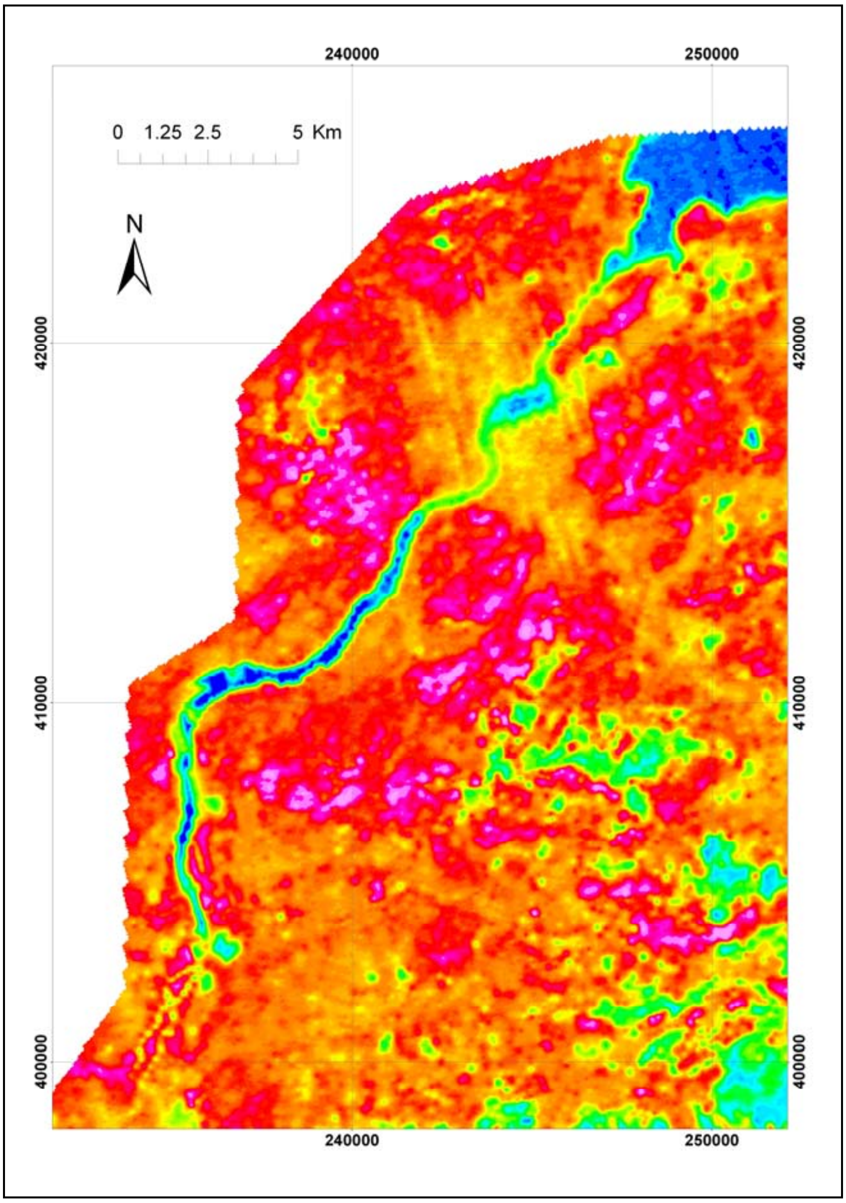


Figure 8. Total count (cps) image of the northern part of the River Foyle valley (colour scale as in Figure 1a) showing the low activity of water (blue) and the alluvium (green) relative to the adjacent solid and superficial geology

count rates (IAEA, 2003). For peat the moisture content could vary considerably. The half-value layer (i.e. the depth that will attenuate 50% of the gamma radiation) for water, for 1.5-2.0 MeV gamma rays (i.e. the approximate energy range of gamma radiation from K, eU and eTh), is 32 cm (Voss, 2004). Thus the signal strength would be reduced to less than one eighth by a 1 m layer of water and saturated peat would be expected to behave in a similar manner, as it is mostly (up to more than 90%) water. The difference in attenuation of dry and wet peat will be appreciable.

Drumlin patterns (see Bazley, 2004) are also evident on the regional images. They are particularly clear in the south-west on the K and total count images (Figures 1a, b and Figure 6), but also present in eTh and eU data (Figure 1c, d). Some of the features to the south and west of Lower Lough Erne appear to match mapped drumlin fields on the inset to the 1: 250 000 Quaternary map of Northern Ireland (Geological Survey of Northern Ireland, 1991), but others to the SE, around Upper Lough Erne, seem to be more extensive than are shown on that map. The drumlins patterns are particularly clear in this area because the drainage pattern is controlled by the drumlins with streams flowing between the drumlins and small loughs occupying the lower

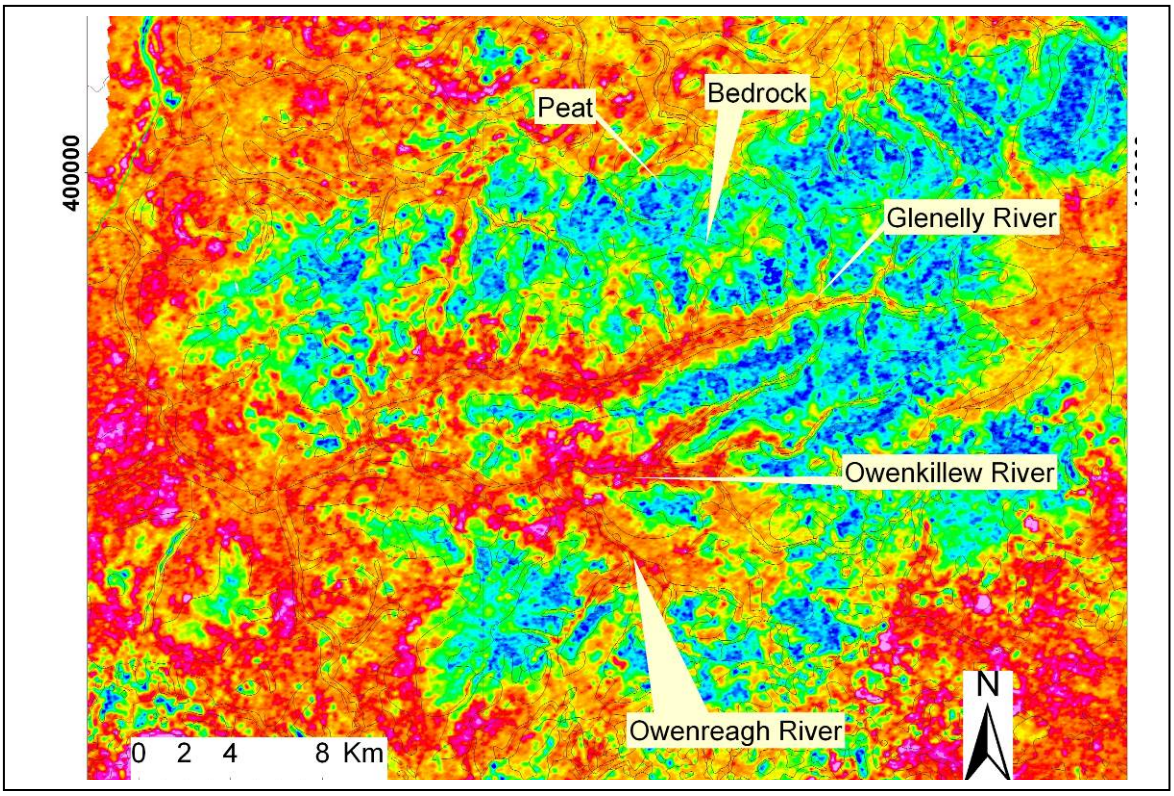


Figure 9. K (%) image of the Sperrin Mountains with superficial geology lines and drainage shown (colour scale as in Figure 10)

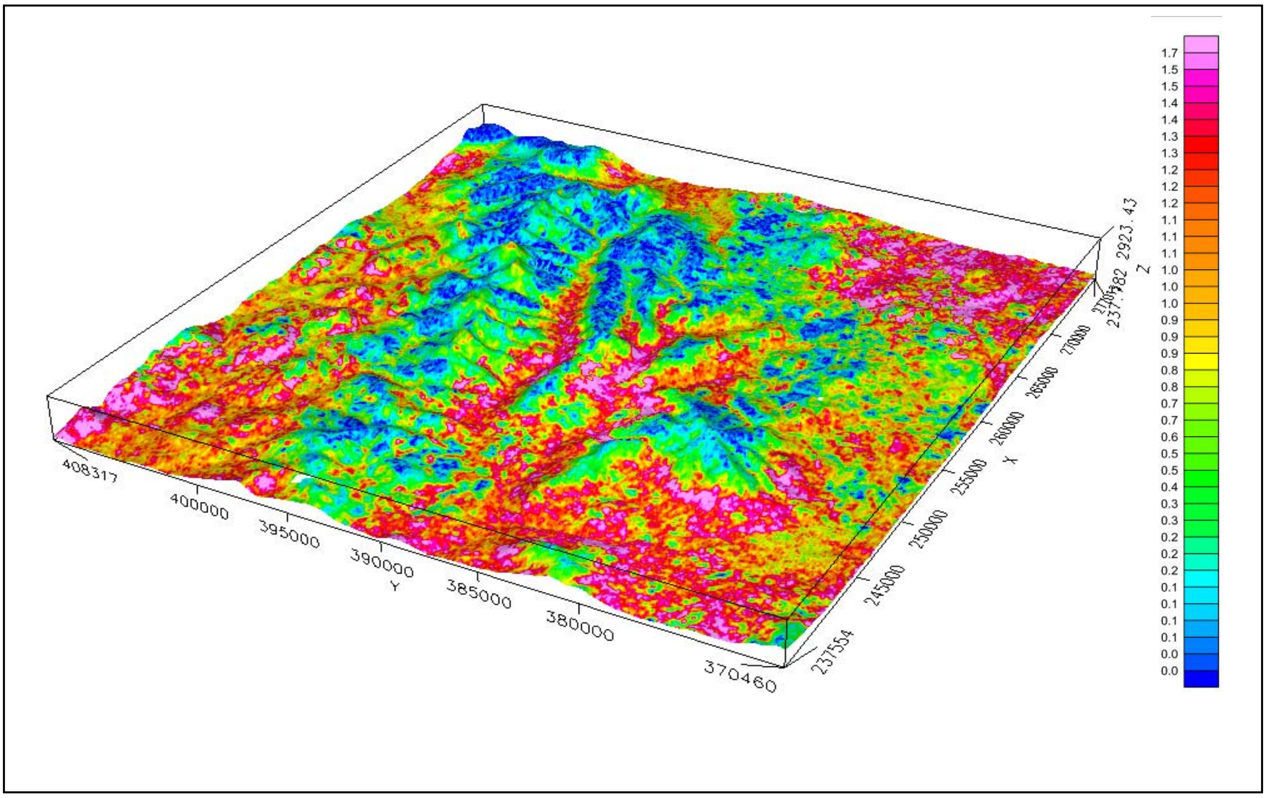


Figure 10. K (%) image draped on DTM, Sperrin Mountains, viewed from the SW. Alluvium has higher K and peat lower K (blue). Exposed bedrock on mountain tops has intermediate values (mostly green)

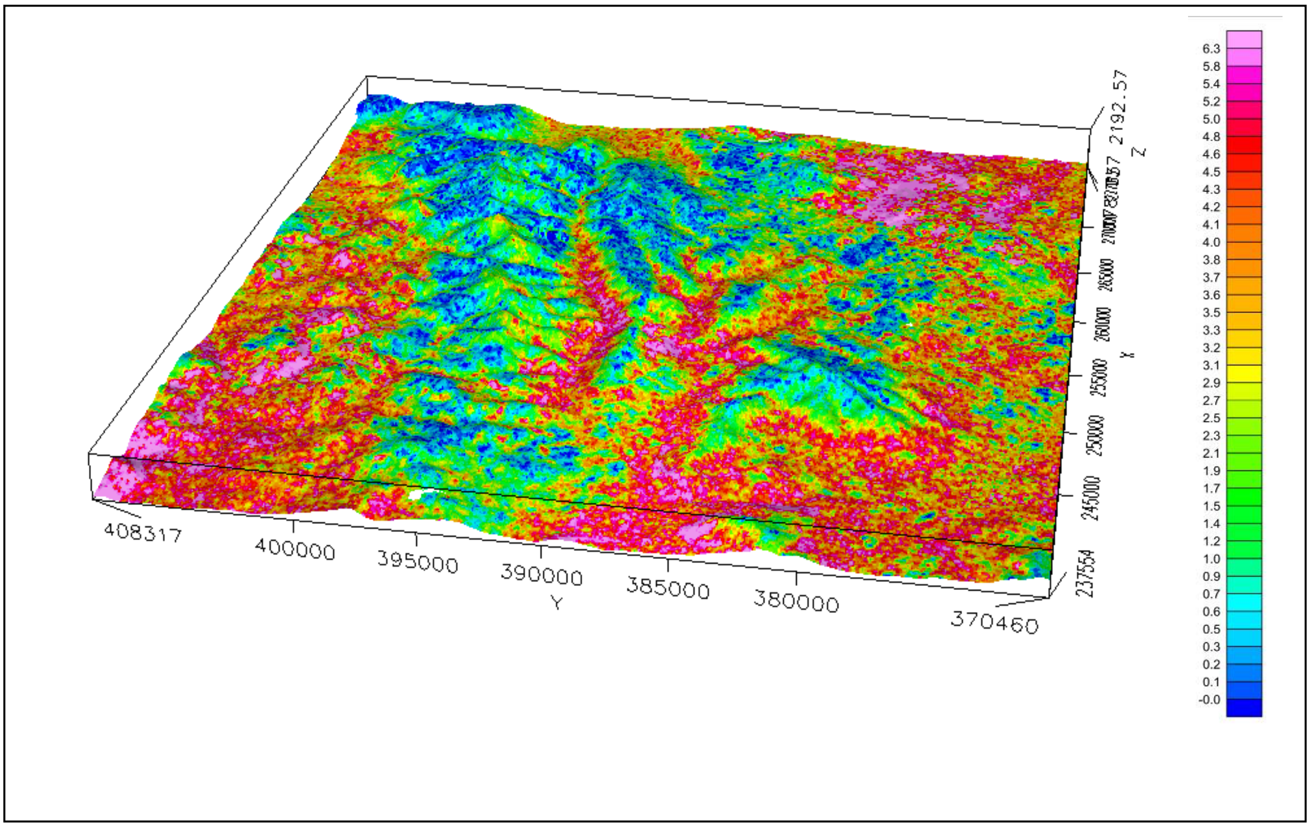


Figure 11. Th (ppm) image draped on DTM, Sperrin Mountains, viewed from the W

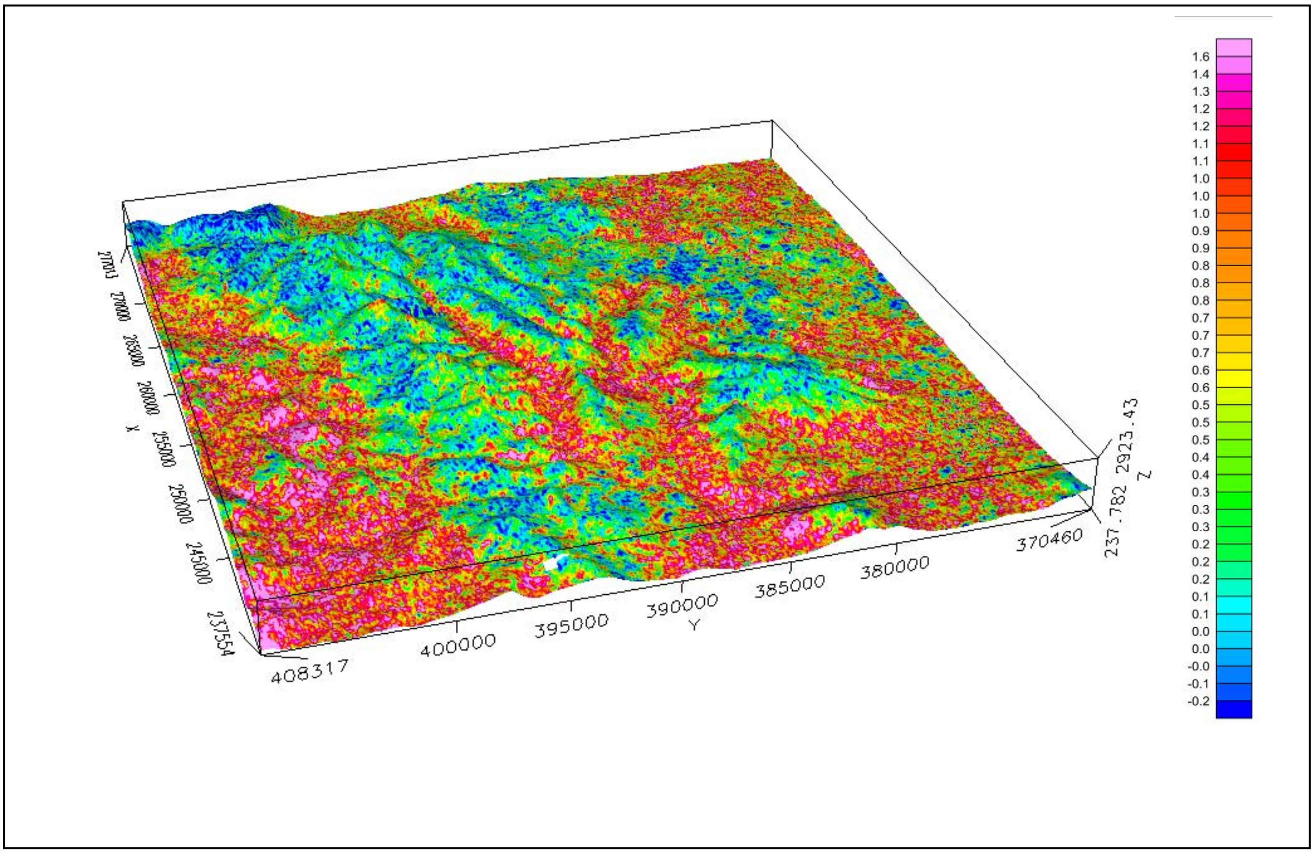


Figure 12. U (ppm) image draped on DTM, Sperrin Mountains, viewed from the NW

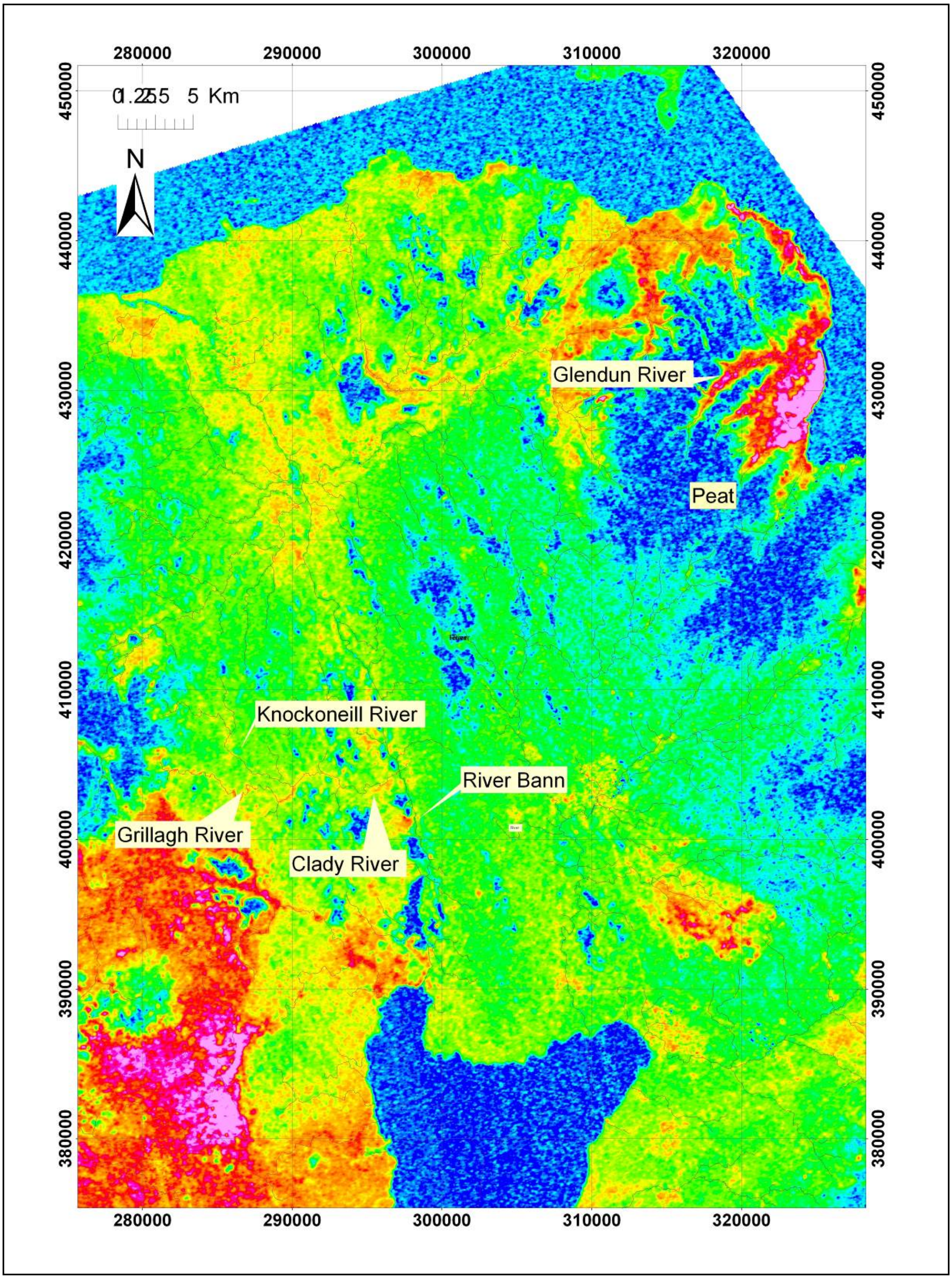


Figure 13. K (%) image of NE Northern Ireland (Antrim basalts) showing drainage related features and peat (colour scale as for Figure 1b)

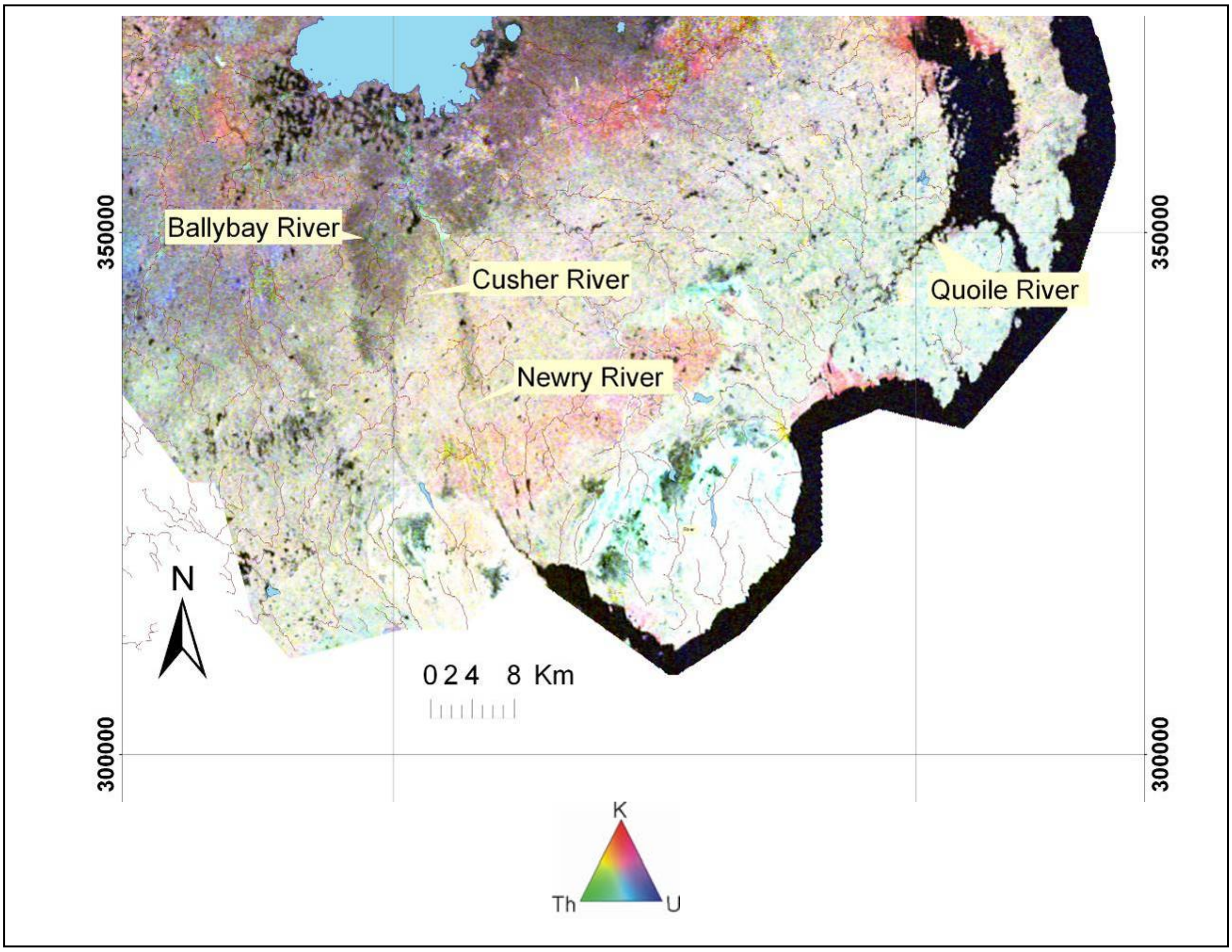


Figure 14. Ternary image of SE Northern Ireland showing relatively low radioelement contents associated with some river valleys

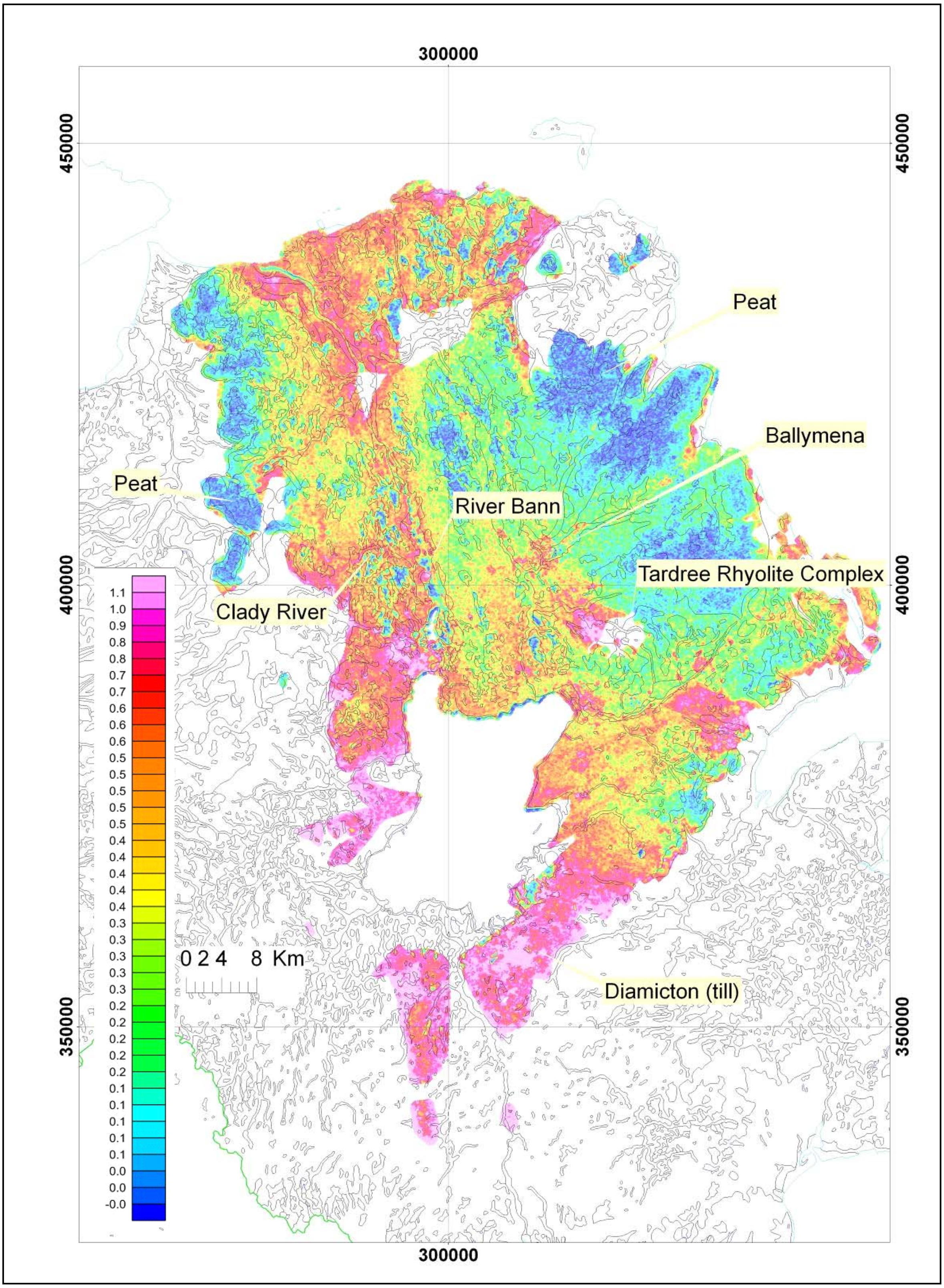


Figure 15. K (%) image for the basalts with superficial geology lines

ground. This provides a strong radiometric contrast owing to the reduced signal from water and wet ground when compared with the drier upstanding features.

2.2 REGIONAL SCALE

When plotted for all of Northern Ireland the images are scaled to the full range of radioelement values for the whole dataset. This may subdue more subtle features that are defined by a smaller range of concentrations. Such features can be investigated by plotting subsets of the data; either for a defined, more localised area, or a specific geological unit or units. We have examined some examples of the latter at a regional scale; the Palaeogene basalts, the turbidites of the Southern Uplands Terrane and the Sperrin Mountains. In addition, specific features at a smaller scale, have been plotted to illustrate examples of what the data show both from a geological and environmental context.

2.2.1 Basalts

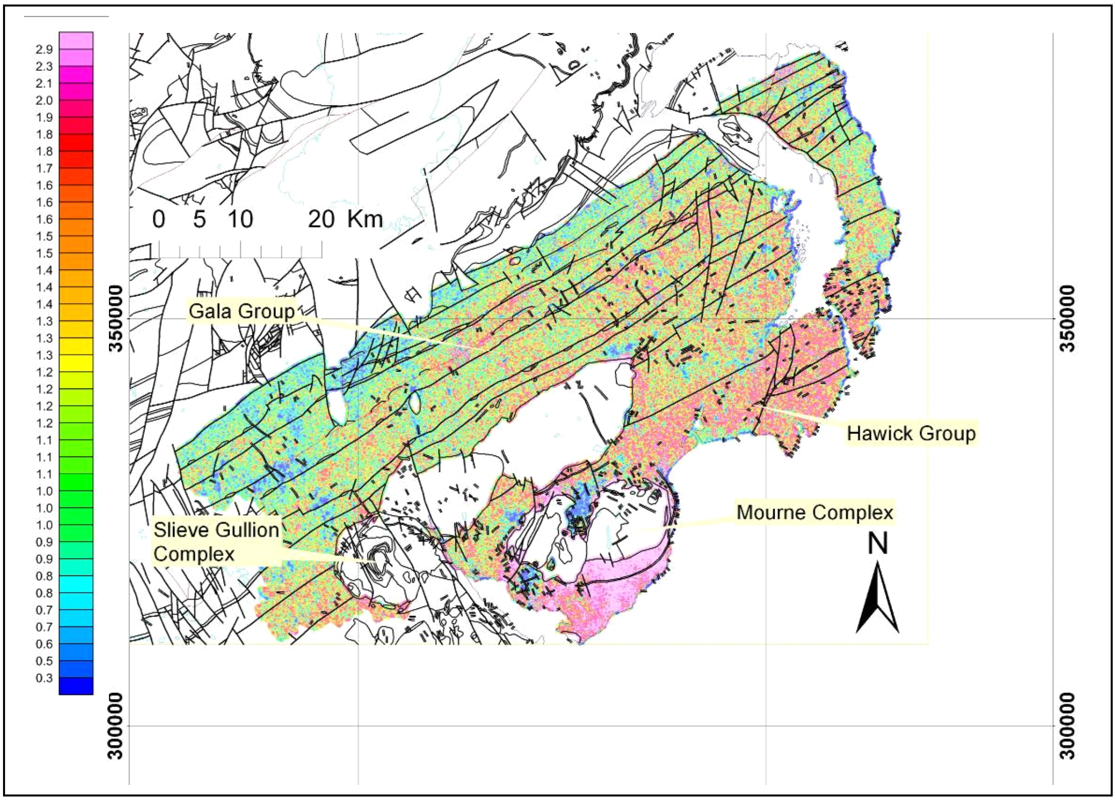
Replotting the data for the basalts enhances the contrast appreciably and brings out additional detail compared to the images of the whole province. The vast majority of features relate to the superficial deposits rather than the solid geology, as is clear from an overlay of the 1: 250 000 Quaternary boundaries on the radioelement images (Figure 15). For example, the deposits related to the NNW-SSE-oriented drainage pattern (River Bann) to the north of Lough Neagh are readily apparent. There are also patterns at right angles to this orientation, which fall along tributaries to the main rivers (e.g. the Clady River). The lowest values reflect peat cover whilst the highest concentrations occur on diamicton (till). All the patterns are clearest on the K image but similar features are present in the eU and eTh data. Within the areas covered by till there is a range of radioelement composition, presumably reflecting differences in source material. For example, there is a zone of higher K, eU and eTh immediately NW of the Tardree Rhyolite Complex which is probably due to material derived from the complex. This extends for at least 4 km from the surface contact between the Rhyolites and the Lower Basalt Formation and is consistent with the later phases of ice movement from the Lough Neagh axis northwards (Bazley, 2004). Till to the west, south and SE of Lough Neagh has higher K, eU and eTh concentrations. Within the till there is also a better defined 'spotty' pattern over drumlins, which was not so apparent on the images of the whole of Northern Ireland. This is well developed to the north of Lough Neagh.

Towns and villages also show up more clearly on the basalt image, with higher radioelement contents; Ballymena and the surrounding villages show up particularly well and are most clearly seen on the K image (Figure 15).

2.2.2 Southern Uplands Terrane

Separate images were also prepared for the main units of Lower Palaeozoic rocks in the SE of Northern Ireland, the Gala, Hawick and Moffat Shale Groups (Figures 16 and 17) (Anderson, 2004). As for the basalts, these images bring out the variation within this area better than the plots of the whole of Northern Ireland. They appear to show a mix of features related to both the solid and superficial geology.

For example, the higher eTh and eU in the Hawick Group is apparent across the outcrop (Figure 16). However, the highest levels of these radioelements (and K) are seen fringing the Palaeogene acid intrusives and presumably reflect diamicton and glacial sands and gravels with a significant contribution of material from the granitic terrain. These fringes to the intrusives are better developed to the south of each body, reflecting the direction of latest ice movement (Bazley, 2004; Geological Survey of Northern Ireland, 1991), with only a very thin marginal development to the north. The best examples are to the south of the Mourne and Slieve Gullion complexes. There are also lower K, eU and eTh areas within these generally higher zones, these seem to



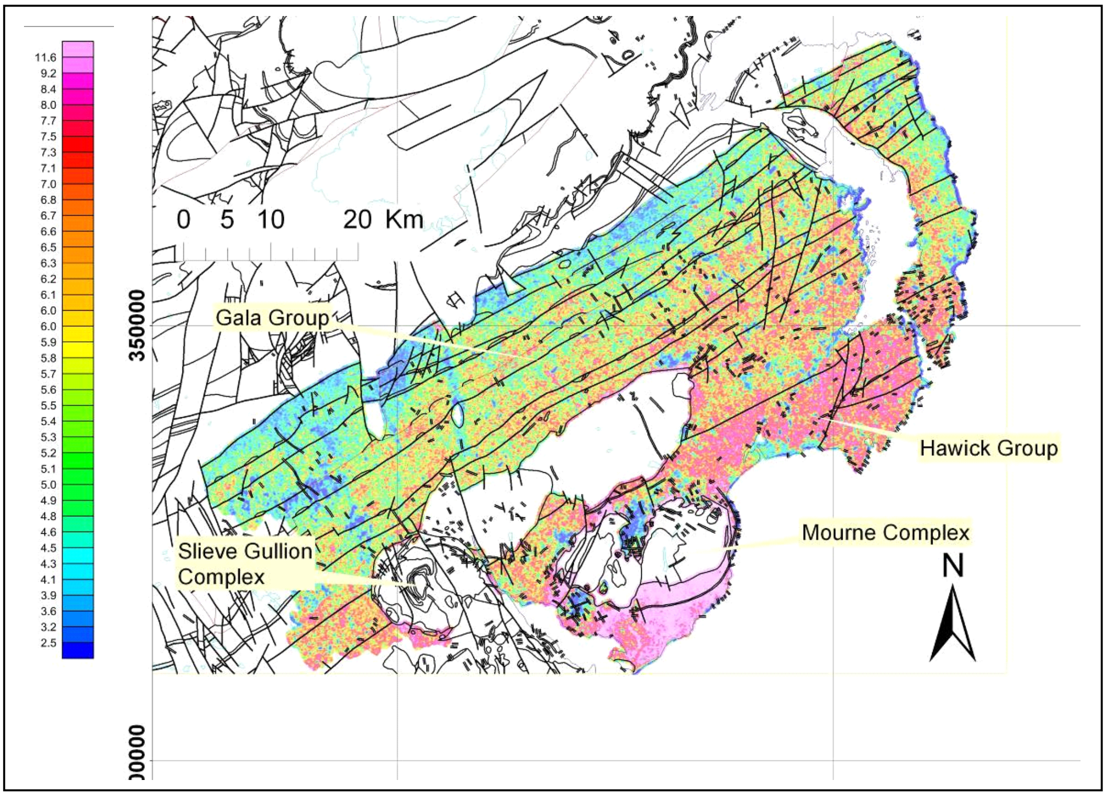


Figure 16. eU (ppm, above) and eTh (ppm, below) images of Southern Uplands Terrane with solid geology lines

coincide with clusters of dolerite dykes around the Western Mournes centre and are clearly seen as dark areas on the ternary image (Figure 17).

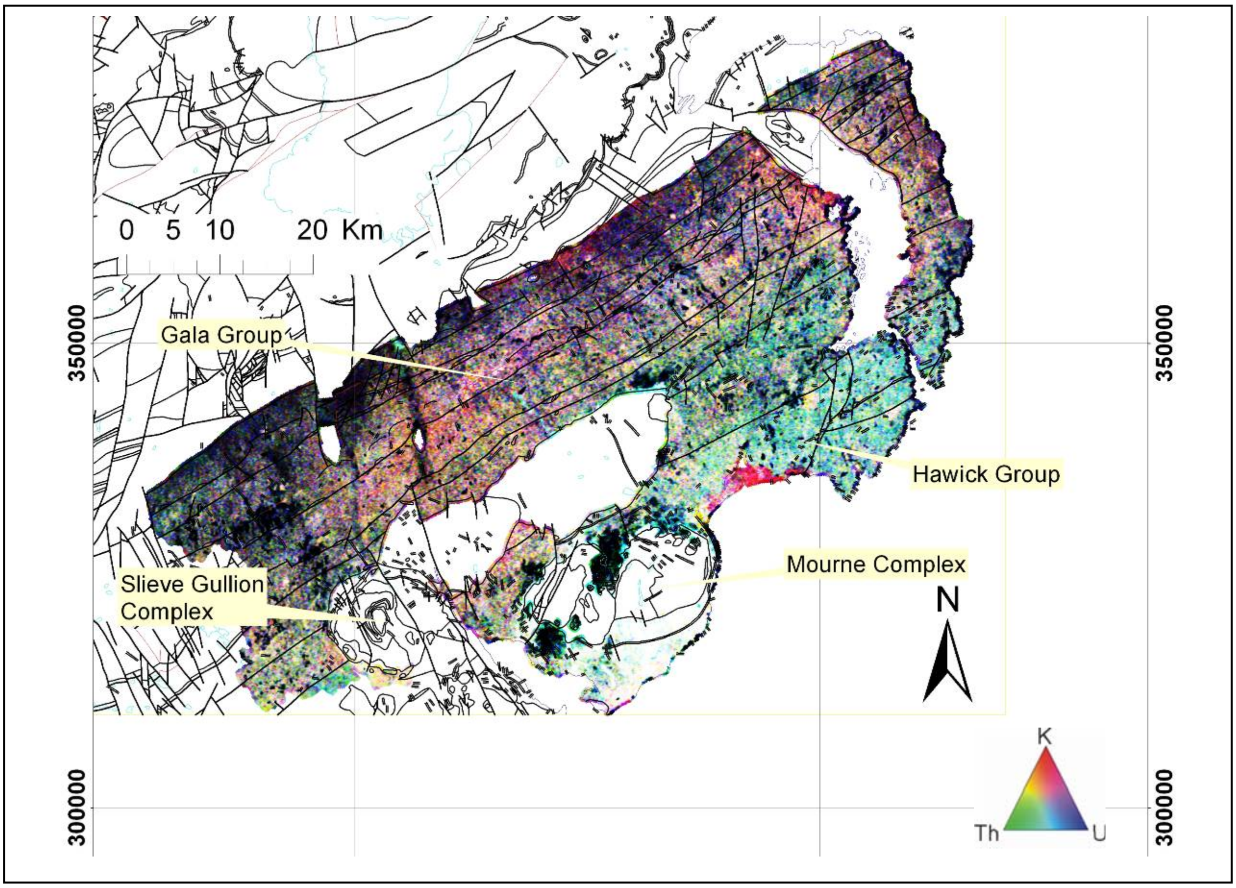


Figure 17. Ternary image of Southern Uplands Terrane with solid geology lines

The ternary plot also shows the higher eU and eTh associated with the Hawick Group and indicates other compositional changes parallel to the strike direction. The upper (SE) part of the Gala Group appears to have similar ratios of radioelements to the overlying Hawick Group, whilst the ratios seem to change towards the NW, going down the tectonostratigraphic pile.

2.2.3 Sperrin Mountains

Replotting the data for this region produces a less marked change relative to the images of the entire province than in the previous examples. There is, however, some improvement in contrast. As noted earlier, the major features revealed are related to the Quaternary at surface with strong contrast between peat, with the lowest radioelement contents, and the valley deposits with the highest levels. Where rock is drift-free that tends, in this area to have intermediate K, eU and eTh contents. These features are illustrated well when the radiometric data are draped on the digital terrain model (Figures 10-12).

2.2.4 Intrusives

Additional detail is apparent on the images of the acid intrusives in County Down (Figures 18 and 19). Differences between the Caledonian Newry complex and the Lower Palaeozoic country rocks, so clearly seen on the regional eTh/K plot (Figure 18), are accentuated on the single element images with the slightly higher K and lower eTh and eU being apparent. This is most strikingly seen on the ternary image (Figure 19) where the older intrusives of the Newry Complex (Figure 20) appear red due to the high relative proportion of K to eU and eTh. The different composition of the NE end of the Newry Complex is clearly delineated, with the

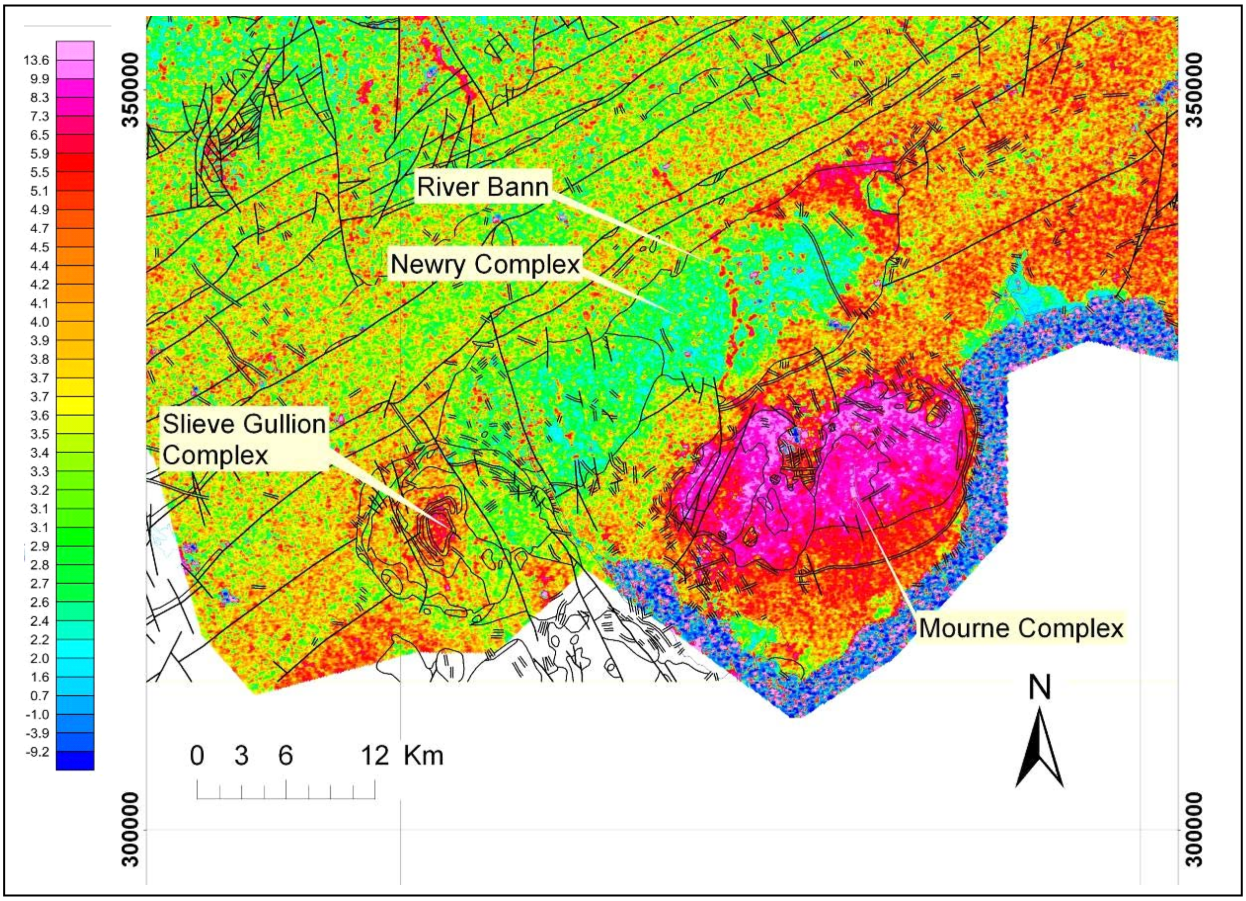


Figure 18. Th/K ratio image of Palaeogene intrusives, Co Down and Co Armagh with solid geology lines

relative importance of eTh and eU being reflected in green and turquoise colours. The relatively high eTh at the NE end of the Newry Complex is interesting. It does not appear to be related to superficial features, unlike the higher values associated with the River Bann draining north from the Mournes, and appears to form a marginal zone with highest eTh at the NE end. This appears to be at odds with the zonation of the NE granodiorite, which is described as being more basic at the margins of the intrusion (Cooper and Johnston, 2004c). However, it does match well with an area of bedrock, free of superficial deposits, but this does not explain why the drift-covered western portion is distinguishable from the country rocks, which are themselves blanketed by the same superficial deposits.

The Mourne Complex stands out on the ternary image (Figure 19) from the other intrusives, with a mix of white areas, where all three radioelements are high, and turquoise where eU and eTh are high relative to K. Slieve Gullion appears to have a slightly different composition reflected in pinkish hues for the Palaeogene intrusives on the ternary plot, whilst the surrounding Caledonian intrusives are similar to the remainder of the Newry Complex. The felsitic ring dyke and the granophyric inner part of the Palaeogene complex appear to have similar compositions in terms of K, eU and eTh. The ring dyke is accentuated when the K, eU and eTh images are draped on the DTM (Figures 21-23) standing out as an arc of higher ground with enhanced radioelement contents. In all the intrusions the more basic rocks stand out as black areas low in all three radioelements. The central granophyre core to the Slieve Gullion complex is also largely black but this appears, from the soil map (Figure 5), to be the result of peat covering the bedrock.

Linear features oriented generally NNW-SSE cross the ternary plot (Figure 19). Although some parallel the flight line direction, there are sinuous sections that reflect the drainage pattern. They show varying radioelement signatures due to differences in the type and composition of the

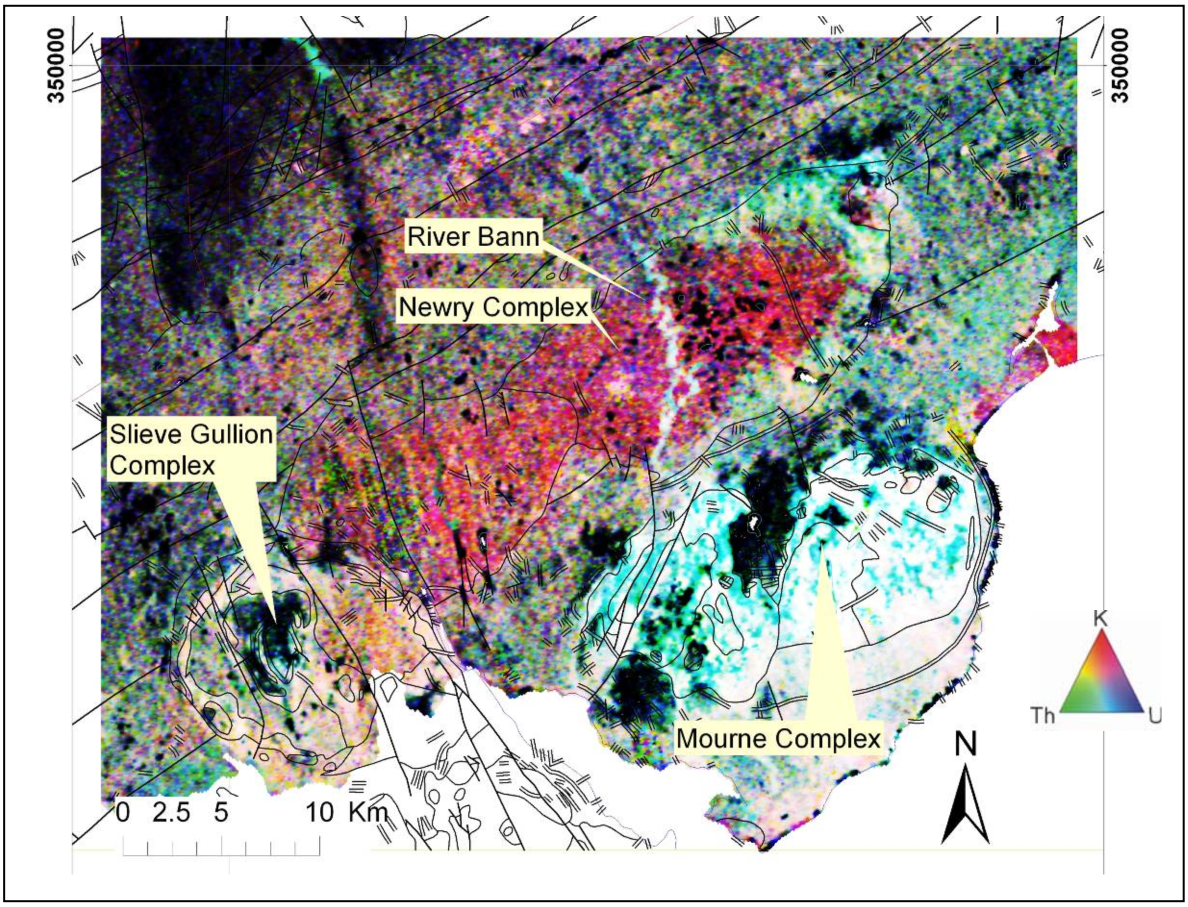


Figure 19. Ternary image of Palaeogene intrusives, Co Down and Armagh with solid geology lines

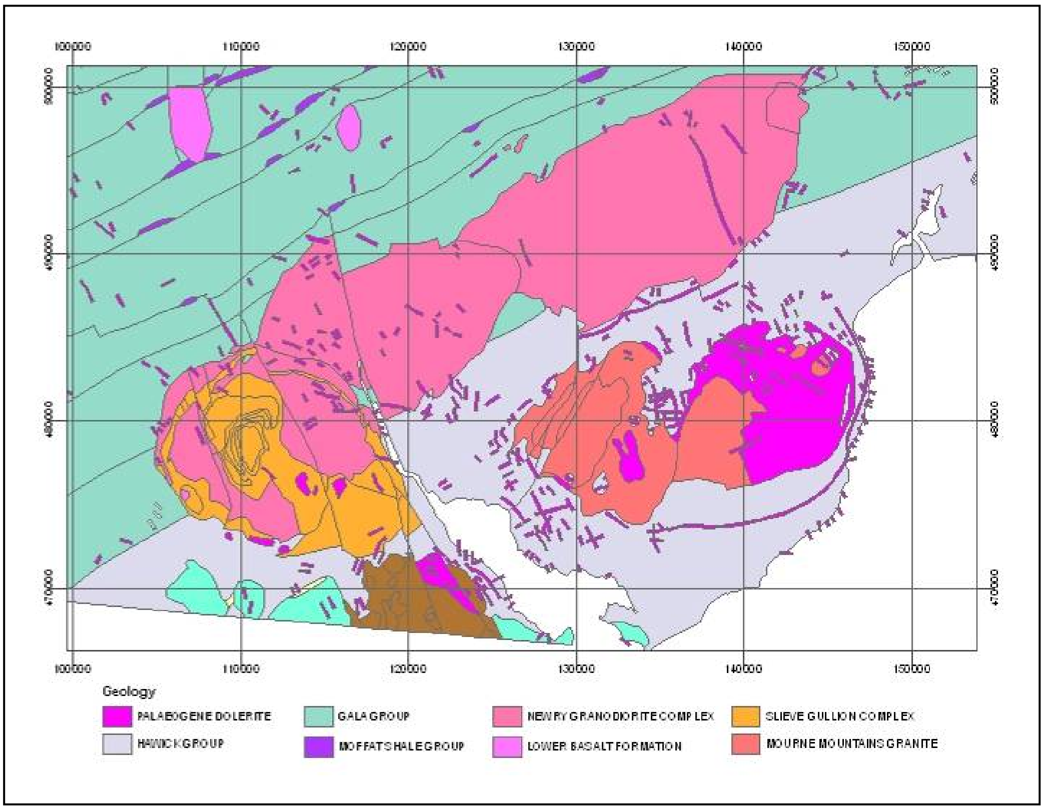


Figure 20. Simplified solid geology of the Palaeogene intrusives of Co Down and Armagh

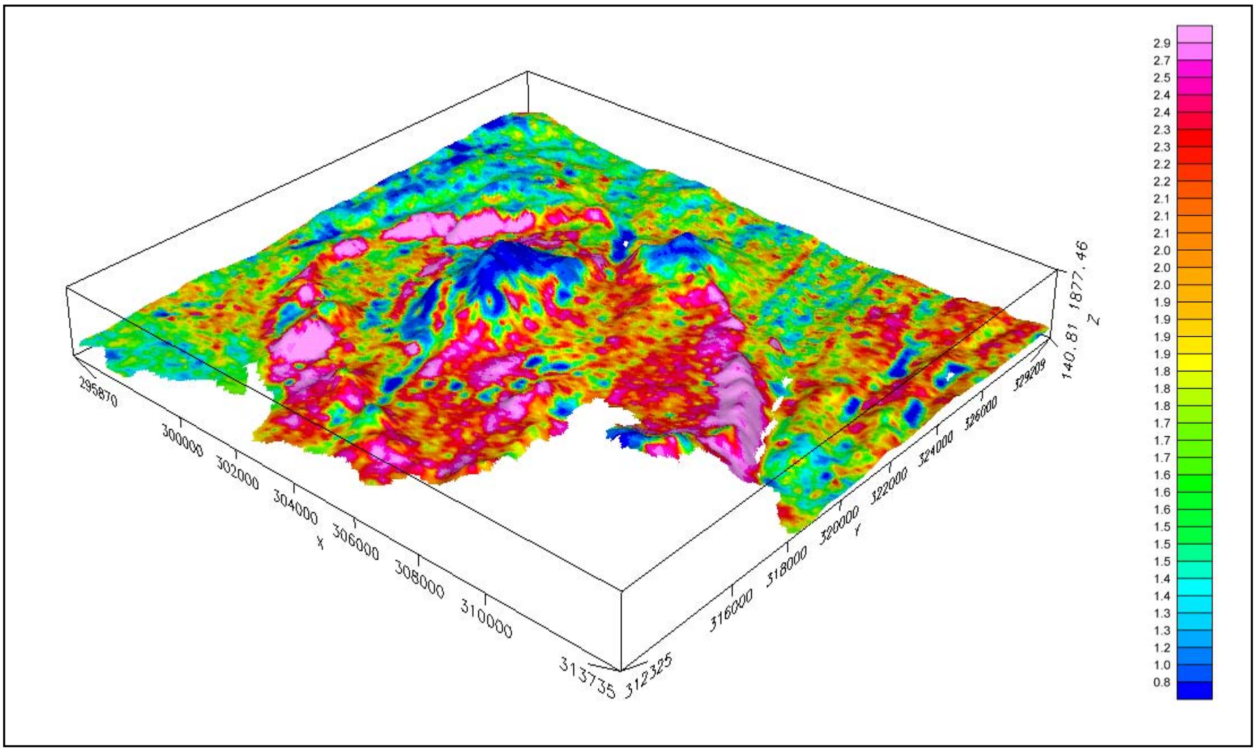


Figure 21. K (%) image draped on DTM, Slieve Gullion Complex, viewed from the SE

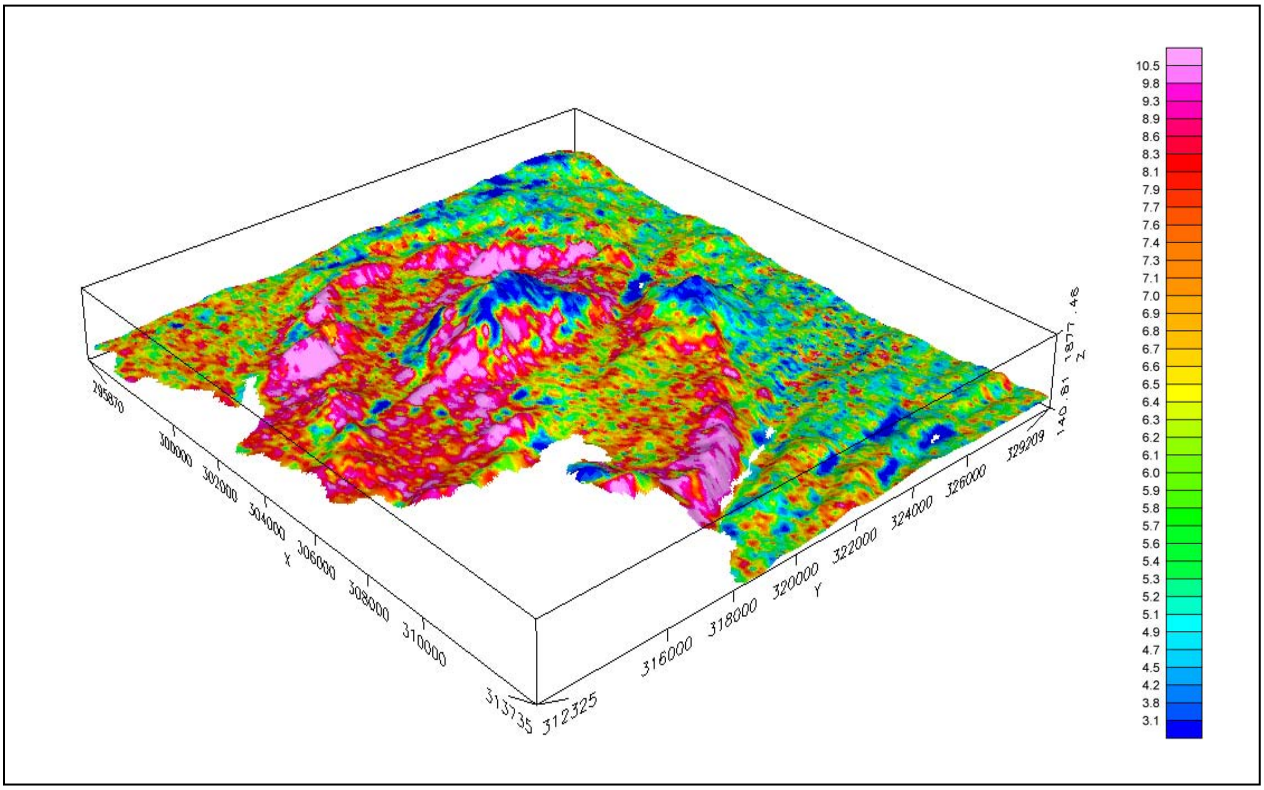


Figure 22. Th (ppm) image draped on DTM, Slieve Gullion Complex, viewed from the SE

superficial deposits. These features mirror the direction of the last ice movement during the Quaternary (Bazley, 2004; Geological Survey of Northern Ireland, 1991).

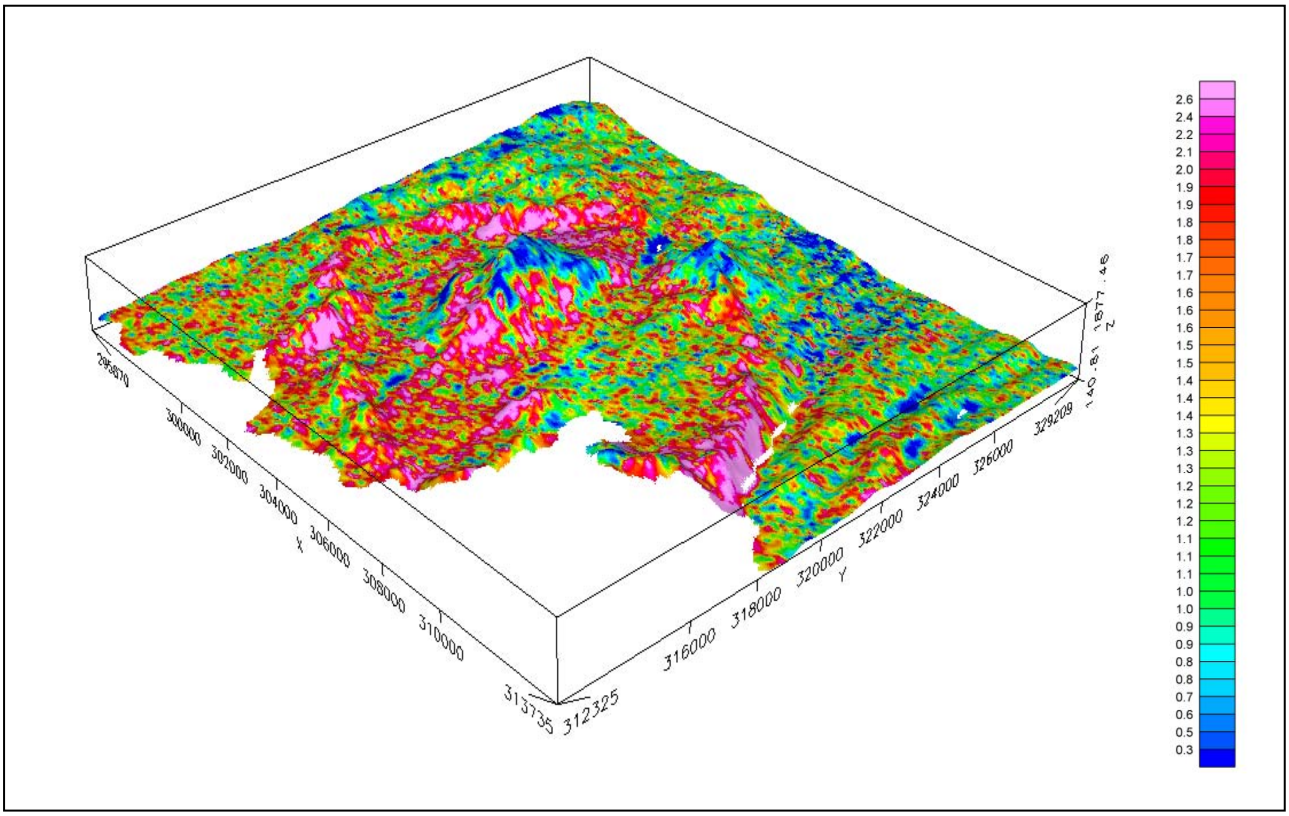


Figure 23. U (ppm) image draped on DTM, Slieve Gullion Complex, viewed from the SE

2.2.5 Other areas

Plots of the SW of Northern Ireland do not show major differences to the images of the whole of Northern Ireland. There is slight enhancement of features for K and eTh, but virtually no difference for eU.

2.3 SITE-SPECIFIC FEATURES

Towns and villages have a distinctive signature. They appear as 'brighter' spots on the ternary image with a very speckled appearance (Figure 24). This speckled appearance is indicative of the greater variability of data acquired at a higher flying height. Collecting data over urban areas at 240 m will reduce greatly the counts obtained, and increase the statistical uncertainty, relative to data obtained at 56 m. During processing, the data are corrected for altitude to 56 m. This will enhance the counts, but has the effect of amplifying the initial much greater uncertainty in each count. The high-fly zones are thus areas of relatively noisy data, manifested in the speckled appearance on the images, as neighbouring values differ by a greater amount. On the basalts, built-up areas have generally higher K than the surrounding countryside (Figure 25) and patchily higher eU and eTh (Figures 26- 27), with the highs not always coincidental. The probable explanation is the higher radioactivity of hard materials in buildings, roads and pavements in an area where the geological background is very low in radioelements and the complex mix of materials and changes in geometry causing a highly variable detector response that adds to the variability due to the flying height effect. There are some features that appear to relate to open ground in built-up areas.

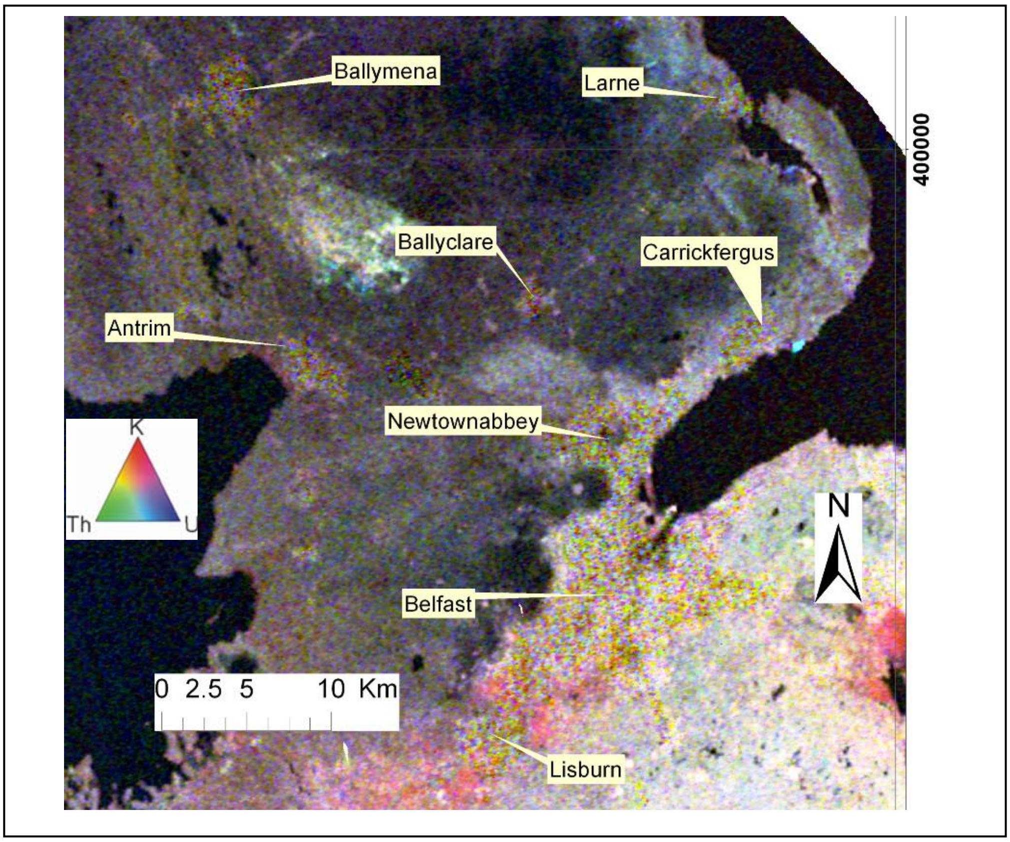


Figure 24. Ternary image showing the effect of urban areas

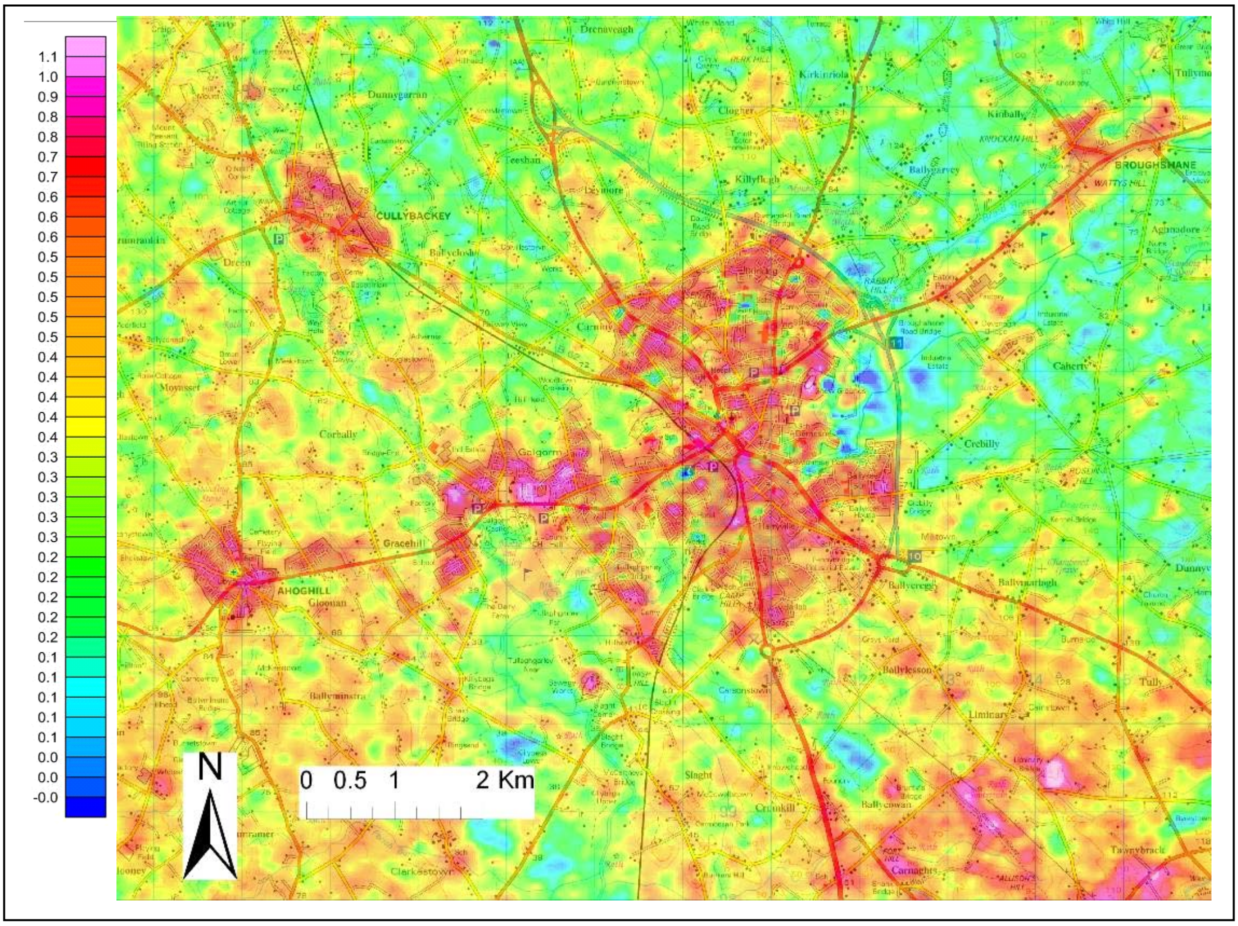


Figure 25. K (%) image of Ballymena and neighbouring towns

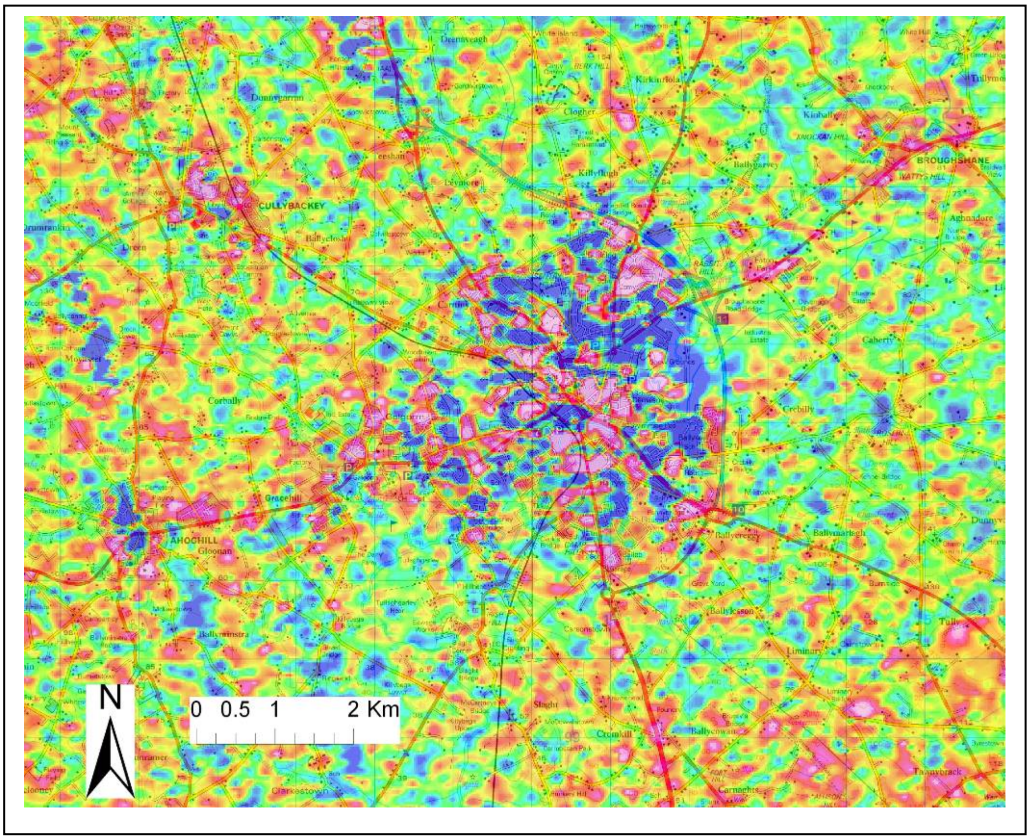


Figure 26. eU (ppm) image of Ballymena and neighbouring towns

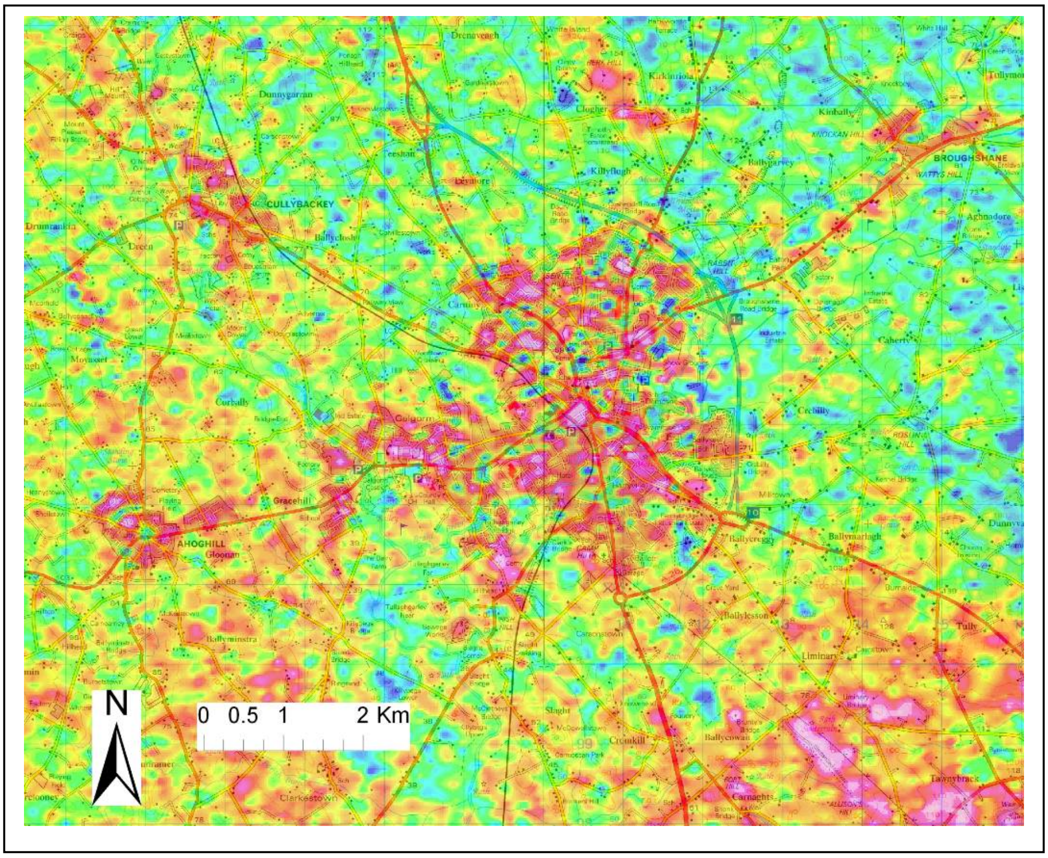


Figure 27. eTh (ppm) image of Ballymena and neighbouring towns

On other rock types the speckled appearance of towns and villages on the ternary image is still present although the levels of K, eU and eTh may not be appreciably higher than the surroundings. For example, Belfast is distinguishable on ternary plots (Figure 24) but shows a lower contrast on individual element plots. In such cases the inherent noisiness of the data appears to be the primary effect, with little average difference between the radioelement signatures of the built environment and the local geology.

Mudflats at the north end of Strangford Lough, in Dundrum Bay, NE of Newcastle and at Greencastle, in the NE of Carlingford Lough, have high K, but low eU and eTh (Figures 2, 14, 17 and 19). Normally fine-grained sediments are higher in all elements. This suggests a particularly K-rich mineral assemblage, dominated perhaps by illitic clay minerals, or an anthropogenic input such as potash fertilisers. Beach sands and dunes associated with the mudflats in Dundrum Bay are high in all three radioelements. Size-fractionation of different K, eU and eTh minerals seems the likeliest explanation. Similar sands are absent in the other sea loughs, or of more limited extent and covered by the tide when data were acquired. High tidal conditions may explain the lack of similar features in Larne Lough and Lough Foyle, or may reflect the differing geology of the hinterland.

The power station at Carrickfergus is associated with higher eU and eTh on the adjoining beach, without associated K (Figure 28). This looks like a typical fly ash signature. The response is very similar to that seen for coal fired power stations in the English Midlands on the Hi-RES-1 airborne radiometric dataset (Beamish *et al*., 2000; Kestell, 2000; Lahti and Jones, 2003; Peart *et al*., 2003). When overlaid on aerial photography (Figure 29) the anomaly is clearly related to an area of land reclaimed from the sea.

A landfill at High Town to the west of Belfast shows up as a high in all three radioelements (Figures 30-32). The Culmore Landfill on Lough Foyle shows similar features. Other landfills are in general not distinguishable on regional plots. Some quarries are associated with radiometric anomalies (Figure 32), such as those around Belfast (e.g. Ballycullo, Castle Robin) and two quarries near Ballynagarrick. There are two features with higher K, eU and eTh on the west side of the Belfast Docks, adjacent to the Belfast City airport, and just north of the dock entrance. These probably reflect finer grained sediment in the harbour area.

3 Results and interpretation: ^{137}Cs

In addition to potassium, uranium and thorium, the naturally-occurring radionuclides detected by gamma spectrometry, ^{137}Cs data were also acquired. Least-squares fitting was applied to spectra to calculate ^{137}Cs concentrations in kBqm^{-2} using the Praga3^{TM} full spectrum processing extension of Geosoft Oasis Montaj^{TM} software (Figure 33). Full details of processing procedures can be found in Beamish *et al.*, (2007). The ^{137}Cs data are not yet calibrated to ground gamma spectrometry measurements and, due to the depth distribution assumptions made in the software, corrections may need to be applied. This could result in a shift in the values but the relative patterns of ^{137}Cs observed in Figure 33 are likely to be maintained.

The most obvious feature of the data is the well developed banding of higher values oriented NNW-SSE and WNW-ESE. Concern arose that some of the banding was parallel to flight line direction. However, it appears in both the full dataset (Figure 33) and in data from only the tie-lines available in Blocks A and B (Figure 34), albeit at a lower resolution in the latter. Consistent results between K, eU, and eTh processed by Praga3 and the JAC processed data also gives confidence in the Praga3 least-squares fitting method (Beamish *et al*., 2007). Figures 35 and 36 are plots of flight line segments with greater than 2.7 kBqm^{-2} ^{137}Cs. They show that individual flight lines are not responsible for the higher values. The banding does not coincide with the boundaries of the blocks of airborne data acquisition (Figures 35 and 36) and the features extend

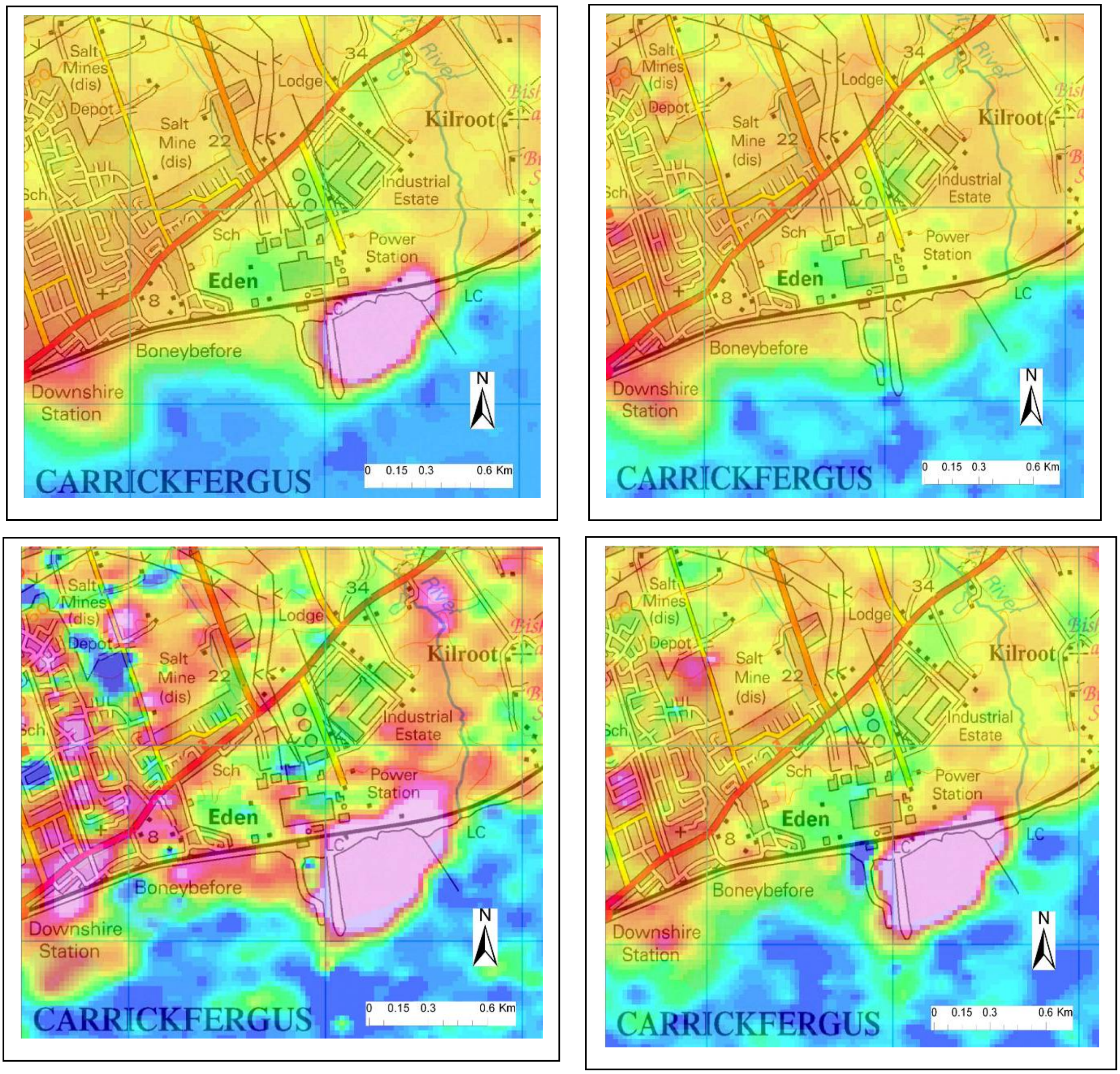


Figure 28. CarrickFergus Power Station: Total (cps), K (%), eU (ppm) and eTh (ppm) images overlaid on Ordnance Survey of NI map (colour scales as in Figure 1 b, c, d)

into the Irish Republic in data acquired there after the Tellus survey was completed (the data contains commercial in confidence information, so plots cannot be shown here).

Higher ^{137}Cs is related to higher ground in some areas, but the banding appears to reflect rainfall which resulted in deposition of ^{137}Cs in linear zones. Linear features are apparent in data from other parts of the UK (Sanderson *et al*., 2001) and in observed and theoretical ^{137}Cs deposition in France (Renaud *et al*., 2003; Roussel-Debel *et al*., 2007).

3.1 SOURCES OF CS IN THE ENVIRONMENT

Sources of ^{137}Cs to the atmosphere include: atmospheric weapons testing, which began in 1945 and peaked between September 1961 and December 1962; release following the Windscale accident on October 10th, 1957 and release following the Chernobyl accident on 26th April, 1986. ^{137}Cs is present in the atmosphere mostly as particulate species with wet deposition mechanisms dominating (Smith and Clark, 1988). Debris from the Windscale accident in 1957 had little

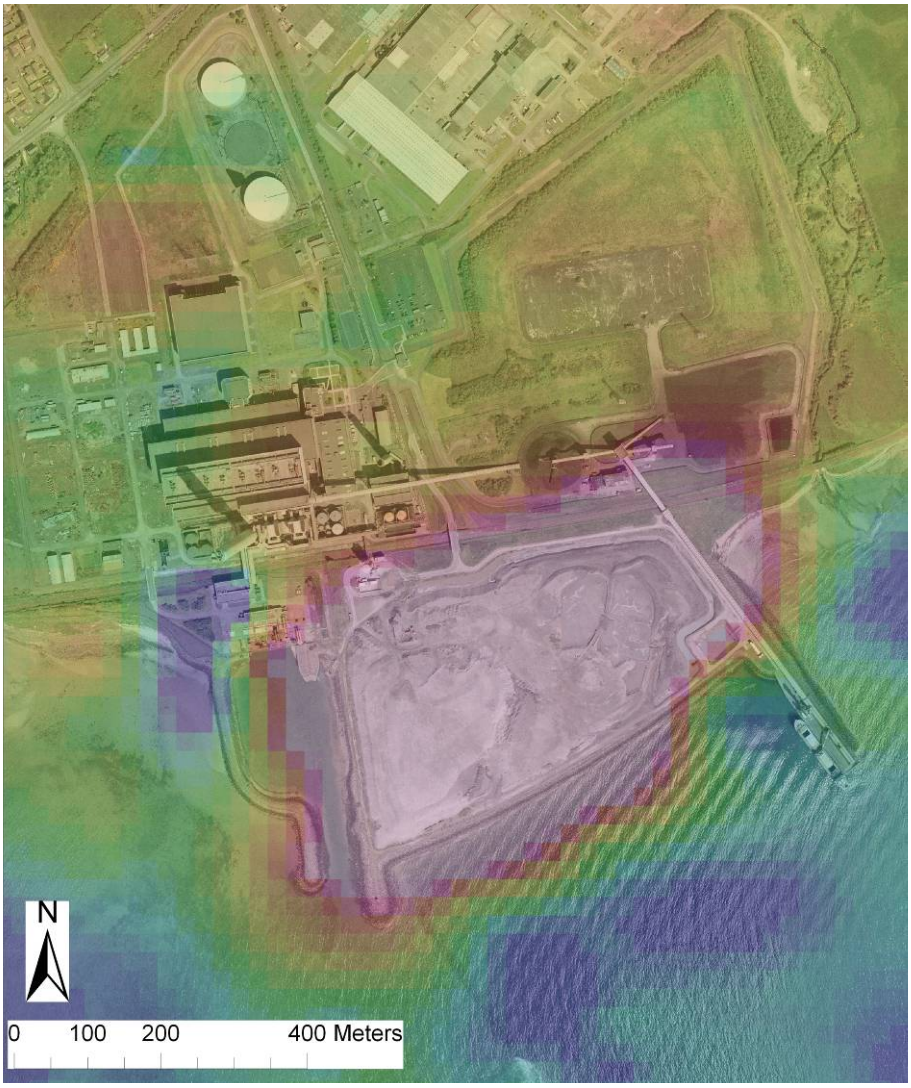


Figure 29. Th (ppm) image superimposed on air photo of Carrickfergus power station (colour scale as in Figure 1d)

impact on Northern Ireland due to the direction of movement of the plume (Crick and Linsley, 1982) so the dominant sources of the ^{137}Cs deposited over Northern Ireland are likely to be atmospheric weapons testing and the Chernobyl accident, with the dominance of the source likely to vary from location to location (McAulay and Moran, 1989). Around the coast, the sediments are likely to include a component derived from discharges from Sellafield into the Irish Sea.

Smith and Clark (1988) reported shortly after the Chernobyl accident that deposited ^{137}Cs was closely related to rainfall intercepting the plume; radar measurements (at the time of the Chernobyl release) showed narrow bands of rain moving across the UK and, where they intercepted the plume, radionuclide deposition would have also occurred in narrow bands. Unfortunately, radar data is not available for Northern Ireland from 1986, the radar images referred to by Smith and Clark related mainly to England and Wales, but showed the type and orientation of rainfall present during the critical plume interception period. In a fuller paper (Smith and Clark, 1989), they expanded, stating that: “Rainfall tends to be quite spatially variable and depends on the nature of the precipitating clouds, and on the underlying topography. Much of the rain affecting the Chernobyl plume over the United Kingdom came from deep

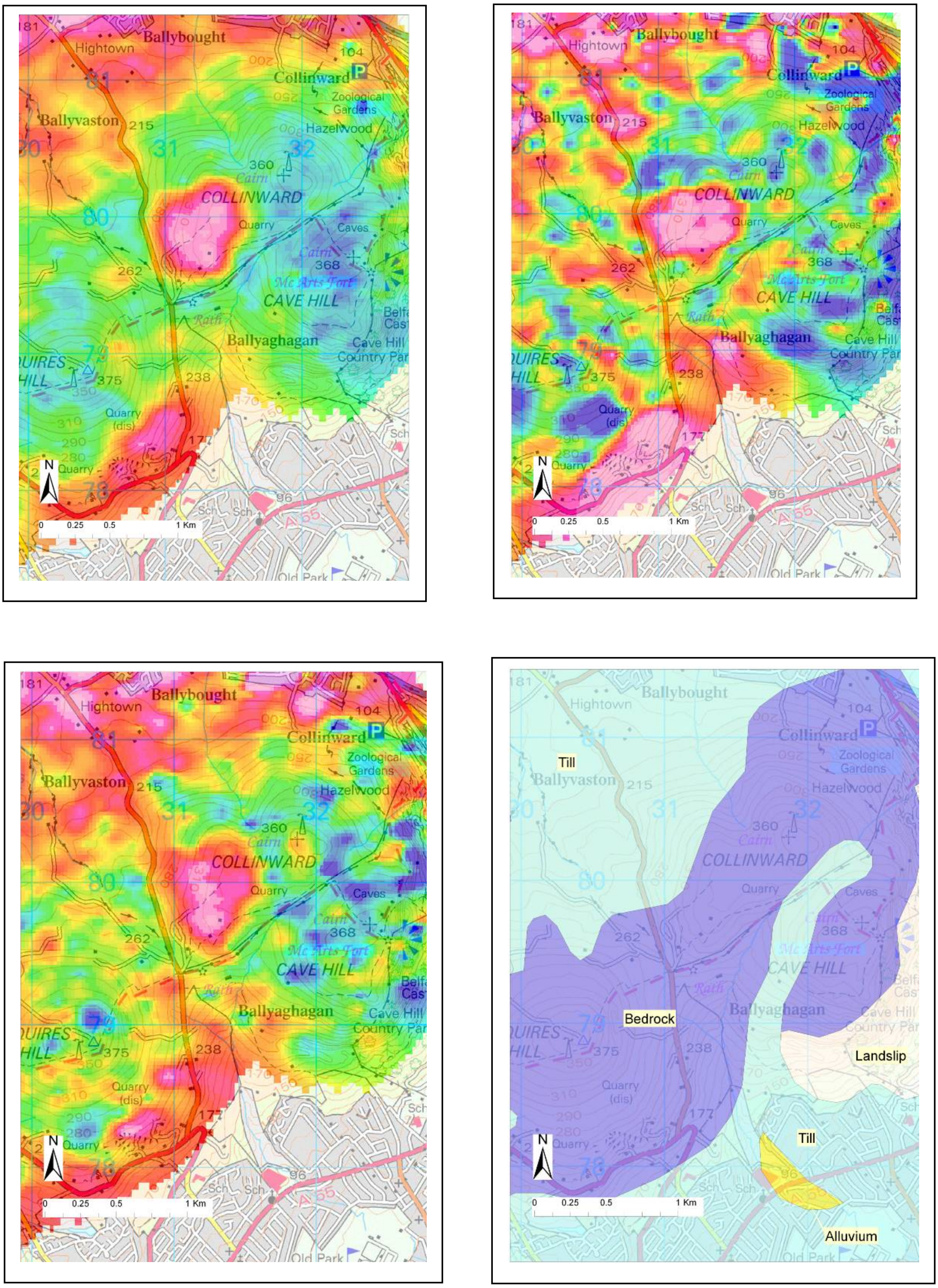


Figure 30. K (%), eU (ppm) and eTh (ppm) and superficial geology images of High Town Landfill site, NW of Belfast superimposed on Ordnance Survey of NI map (colour scales as in Figures 25- 27)

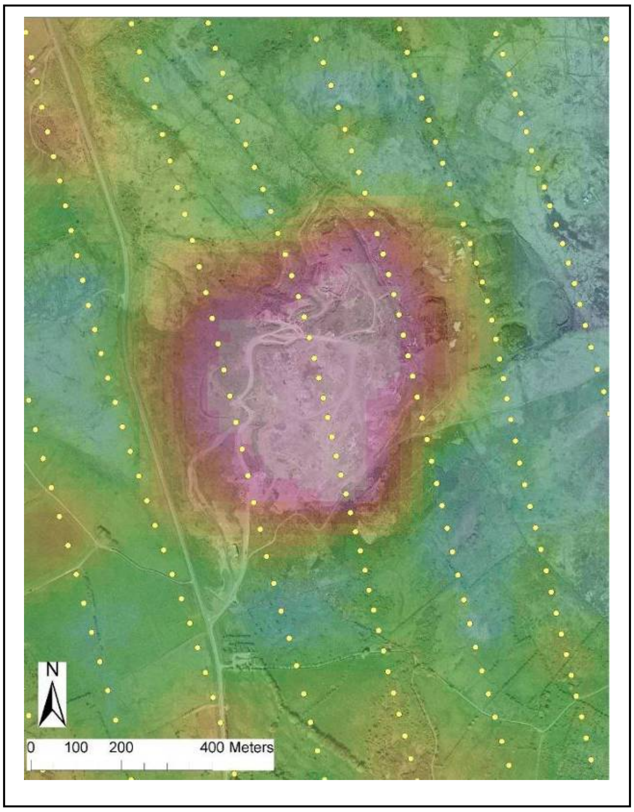


Figure 31. K (%) image for the basalts superimposed on air photo for High Town landfill site (colour scale as in Figures 15 and 25) with data points shown

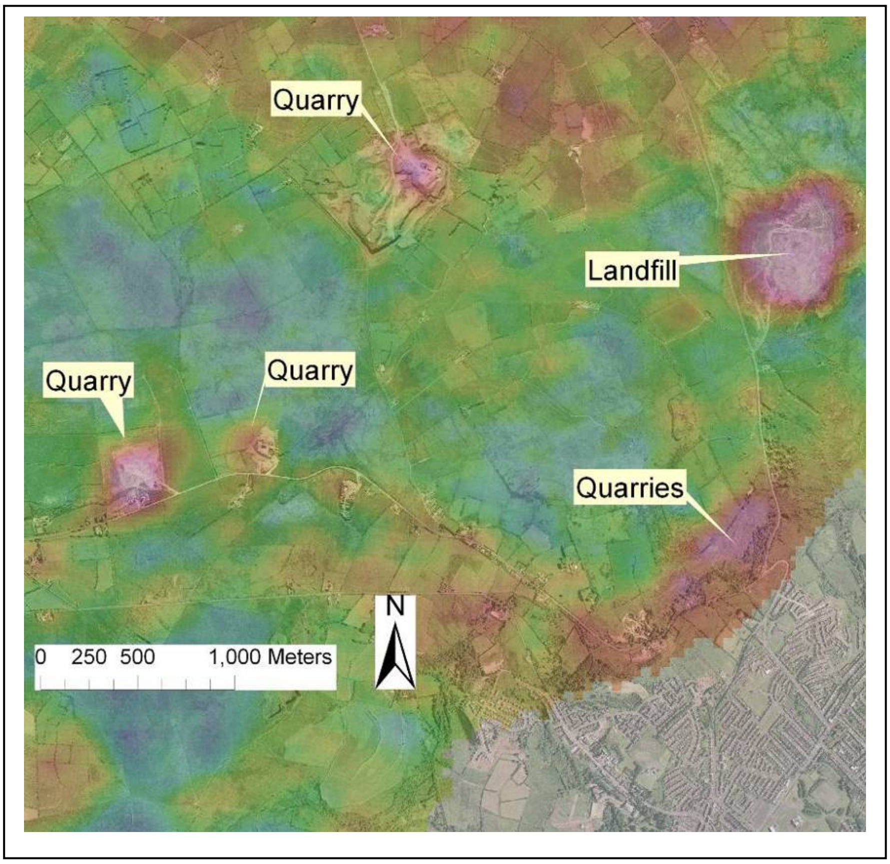


Figure 32. K (%) image of basalts superimposed on air photo shows quarries to W of High Town Landfill NW of Belfast (colour scale as in Figures 15 and 25)

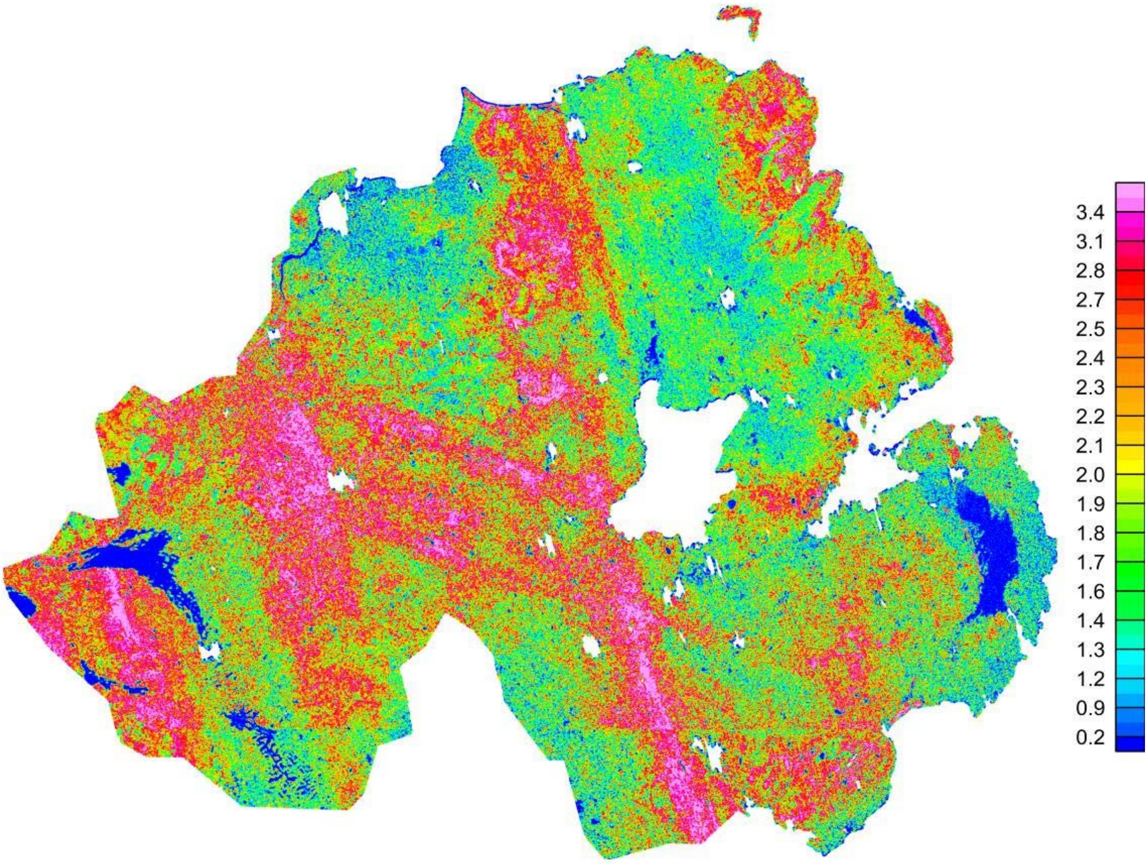


Figure 33. **^{137}Cs over Northern Ireland (kBqm^{-2}). When aircraft altitude was greater than 160 m, data appear masked**

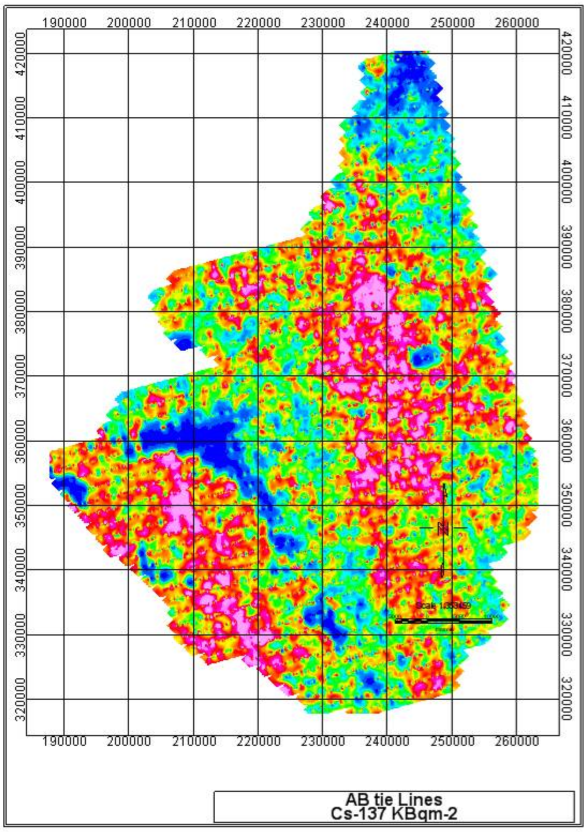


Figure 34. ^{137}Cs (kBqm^{-2}) for Block A and B tie-lines (tie-line spacing 2000 m)

Figure 35. Plot of TELLUS survey flight lines over Northern Ireland showing line segments where ^{137}Cs > 2.7 kBqm^{-2}. Block C from the 2005 survey outlined in black to demonstrate that band structure is not on the block boundary

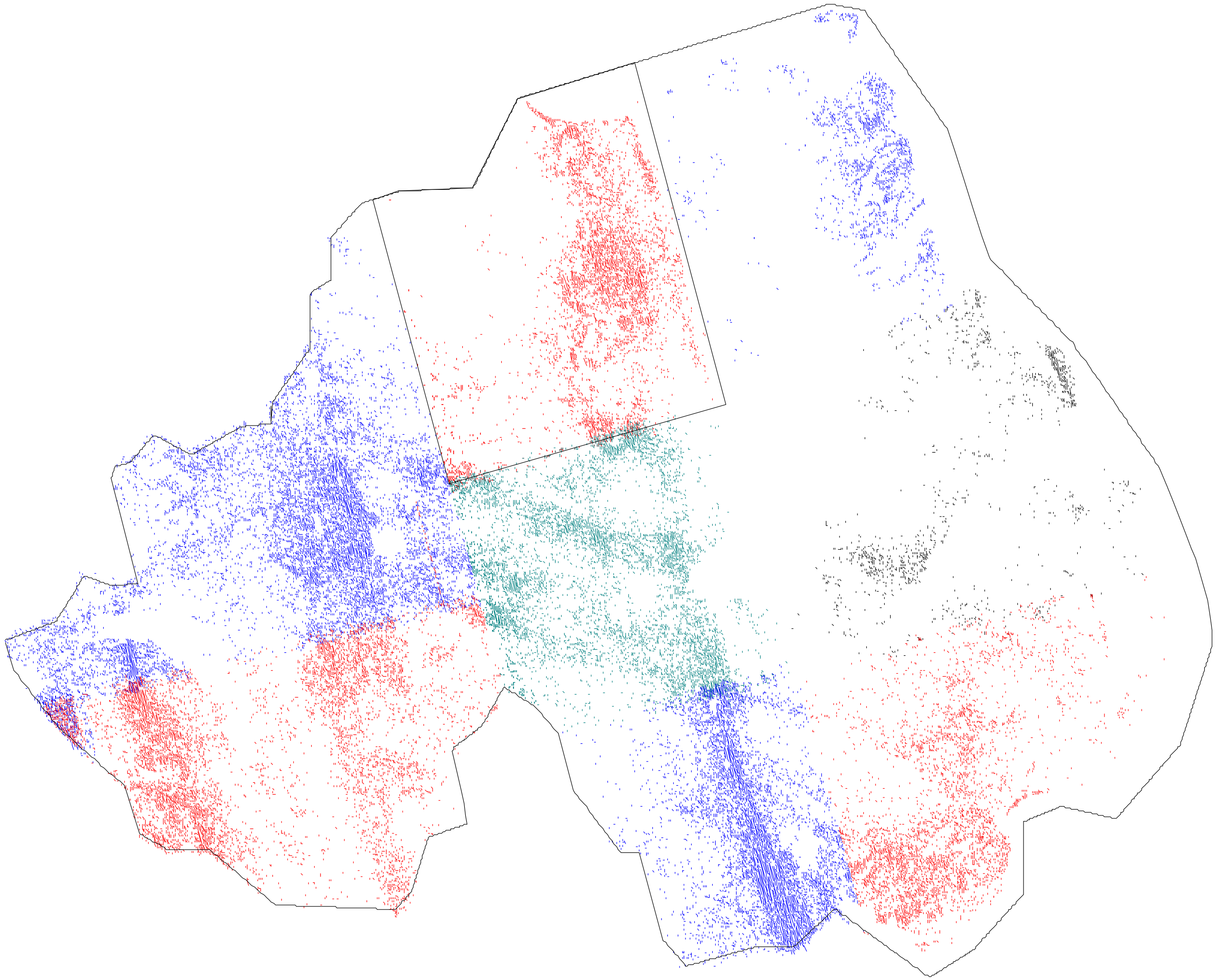


Figure 36. Plot of TELLUS survey flight lines over Northern Ireland where $^{137}Cs > 2.7$ $kBqm^{-2}$, coloured by block (data not trimmed to ideal block, so overlap occurs). Block C from the 2005 survey outlined in black to demonstrate that banding is not the block boundary

convective storms. These left narrow footprints of rainfall elongated along wind, with similar footprints of activity-deposition." This observation is consistent with our high-resolution ^{137}Cs data of Northern Ireland; indeed the estimated total deposition of ^{137}Cs calculated by Smith and Clark using rainfall data, air concentrations, and a dimensionless washout factor of $6.5\ 10^{5}$, displays a banded spatial pattern with an orientation consistent with the Tellus ^{137}Cs data. Contours of empirically derived total deposition of ^{137}Cs from Chernobyl, over the United Kingdom agree well both spatially and in magnitude with the high-resolution ^{137}Cs data of Northern Ireland (Smith and Clark, 1989).

Previously, Chernobyl fallout was distinguished from weapons testing fallout by a ^{137}Cs to ^{134}Cs ratio of 1.90 (McAulay and Moran, 1989). Results of soil analysis from their study, from over 110 sites, showed a mean deposition of 3.2 $kBqm^{-2}$ of ^{137}Cs due to Chernobyl (range 0.3 to 14.2 $kBqm^{-2}$). Total values, measured over Northern Ireland by the Tellus airborne gamma spectrometry survey ranged up to 9.92 $kBqm^{-2}$, consistent with McAulay and Moran's findings, when the decay of ^{137}Cs (half-life of 30.17 years) that has occurred since 1986 is taken into account. McAulay and Moran (1989), also noted that 24 hr rainfall figures may not have represented the fallout levels in view of the rapid movement and dispersion of the radiation cloud. In effect, a rainfall map could only indicate areas with relatively low deposition due to minimal or zero rainfall. It is known that ^{137}Cs is strongly bound to the upper or litter horizons in soil and to micaceous minerals in poor or bare earth (McAulay and Moran, 1989). Pre-Chernobyl ^{137}Cs figures for the 111 sites across Ireland were found to be in the range 0.6-0.8 $kBqm^{-2}$ (McAulay and Moran, 1989). In a few shallow upland soils up to 5 $kBqm^{-2}$ of pre-Chernobyl ^{137}Cs were found reflecting high annual rainfall in these areas (McAulay and Moran, 1989).

3.2 RAINFALL DATA

Average 24-hour rainfall data from 181 stations over Northern Ireland were obtained from the Meteorological Office for the 3rd and 4th of May, 1986, when the Chernobyl plume passed over the UK. These data show little correlation with the ^{137}Cs data (Figure 37) and do not account for

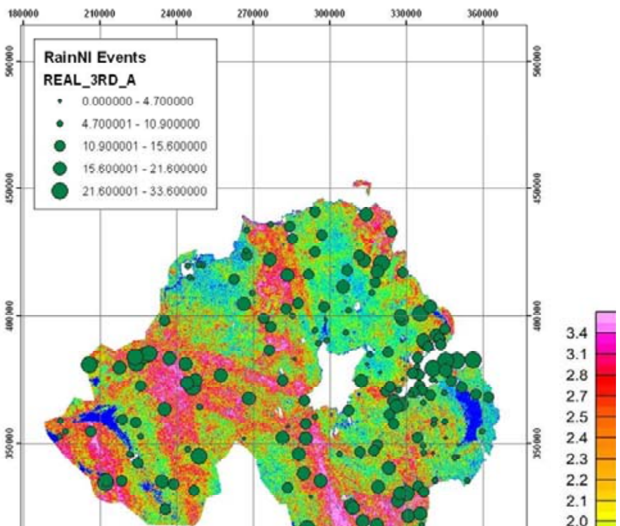


Figure 37. ^{137}Cs over Northern Ireland $kBqm^{-2}$ showing average 24-hour rainfall for the 3rd and 4th of May, 1986 in mm (●).

variation in the ^{137}Cs data indicated by an analysis of variance. As McAulay and Moran (1989) noted, 24-hr rainfall figures may not have represented the fallout levels in view of the rapid movement and dispersion of the radiation cloud. In addition, although the deposition from the Chernobyl accident was a discrete event when compared to years of weapons testing fallout, deposition from different phases of the plume, with different heights of material will have contributed to a variable deposition pattern. The Met. Office NAME dispersion Model (http://www.metoffice.gov.uk/environment/name.html) demonstrates the passage of the Chernobyl plume over time (Figures 38-43). Smith and Clark (1989) showed a map of rainfall which intercepted the Chernobyl plume, excluding rain that fell but which did not intercept the plume. This contoured map shows a much better correlation to the high-resolution ^{137}Cs data of Northern Ireland, than the 24-hour average rainfall

3.3 DETAILED PATTERNS

Figures 44 to 50 show the ^{137}Cs in more detail, over selected areas, and allow examination of the spatial patterns. The eastern coast of Northern Ireland received heavy rainfall during the passage of the Chernobyl plume and therefore received elevated ^{137}Cs deposition (Smith and Clark, 1989). This can be seen in the high-resolution ^{137}Cs data for this part of Northern Ireland (Figure 44).

Figure 45 shows high ^{137}Cs over the high ground of the Mourne Mountians and Slieve Croob with a band of higher values extending from the high ground of Slieve Gullion to the south-west corner of Lough Neagh. This NNW-SSE band is parallel to flight line direction, but is approximately 6 km wide and does not relate to a single flight line, or group of flight lines. The cause of this band is likely to be narrow footprints of rainfall elongated along wind, which intercepted the Chernobyl plume (Smith and Clark, 1989).

Moving to the north, in addition to the NNW-SSE banding described, banding in a WNW-ESE direction is evident (Figure 46), probably reflecting a different orientation of rainfall over that section of the country, or reflecting a different phase of deposition either from the Chernobyl plume (see Figures 38-43) or from earlier weapons fallout High ^{137}Cs is also related to the high ground over Slieve Gallion, and relief features over the Sperrin Mountains are evident in the data (Figure 47).

Further to the north, on the North Coast east of Portrush, high ^{137}Cs is observed along the coast (Figure 48). This is likely to be related to discharges from Sellafield. High ^{137}Cs is also observed on the topographic highs of Round Knowe, Keady Mountain, Craiggore and Benbradagh. A thin band (1.5 to 2 Km wide) of higher ^{137}Cs values in a NNW-SSE direction is apparent to the west of Coleraine, and again probably relates to rainfall.

To the far west of Northern Ireland, high ^{137}Cs is apparent to the south of Lower Lough Erne, again in a banded structure. The drumlin fields are also apparent in the texture of the ^{137}Cs data, reflecting the drainage network around the drumlins (Figure 49) as observed in the data for naturally-occurring radionuclides (Figures 2 and 6).

^{137}Cs appears low over the High Town landfill area, in contrast to the natural radionuclides (Figures 30-32 and 50). This is probably due to material unaffected by ^{137}Cs deposition covering the ground, and therefore masking the ^{137}Cs signature.

3.4 FURTHER INVESTIGATION AND GEOSTATISTICAL ANALYSIS

The ^{137}Cs data comprise 1, 195, 751 measurements, ranged from -4.58 $kBqm^{-2}$ to 9.92 $kBqm^{-2}$, with a mean of 2.03 $kBqm^{-2}$ and a standard deviation of 0.99. In order to look at the data in more detail, the Version-2 ^{137}Cs database (masked when aircraft altitude was greater than 160m) was exported to a GIS and a random sub sample of 50,000 points was selected using Hawth's tools. Data points that had been selected in this sub sample but had been masked due to an aircraft

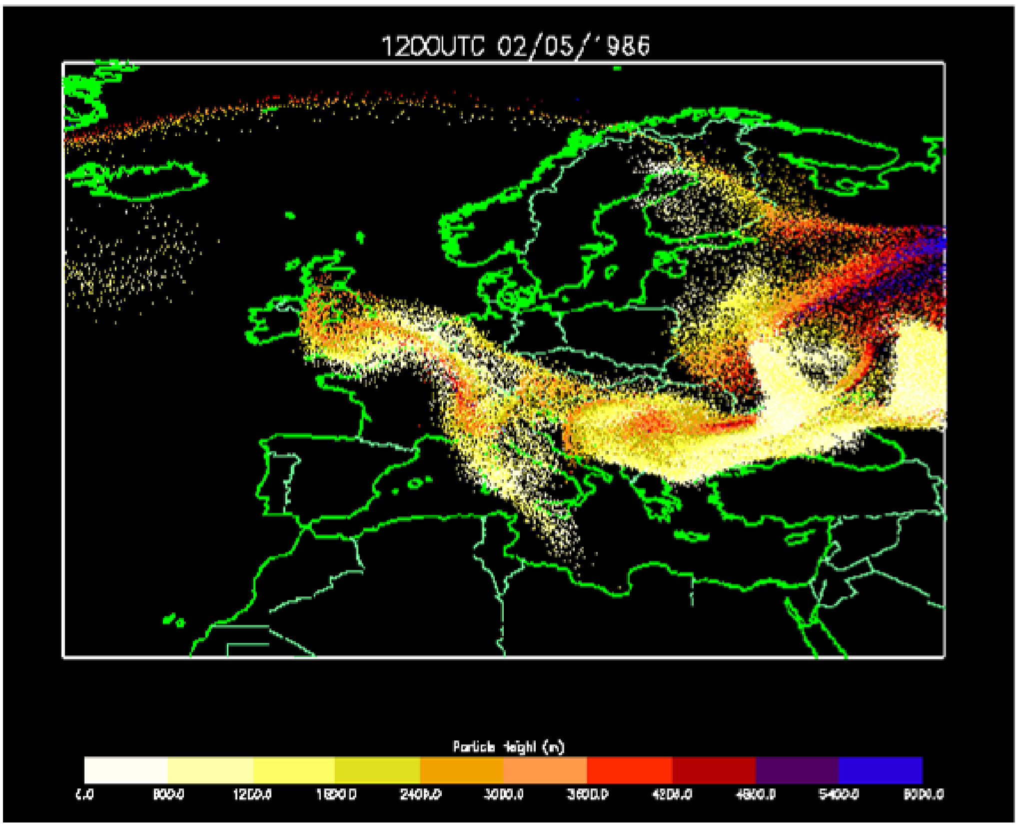


Figure 38. Met Office NAME dispersion Model of the Chernobyl plume at 12:00 on the 2nd May 1986

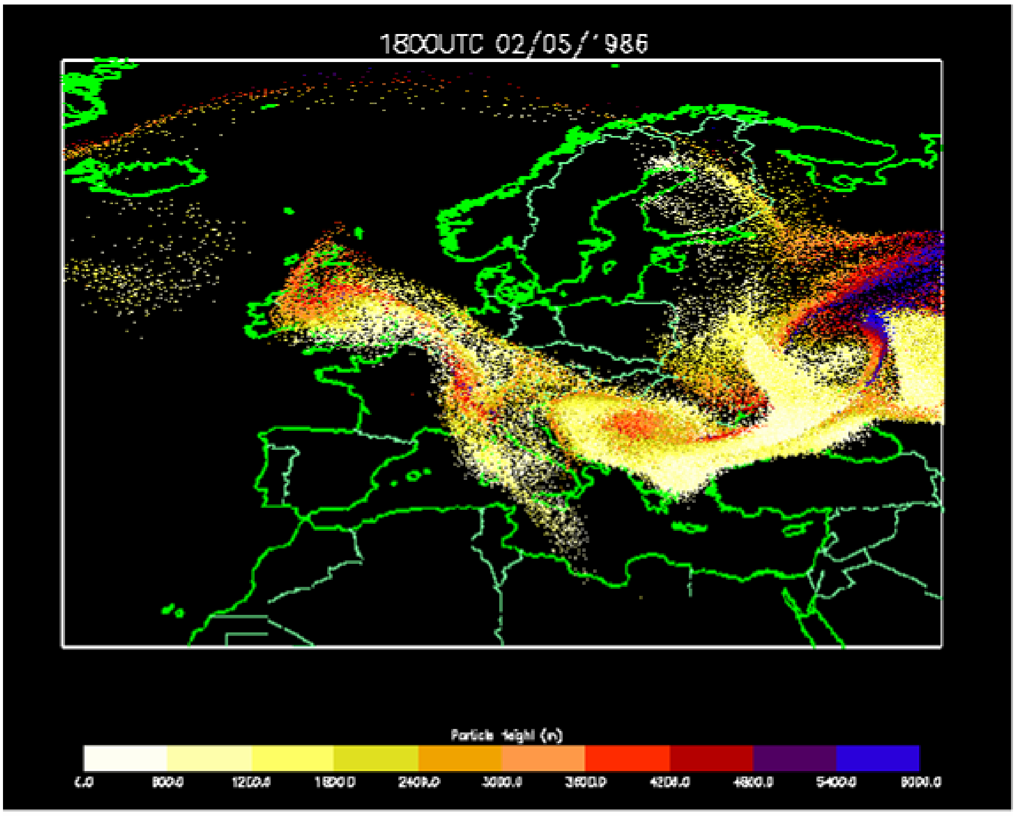


Figure 39. Met Office NAME dispersion Model of the Chernobyl plume at 18:00 on the 2nd May 1986.

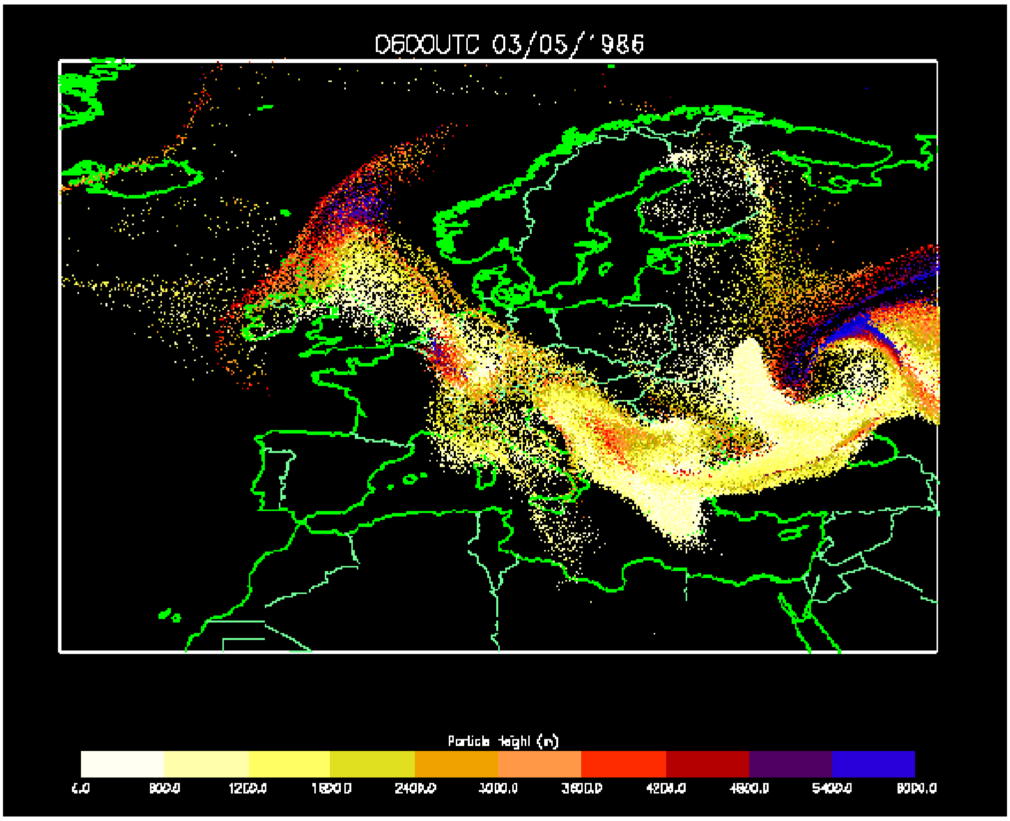


Figure 40. Met Office NAME dispersion Model of the Chernobyl plume at 06:00 on the 3rd of May, 1986.

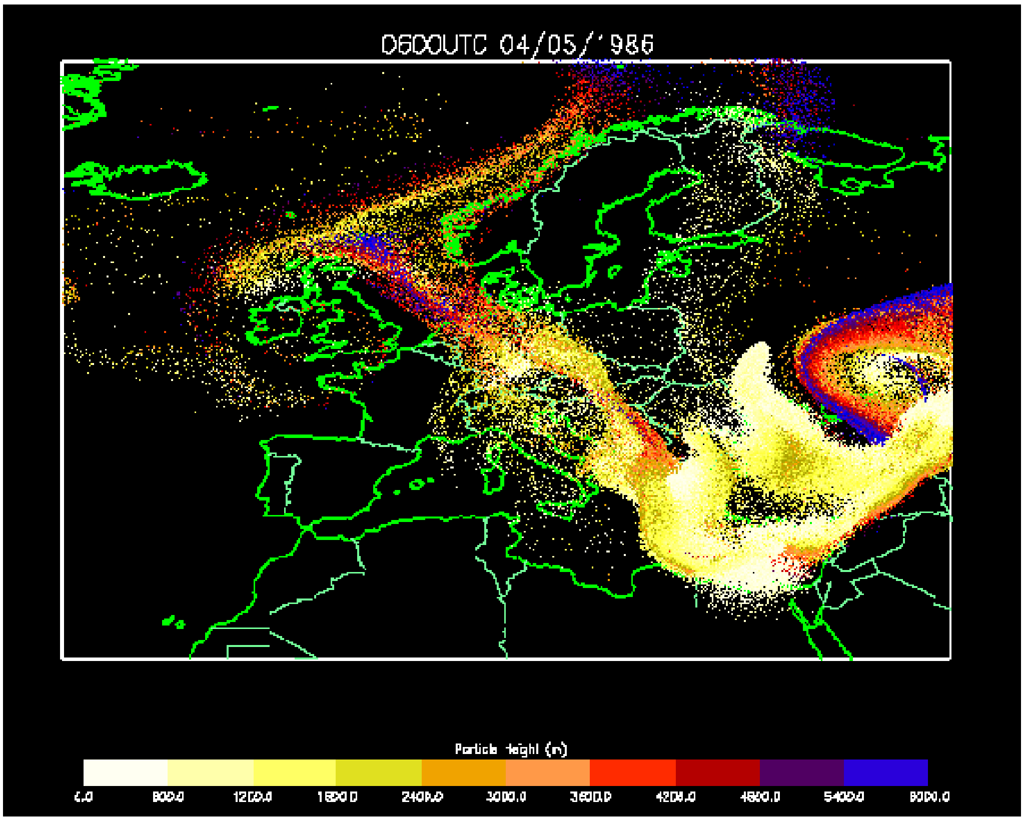


Figure 41. Met Office NAME dispersion Model of the Chernobyl plume at 06:00 on the 4th of May, 1986.

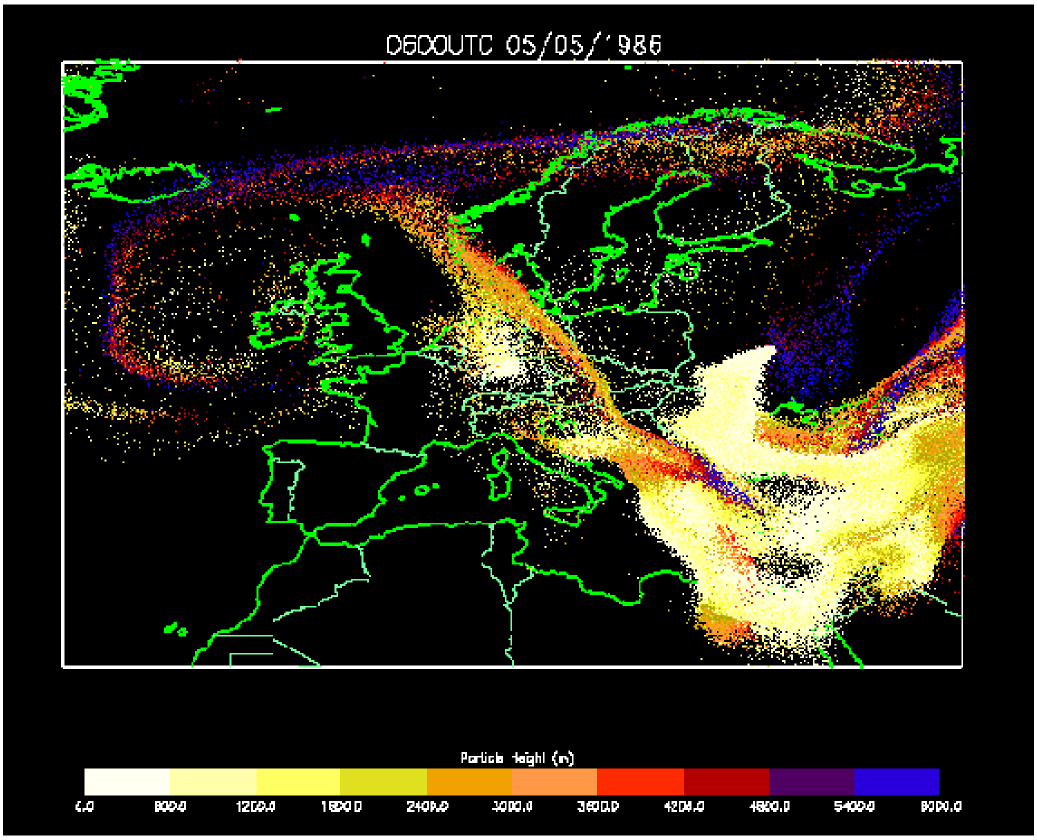


Figure 42. Met Office NAME dispersion Model of the Chernobyl plume at 06:00 on the 5th of May, 1986.

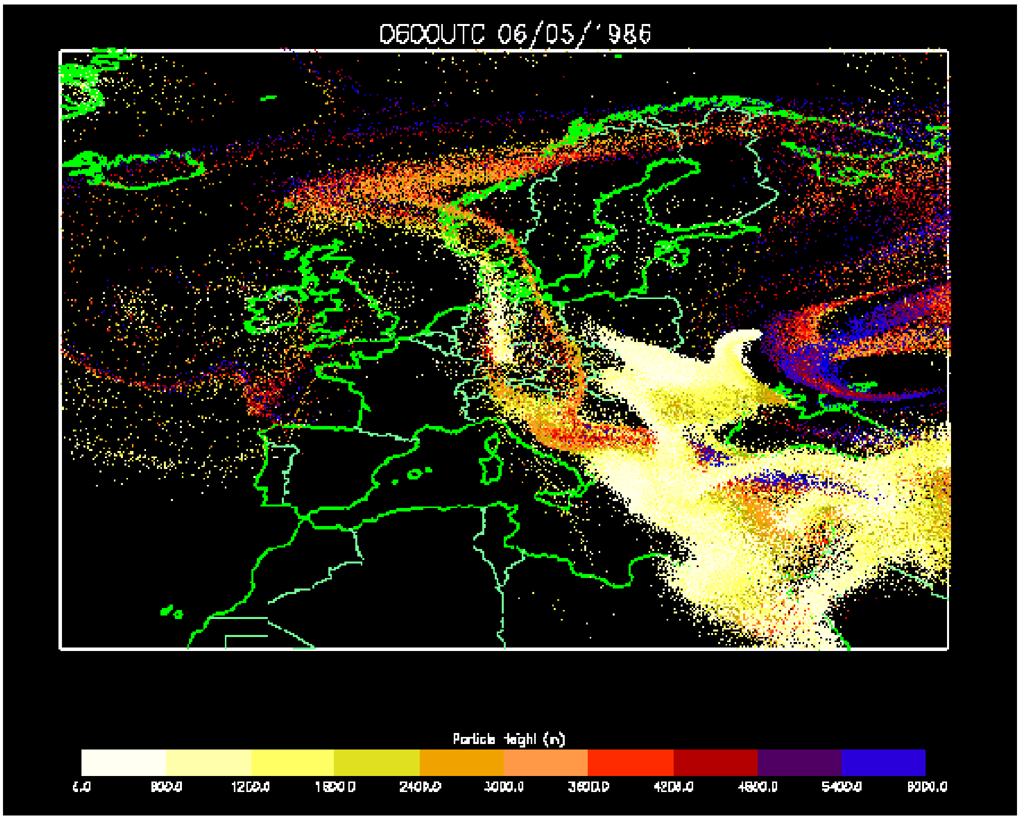


Figure 43. Met Office NAME dispersion Model of the Chernobyl plume at 06:00 on the 6th of May, 1986.

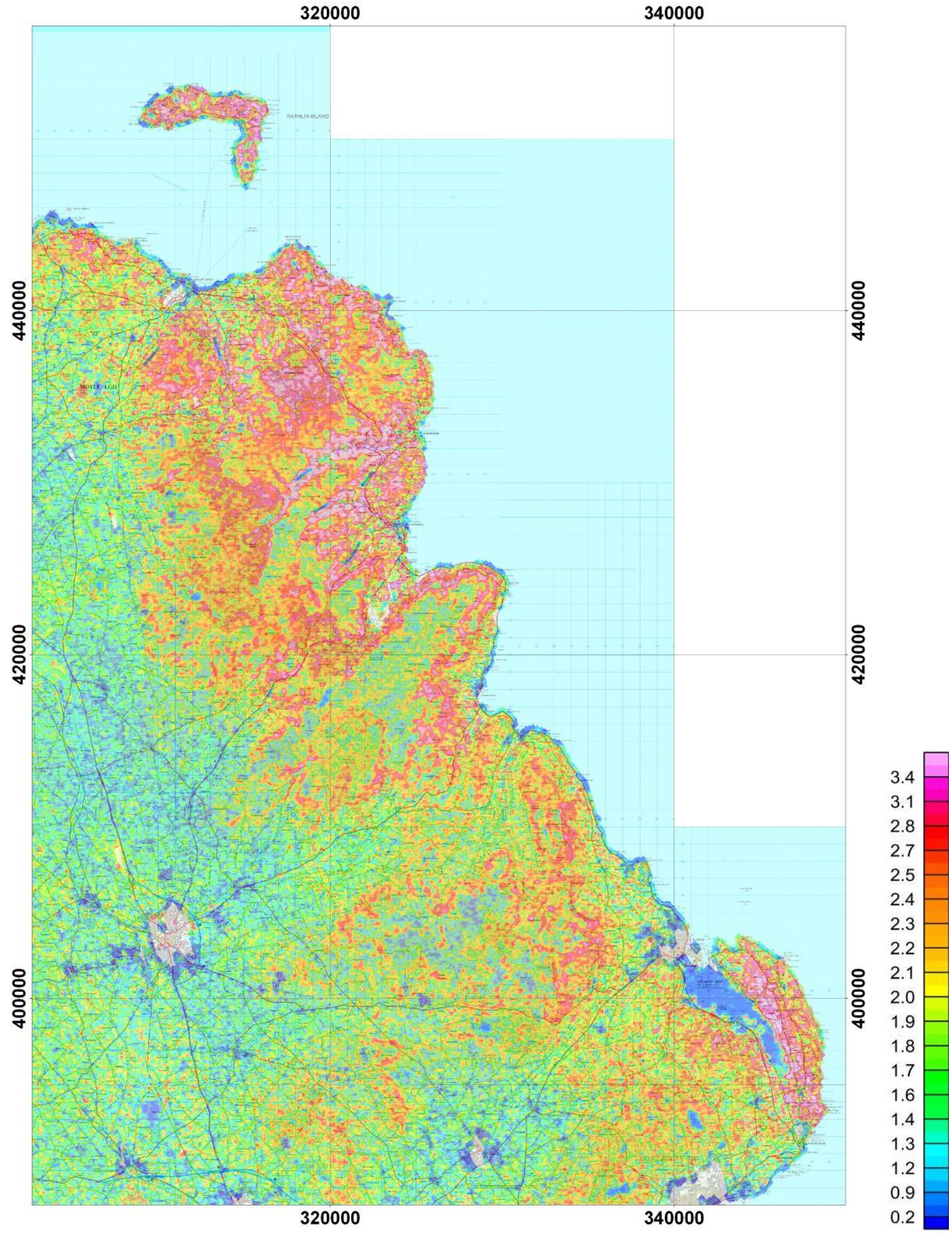


Figure 44. ^{137}Cs ($kBqm^{-2}$) over the eastern coast of Northern Ireland from Rathlin Island to Carrickfergus.

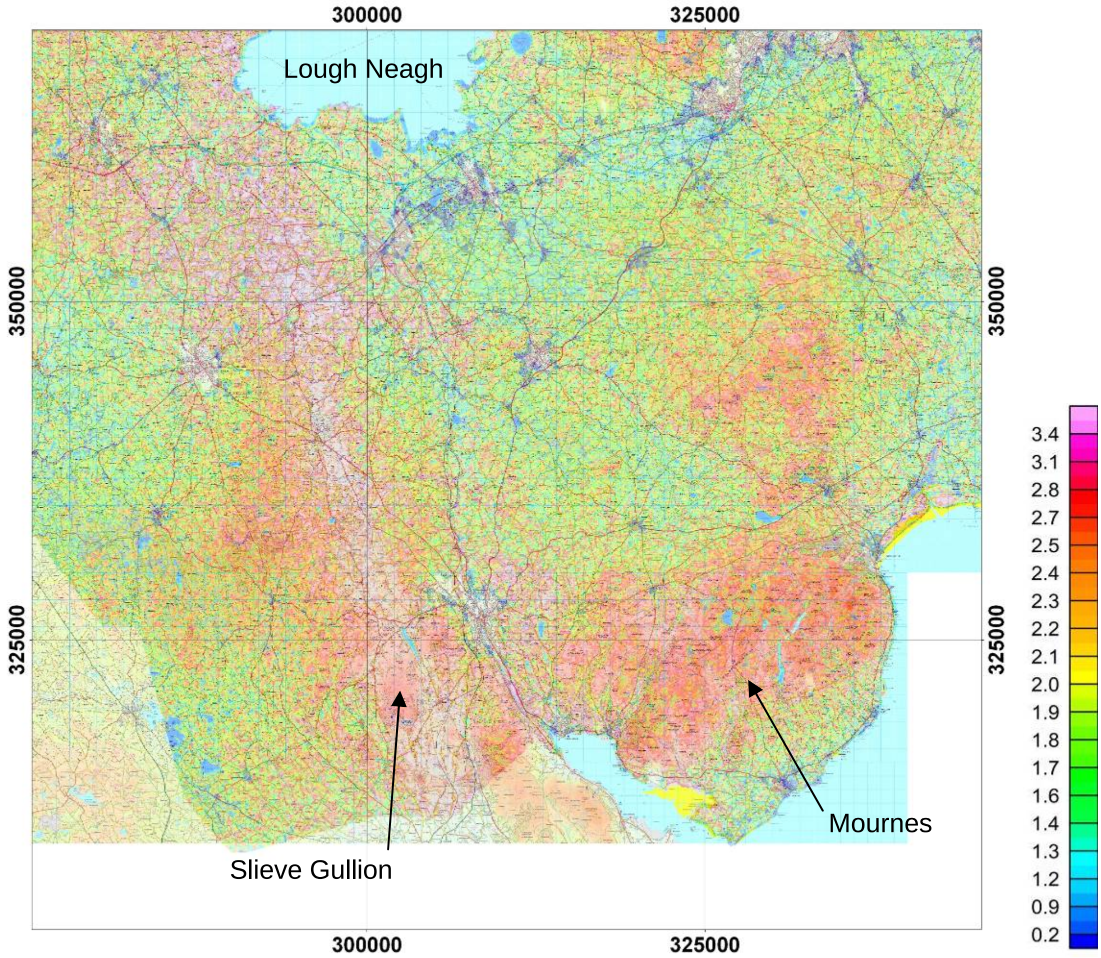


Figure 45. ^{137}Cs (kBqm^{-2}) over eastern County Armagh and western County Down, showing the south of Lough Neagh and southern Belfast to the north and the Mourne Mountians to the south.

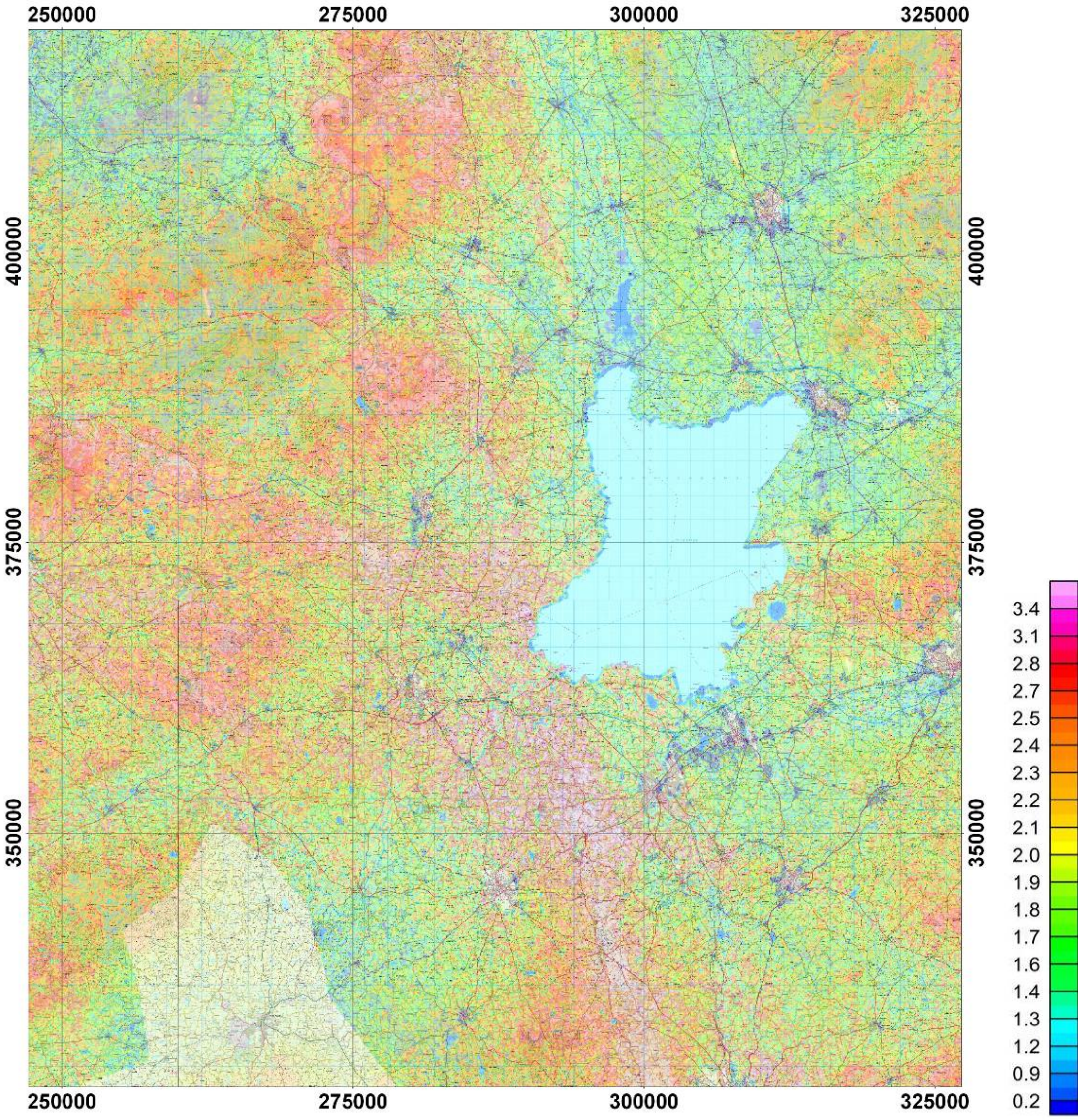


Figure 46. ^{137}Cs ($kBqm^{-2}$). Image showing Lough Neagh and surrounds; encompassing areas from Countys Down, Antrim, Londonderry, Tyrone, and Armagh.

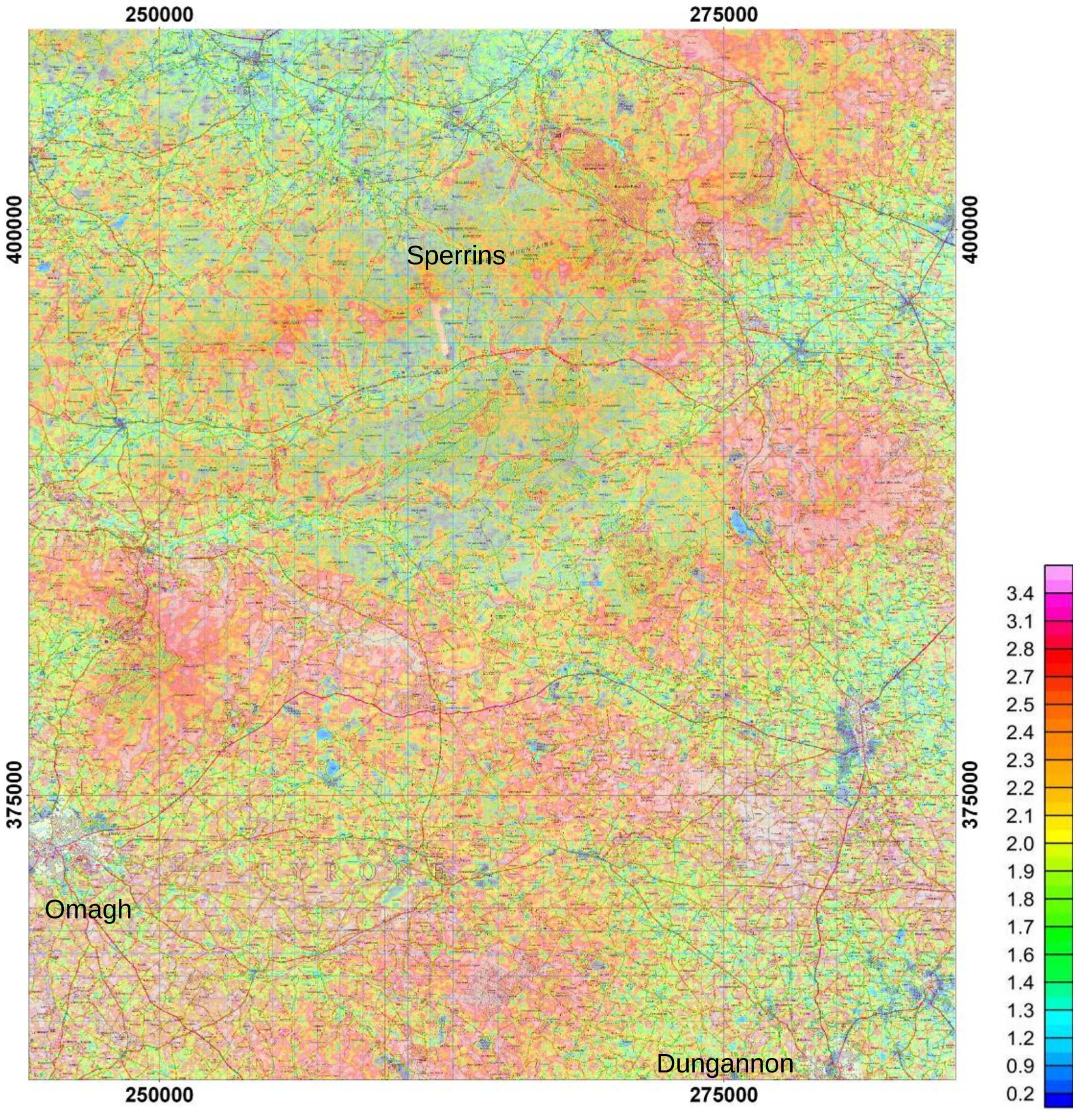


Figure 47. ^{137}Cs (kBqm^{-2}) over the Sperrin Mountains in the north, to Omagh and Dungannon to the south.

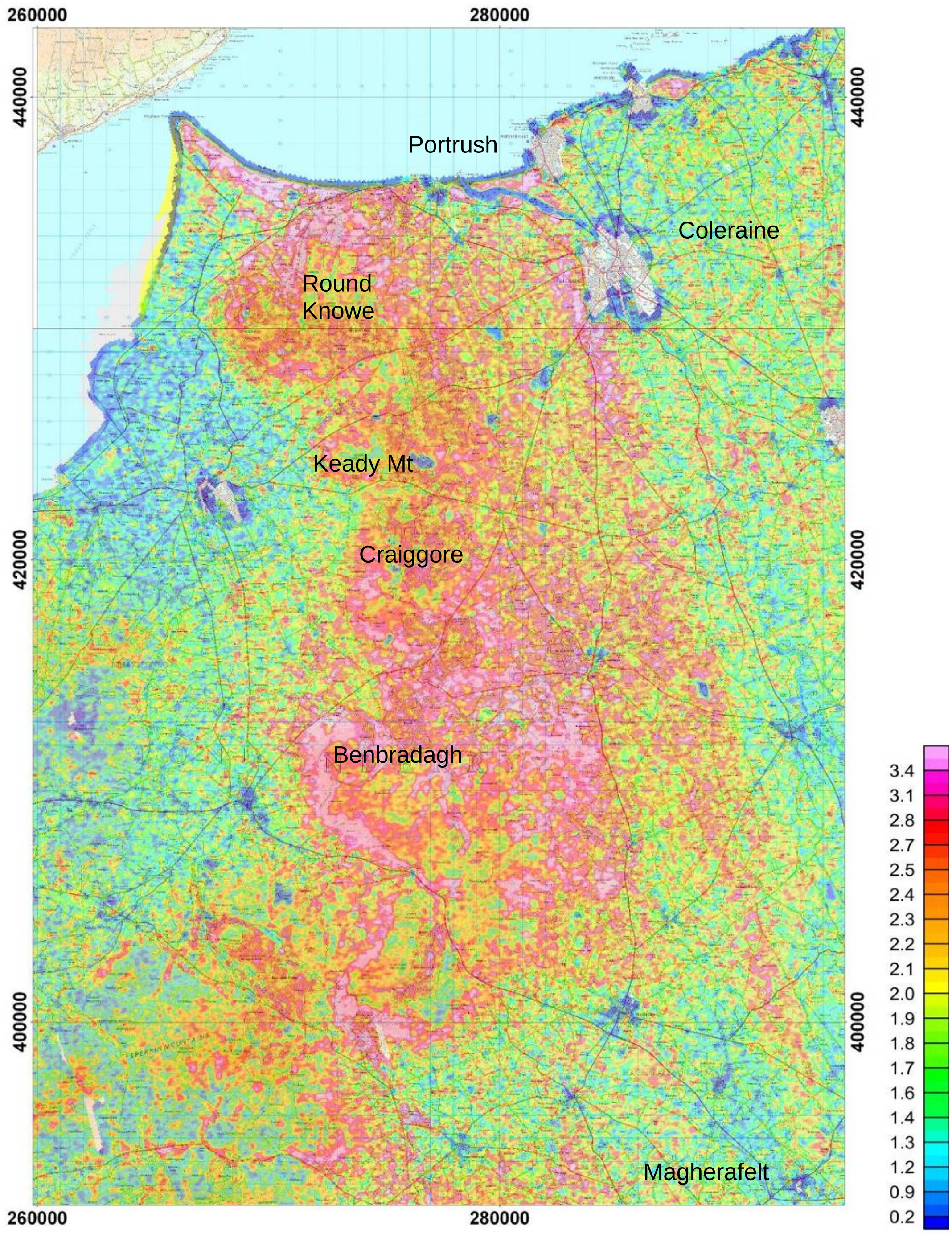


Figure 48. ^{137}Cs (kBqm^{-2}). Image showing eastern County Londonderry from Portrush in the north to Magherafelt in the south.

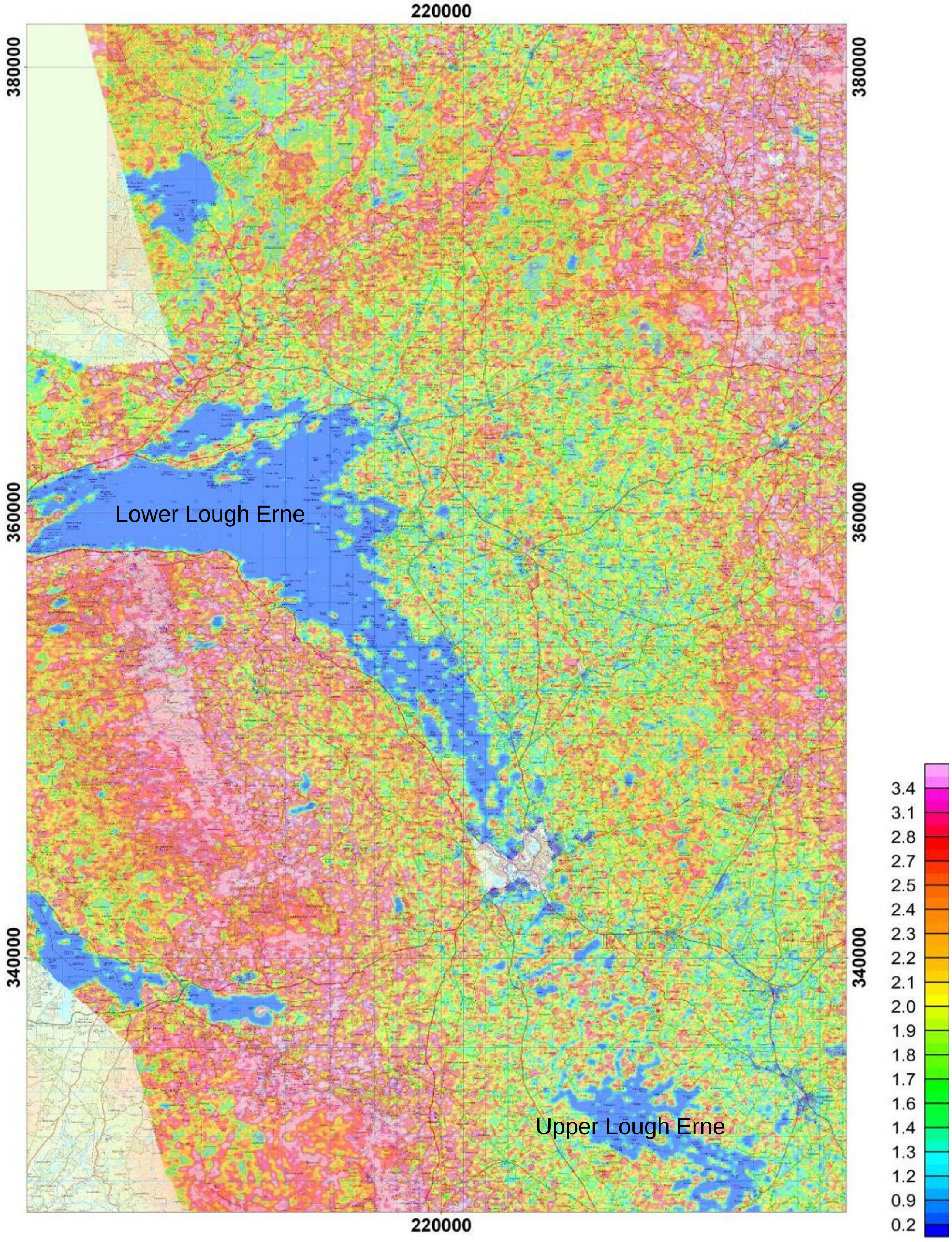


Figure 49. ^{137}Cs (kBqm^{-2}). Image showing Lower Lough Erne to Upper Lough Erne, extending into County Tyrone to the north-east.

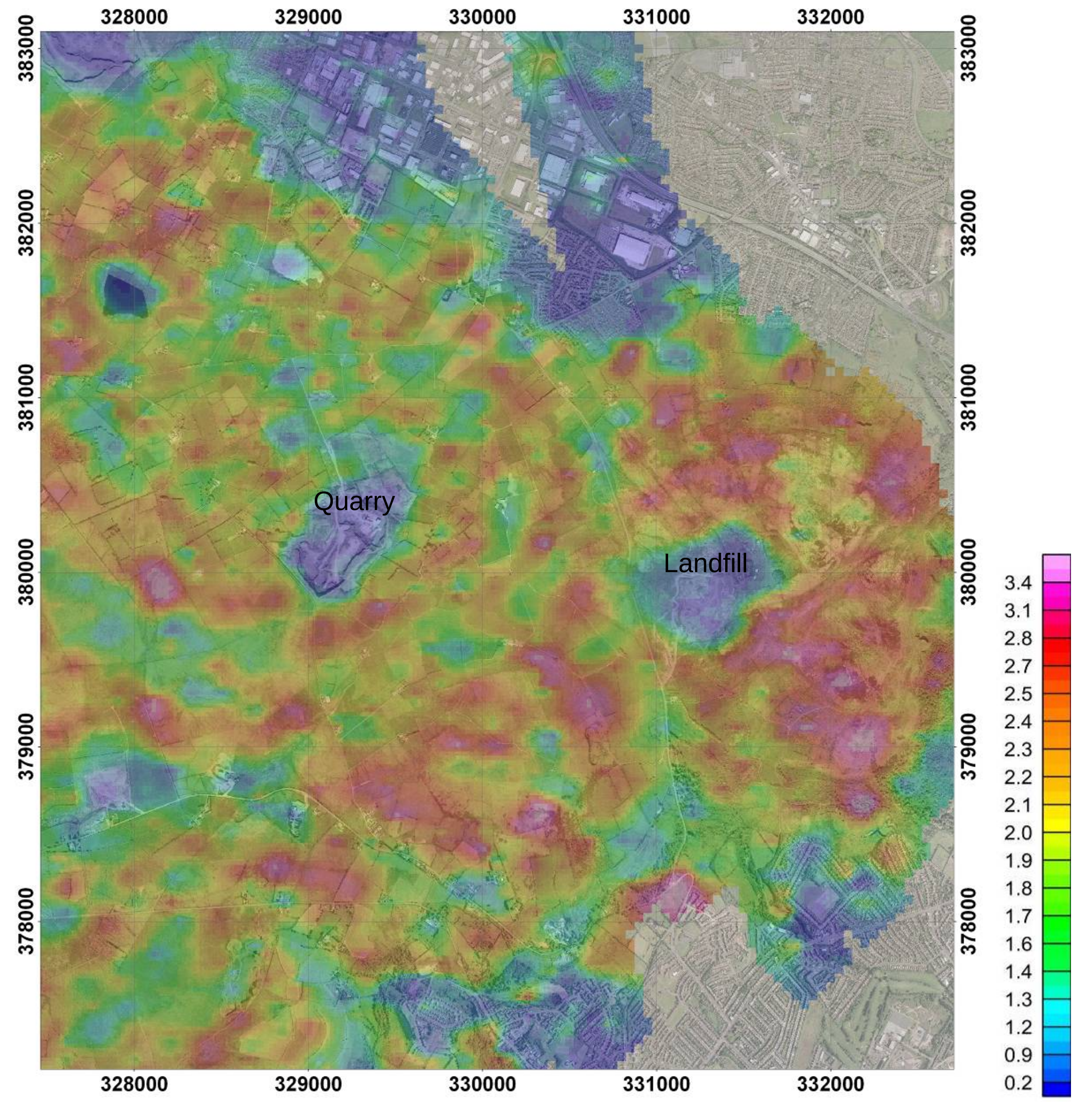


Figure 50. ^{137}Cs (kBqm^{-2}). Image showing the High Town Landfill and surrounds. ^{137}Cs appears low over the landfill area and the nearby quarry.

altitude of greater than 160 m were then excluded from the sub sample. This left a remaining 41,998 samples in the sub sample. The data was then imported to S-PLUS for exploratory analysis. The ^{137}Cs data showed an approximately normal distribution (Figure 51) with a skewness coefficient of 0.22. Geostatistical analysis based on these data showed that there are two distinct spatial structures in the ^{137}Cs data, one at a short range of approximately 0.6 km, and a longer-range structure up to scales of approximately 15 km (Figure 52). Around 50% of the variance was spatially correlated whilst the remaining 50% comprised short-scale spatial variation and measurement error. The proportion of correlated variance for ^{137}Cs was greater than that for U, but less than K and Th which suggests that the magnitude of the measurement error decreases in the following order: K<Th<Cs<U. A classification based on the CORINE1 land use classes accounted for approximately 16 % of the total variance in the sub-set of ^{137}Cs data points. Salt marsh areas, forests, natural grassland, pastures and similar classes exhibited higher median ^{137}Cs values (Figure 53, Table 1).

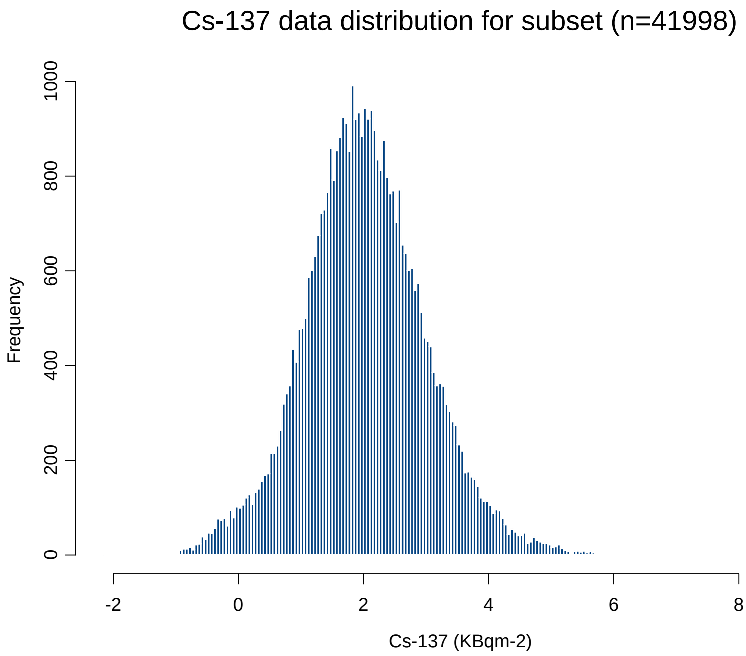


Figure 51. Frequency distribution of ^{137}Cs kBqm^{-2} (n=41998)

Aspect, generated in a GIS from a Digital Terrain Model (DTM) (Figure 54) showed correlation with the Northern Ireland ^{137}Cs data at a local scale (Figure 55), but did not correlate with the entire ^{137}Cs dataset.

Laboratory gamma spectrometry analysis of soil samples from 5 separate areas was carried out as a check on the airborne results; to verify the spatial patterns observed. Soil samples were collected as part of the 2006 ground-based gamma spectrometry field investigation in 3 areas: Newtonards Airfield (Figure 56), along the airborne calibration line to the south-west of Banbridge (Figure 57) and in the Longstone area on the northern edge of Slieve Gullion (Figure 58). Further to this, soil samples were selected from the main suite of TELLUS geochemical samples, that crossed two of the bands observed in the airborne ^{137}Cs data (Figures 59 and 60). The soil samples represent a much smaller sampling area than that covered by the larger airborne "footprint". Laboratory results in Bqkg^{-1} have not yet been converted to represent surface area, to be directly comparable to the airborne measurements. However, the results will be explored in more detail in the ground to airborne comparison report (CR07/062). The laboratory analysis showed a good correlation to the airborne measurements (Figure 61, R^2=0.5015, p =0.0005, n =119) giving confidence in the airborne measurements.

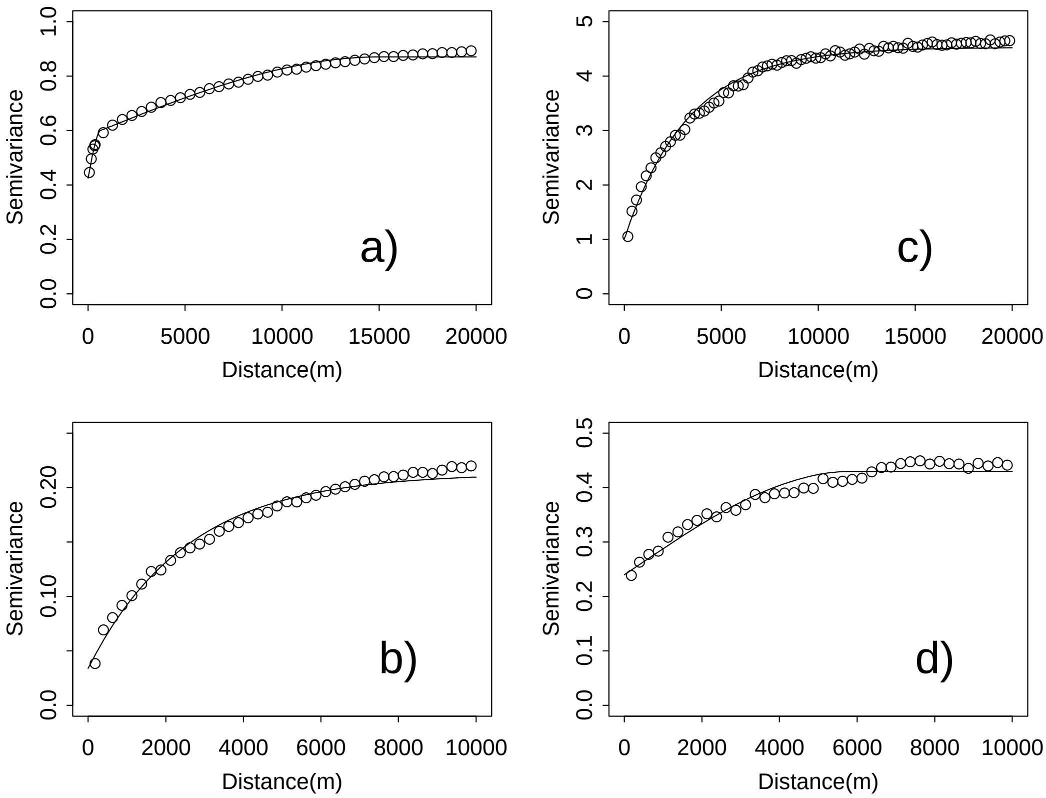


Figure 52. Experimental variograms (symbols) and models (lines) fitted to the variograms for a) ^{137}Cs, b) K, c) Th, and d) U

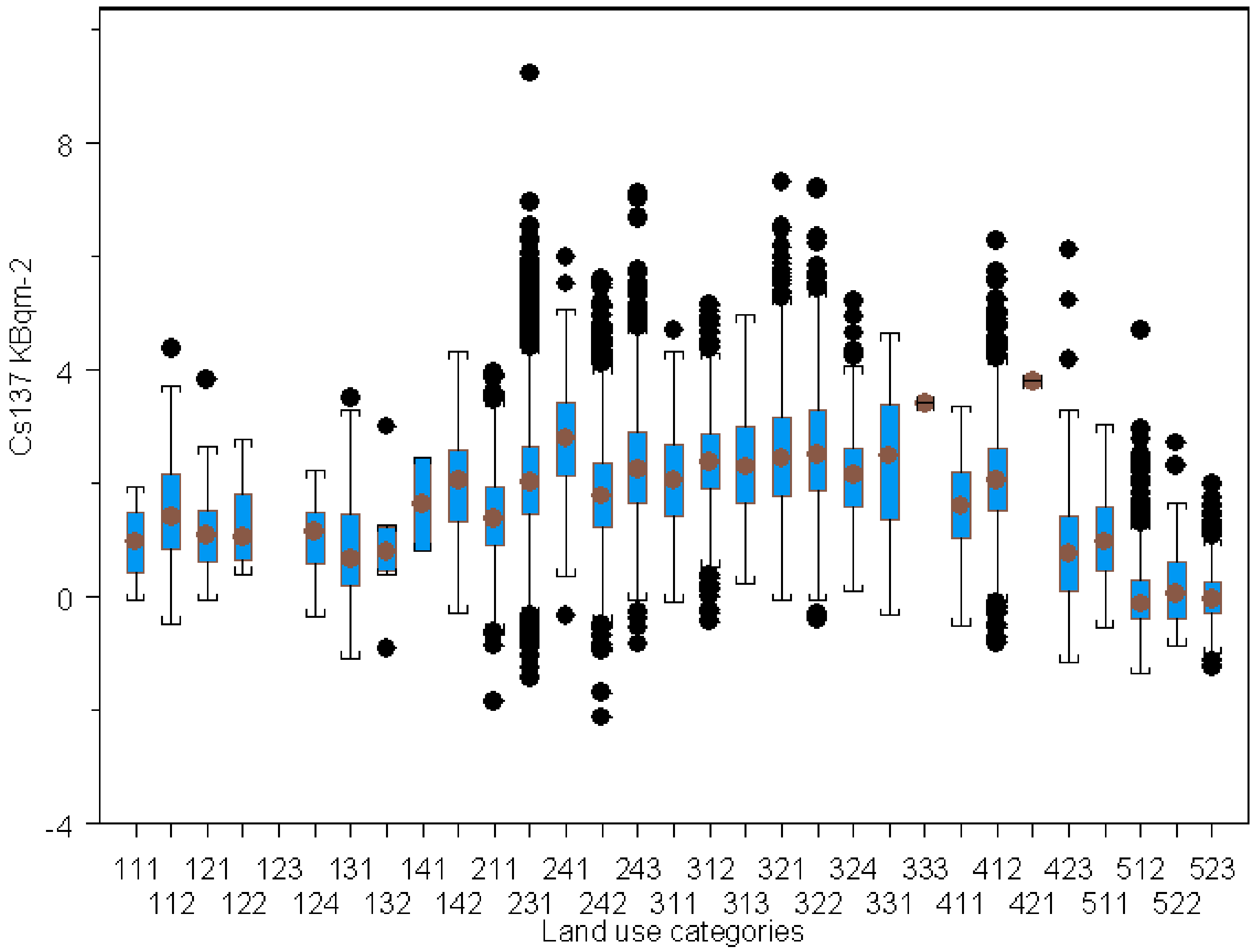


Figure 53. ^{137}**Cs data (kBqm**$^{-2}$**) grouped by CORINE1 land-use classes (see Table 1 for CLC-code legend).**

Table 1 CORINE1 Land-use classes (CLC-Code).

Pixel-value	CLC-Code	CLC-Class	R	G	B
21	111	Continuous urban fabric	211	0	0
22	112	Discontinuous urban fabric	239	42	71
23	121	Industrial or commercial units	211	0	155
24	122	Road and rail networks and associated land	126	126	126
25	123	Port areas	155	155	211
26	124	Airports	99	99	99
27	131	Mineral extraction sites	155	71	42
28	132	Dump sites	155	13	42
29	133	Construction sites	183	99	126
30	141	Green urban areas	99	239	0
31	142	Sport and leisure facilities	239	71	0
32	211	Non-irrigated arable land	239	239	126
33	212	Permanently irrigated land	0	0	0
34	213	Rice fields	0	0	0
35	221	Vineyards	239	155	13
36	222	Fruit trees and berry plantations	239	211	155
37	223	Olive groves	0	0	0
38	231	Pastures	155	211	13
39	241	Annual crops associated with permanent crops	0	0	0
40	242	Complex cultivation patterns	239	211	99
41	243	Land principally occupied by agriculture, with significant areas of natural vegetation	183	183	71
42	244	Agro-forestry areas	0	0	0
43	311	Broad-leaved forest	0	183	0
44	312	Coniferous forest	0	126	99
45	313	Mixed forest	0	126	0
46	321	Natural grasslands	155	183	99
47	322	Moors and heathland	211	211	0
48	323	Sclerophyllous vegetation	0	0	0
49	324	Transitional woodland-shrub	183	239	0
50	331	Beaches, dunes, sands	239	239	183
51	332	Bare rocks	211	211	155
52	333	Sparsely vegetated areas	126	211	155
53	334	Burnt areas	0	0	0
54	335	Glaciers and perpetual snow	0	0	0
55	411	Inland marshes	183	71	239
56	412	Peat bogs	126	71	211
57	421	Salt marshes	183	126	211
58	422	Salines	0	0	0
59	423	Intertidal flats	239	183	239
60	511	Water courses	0	99	239
61	512	Water bodies	0	155	239
62	521	Coastal lagoons	0	211	239
63	522	Estuaries	99	211	239
64	523	Sea and ocean	159	215	248
255	999	no data	255	255	255

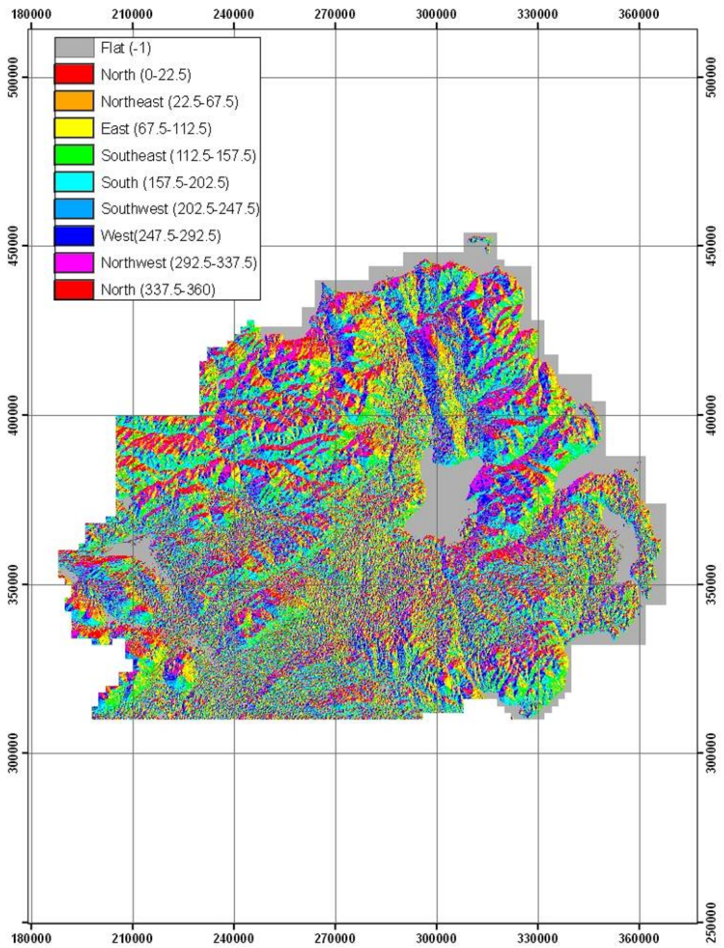


Figure 54. Aspect over Northern Ireland, generated from the DTM in a GIS.

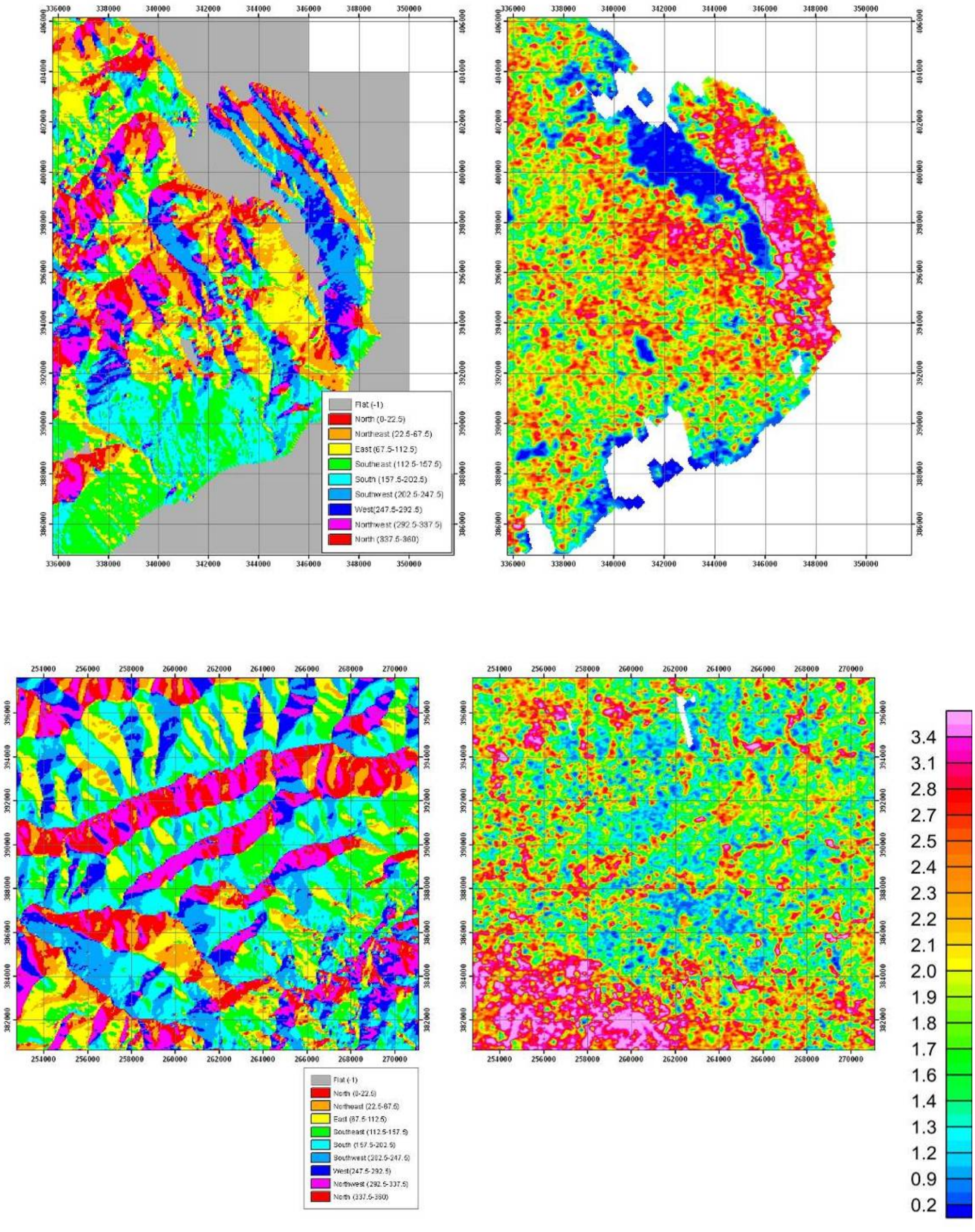


Figure 55. Aspect (left-hand side) with ^{137}Cs (kBqm^{-2}) (right-hand side).

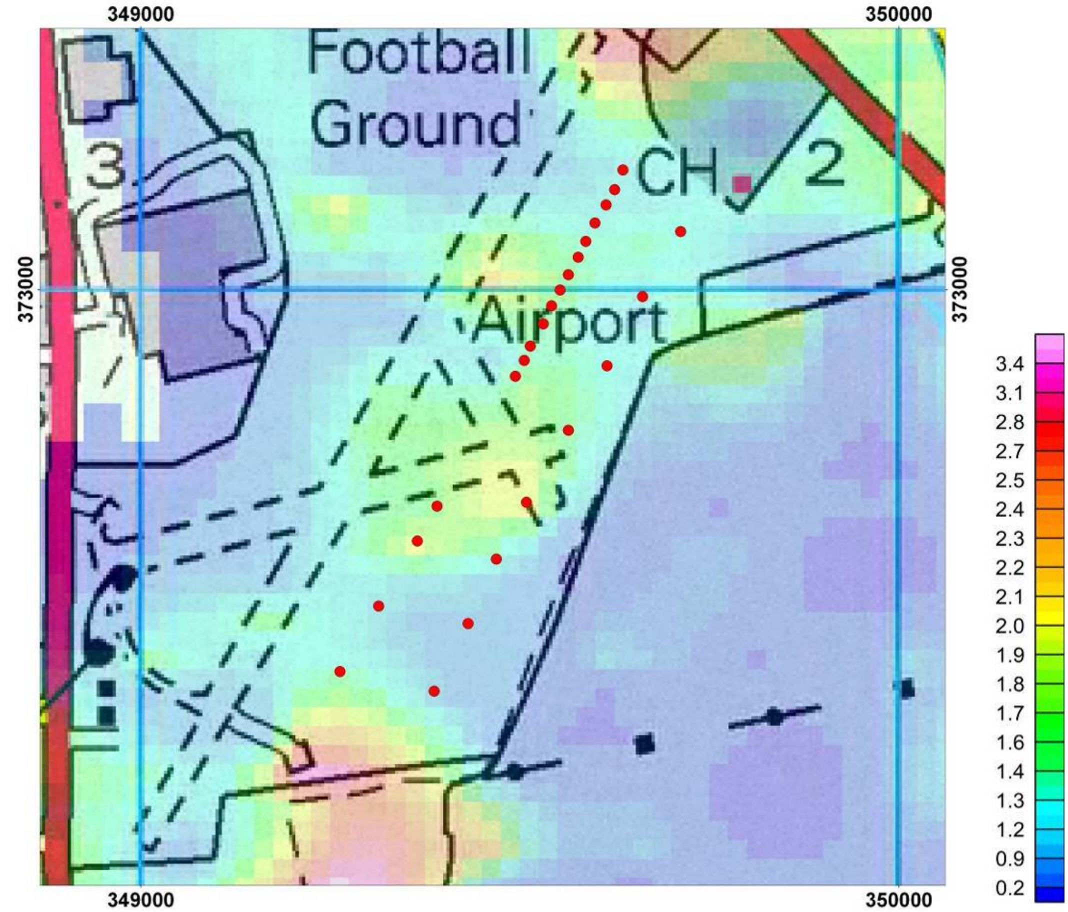


Figure 56 Newtonards Airfield showing airborne ^{137}Cs (kBqm^{-2}) (● depicts site of soil sample).

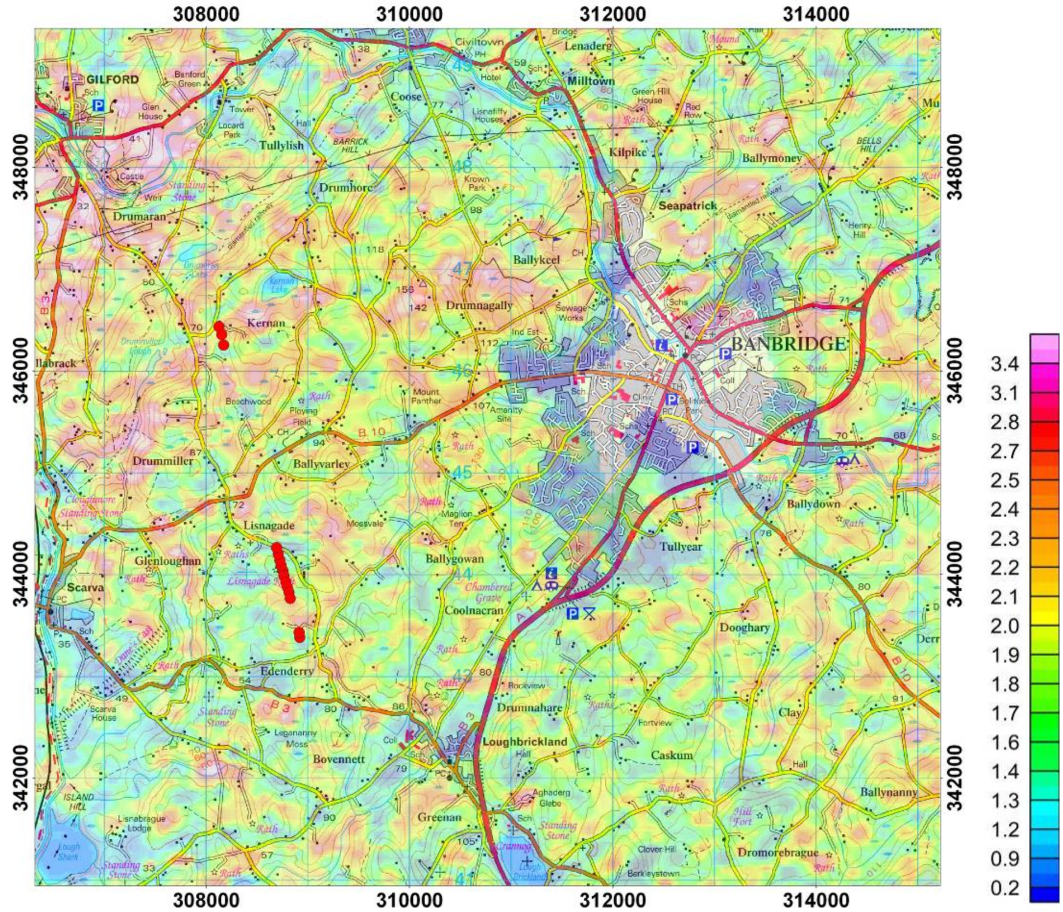


Figure 57. Calibration line south west of Banbridge showing airborne ^{137}Cs ($kBqm^{-2}$) (● depicts site of soil sample)

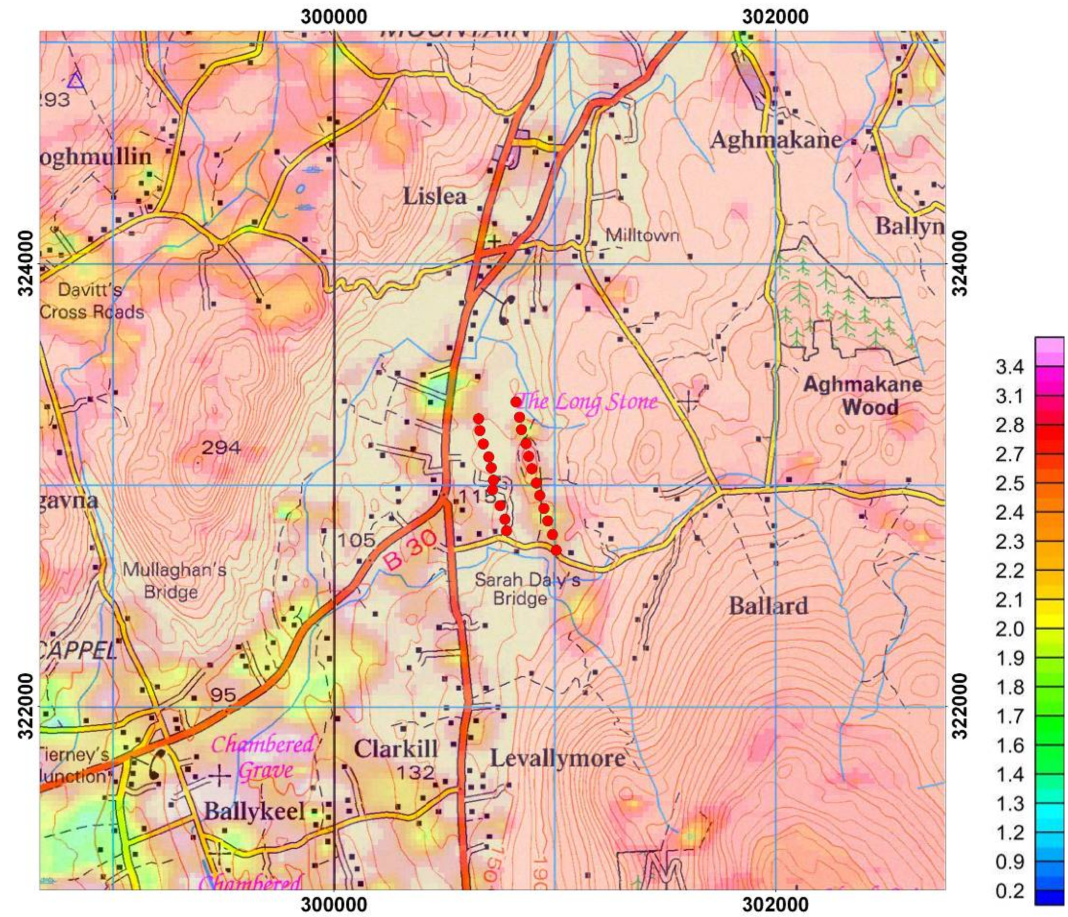


Figure 58. Longstone on the northern edge of Slieve Gullion showing airborne ^{137}Cs (kBqm^{-2}) (● depicts site of soil sample)

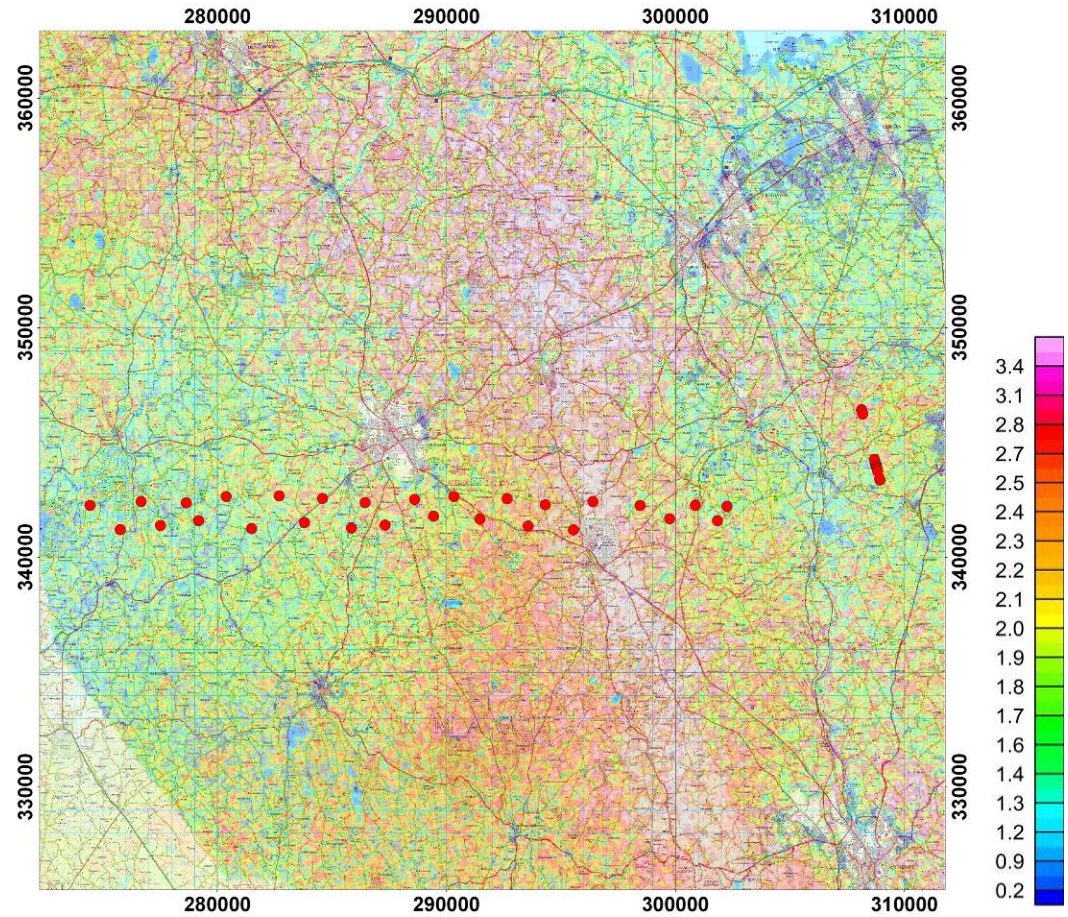


Figure 59. Location of selected TELLUS soil samples south of Lough Neagh for laboratory gamma spectrometry (● depicts site of soil sample). Shows airborne ^{137}Cs ($kBqm^{-2}$)

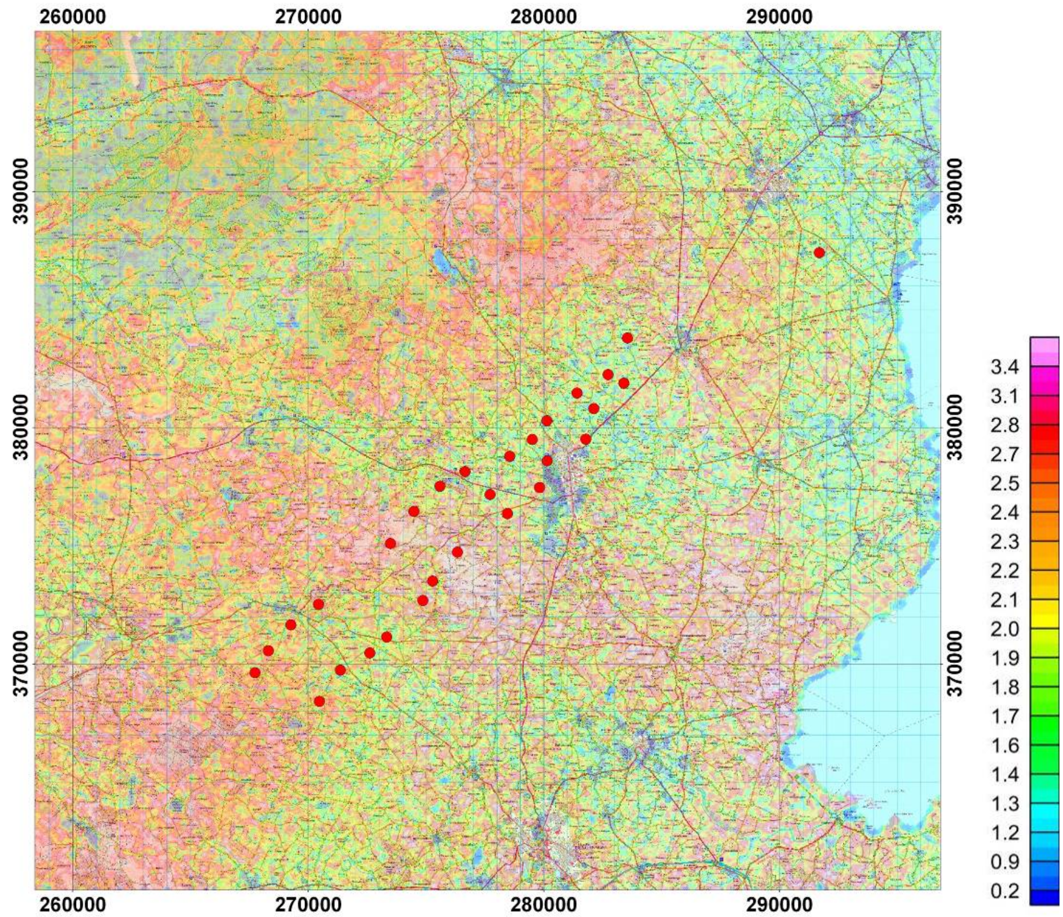


Figure 60. Location of selected TELLUS soil samples west of Lough Neagh for laboratory gamma spectrometry (● depicts site of soil sample). Shows airborne ^{137}Cs ($kBqm^{-2}$).

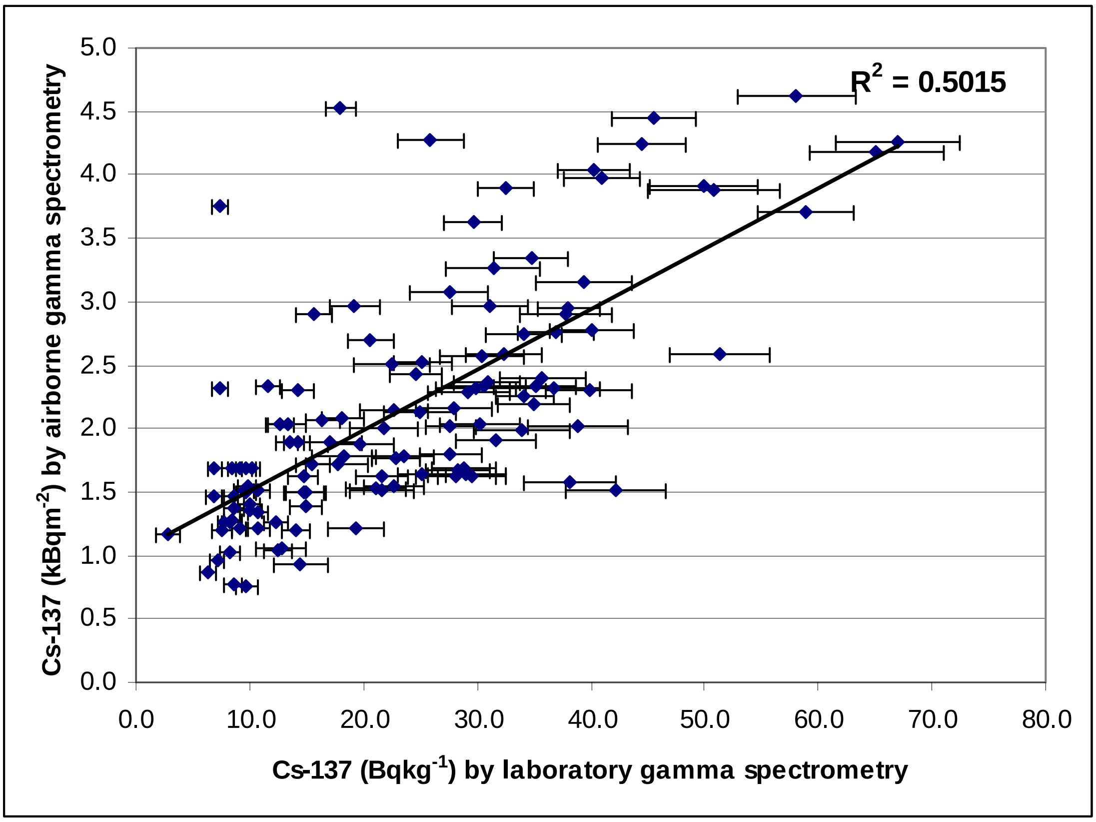


Figure 61. ^{137}**Cs (kBqm**$^{-2}$**) by airborne gamma spectrometry against** ^{137}**Cs (Bqkg**$^{-1}$**) by laboratory gamma spectrometry (n= 119, p= 0.0005). Laboratory results show 2 sigma error bars.**

4 Conclusions

At the scale of all of Northern Ireland the Tellus airborne radiometric data reflect the major solid geological subdivisions; the Lower Palaeozoic greywackes and the late Caledonian and Palaeogene intrusives of the SE have relatively high K, U and Th contents. In contrast the Palaeogene basalts in the NE have much lower radioelement concentrations. However, Palaeogene rhyolites, and inliers of Palaeozoic and Precambrian rocks in this area, have higher values. Surrounding the basalts to the south and west, the Triassic sedimentary rocks (Mercia Mudstone and Sherwood Sandstone groups) have moderate K, eU and eTh levels. The more heterogeneous geology of the western part of Northern Ireland is reflected in the radiometric data with juxtaposed areas of relatively high and low radioelement content. Formation boundaries within the basement and Upper Palaeozoic (Devonian-Carboniferous) rocks, sometimes faulted, are clear in places as ENE-WSW and NE-SE-trending features.

Regional effects of superficial deposits and soil overlying the solid rocks are also readily apparent. River valleys form distinctive features with the water or wet sediments having lower count rates because of the attenuating of gamma rays, whilst compositional difference between alluvial deposits and the surrounding terrain can also provide a marked contrast. Low radioactivity results from peat cover, whilst there are higher zones where glacial tills are derived from areas of relatively radioelement-rich geology. Drumlin fields produce very distinctive patterns in the radiometric images, especially in the SW and NE of Northern Ireland.

Features reflecting both the solid and superficial geology are enhanced by plotting subsets of the data. This improves contrast and brings out compositional differences in the glacial deposits resulting from their derivation and transport direction. Variations within the solid geology are also enhanced.

The influence of man is clear both in the urban environment and as wastes produced from power generation and those deposited in landfill sites or associated with mineral extraction. Towns have a distinctive speckled appearance. This results from greater point to point variability due to increased statistical noise arising from the higher flying height and correction of the data to an altitude of 56 m. Added to this may be a contrast resulting from differences in radioelement content between the built environment and surrounding rural areas.

Data for ^{137}Cs show pronounced banding with NNW-SSE and WNW-ESE orientations. This pattern is consistent with rainfall intercepting the plume of contamination after the Chernobyl nuclear accident and probably also reflects longer term deposition of nuclear weapons fallout. It is in part controlled by topography and aspect. The bands extend into the Irish Republic and are clearly not related to single flight lines, groups of lines flown together or blocks of data. Similar linear features are seen, or predicted, in data from other parts of the UK and France but are probably more pronounced in the Tellus data owing to the close line spacing (200m). Concentrations of Cs are in line with previously published values, allowing for decay of ^{137}Cs. Laboratory analysis of soil samples correlated well to airborne measurements, giving confidence in the airborne ^{137}Cs results.

5 Suggestions for Further Studies

This overview of the radiometric data has shown some of its possible uses. There is scope for more detailed studies in a range of areas including:

Geological and soil mapping

We have illustrated examples of features that relate to both the solid and superficial geology (including soils). The data have the potential to be used more extensively to assist with mapping and to examine compositional and other variations. For example, the use of the data for estimating peat thickness is already being undertaken. Potassium is an important element in soil fertility and the data provide a direct measure of the K content of the surface layers. The composition of the superficial deposits reflects their origin and the direction of transport.

Mineral exploration

Radioelements are components of economic minerals (e.g. U ores and phosphates, heavy minerals, evaporates and feldspars) and may thus be direct indicators of mineralisation. Ore deposits are often associated with zones of hydrothermal alteration and this may be apparent through changes in the content and ratios of K, eU and eTh, especially for potassic alteration.

Radon potential mapping

The eU content of the near surface is an important factor in determining the radon potential as a daughter of radon (^{214}Bi) is the radionuclide actually measured. A pilot study of the use of the airborne data, in conjunction with soil geochemical data for radon mapping has been completed for the south-east of Northern Ireland (Appleton and Miles, 2007).

Environmental studies

Examples have been shown of higher K, eU and eTh values associated with human activity, such as quarrying, power generation and waste disposal to landfills. These have the potential for adverse environmental impacts. A more rigorous assessment of radiometric anomalies would no doubt provide further examples. These could be assessed by examining all data, particularly airborne EM and ground geochemical data.

There is scope for a more in-depth assessment of the ^{137}Cs data. We are trying to obtain the rainfall that intercepted the plume (RITP) data used in the Smith and Clark (1989) paper. If it is available then linear regression could be used to determine the proportion of the variance in the ^{137}Cs data accounted for by wet deposition from the Chernobyl plume. Pre-Chernobyl ^{137}Cs in the environment could be assessed using the method of Wright *et al*. (1999). This uses the relationship between deposition of ^{137}Cs and precipitation to predict the atmospheric weapons testing fallout levels and was applied in a preliminary way to the HiRES-1 data for Central England (Lahti and Jones, 2003).

The study of soil cores by gamma spectrometry would allow the depth distribution of ^{137}Cs to be evaluated. This could shed light on the relative inputs from weapons fallout and Chernobyl and, taken with the airborne data, would allow estimates of total ^{137}Cs inventories to be made. The core data would help establish if the depth distribution assumptions used for the ^{137}Cs data processing were valid. The strength of any statistical relationships between areas of soil accumulation (using a DEM) and ^{137}Cs, in areas of arable agriculture (Comber catchment) and upland peat deposits could also be investigated.

Environmental baseline

The survey provides a snapshot in time of the both naturally-occurring radionuclides and ^{137}Cs. This may be used as a baseline to assess the impact of future activities or events, for example extractive or manufacturing industries, accidental or deliberate releases of radioactivity ('dirty bombs').

Combining datasets

Essentially we have looked only at the radiometric data in this report. Combining different datasets is likely to add significantly to what is achievable with a single dataset alone. Using the data in conjunction with aerial photography and the DTM has assisted in the visualisation of the results presented here and their interpretation. Combining the radiometric data with other geophysical and geochemical results from the Tellus project has the potential to extend the value of the data.

Ground truth

To understand and investigate radiometric features ground measurements and sampling would be desirable. Ground gamma measurements have much higher spatial resolution and can provide additional detail and higher values because of the reduced footprint.

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