An interpretation of the Ayrshire high-resolution airborne geophysical data

National Geosciences Framework Programme

Open Report OR/07/024

BRITISH GEOLOGICAL SURVEY

NATIONAL GEOSCIENCES FRAMEWORK PROGRAMME

OPEN REPORT OR/07/024

An interpretation of the Ayrshire high-resolution airborne geophysical data

J Busby, M C Akhurst, A S D Walker and L-A Baker

Contributor

W S McLean

Keywords

Airborne data,, bedrock mapping, industrial land use.

Front cover

The survey aircraft during an EM calibration run over Loch Lomond.

Bibliographical reference

BUSBY, J, AKHURST, M C, WALKER,A S D & BAKER, L-A. 2007. An interpretation of the Ayrshire high-resolution airborne geophysical data. *British Geological Survey Open Report*, OR/07/024. 67pp.

Keyworth, Nottingham British Geological Survey 2007

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276

email enquires@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

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

Tel 029 2052 1962 Fax 029 2052 1963

Forde House, Park Five Business Centre, Harrier Way, Sowton EX2 7HU

Tel 01392 445271 Fax 01392 445371

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

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

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

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

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Foreword

This report is the published product of a study by the British Geological Survey (BGS) of high-resolution airborne geophysical data acquired and interpreted as part of the Science Budget-funded scientific research to enhance understanding of the UK for the national good. The research was undertaken within the National Geoscience Framework and Geology and Landscape of Britain programmes by the Hi-RES and Midland Valley and Strathmore Basin projects, respectively.

Acknowledgements

External data sets used to assist in the interpretation of the high-resolution geophysical survey results were provided by the following organisations under data license contracts. Soil series data were provided by the Macaulay Land Use Research Institute, license number MI/2006/246. PASTMAP archaeological and industrial archaeological survey data were provided by Royal Commission Architectural and Historical Monuments Scotland (RCAHMS), reference 1669. Digital mine plan data for Ardeer were provided by the Coal Authority, reference NGW/01/2007/BGS. Ayrshire Joint Structure Plan staff collated sites designated as 'Vacant and derelict land' and waste facilities and presented them in GIS format from North, East and South Ayrshire councils. Aerial photographic data were provided by © UKP/Getmapping Licence No. UKP2006/01. We acknowledge consent for permission to publish by The Macaulay Institute for Figures 3a and b, The Coal Authority for Figure 19c and RCAHMS for Figures 23b and c.

Contents

FIGURES

TABLES

Summary

A high-resolution airborne geophysical survey (Hi-RES) was acquired over part of Ayrshire in south-west Scotland by the Geological Survey of Finland (GTK) under contract to the British Geological Survey (BGS) during 2004 with flight lines spaced at 200 m. Three smaller infill areas were surveyed with flight lines spaced at 50 m, with increased spatial resolution,in the vicinity of Ardeer, Mauchline and Muirkirk. The geophysical data sets comprise magnetic, electromagnetic (EM) and radiometric data. A qualitative interpretation is presented of selected geophysical anomalies of interest for geological survey, environmental concern, redevelopment of land and appraisal of natural resources. The interpretation is based on remotely sensed data and data available from published or licensed sources. No ground investigations were carried out as part of this study.

The main findings are:

Geological mapping

- Igneous dykes and volcanic vent rocks can be mapped from the regional magnetic data, extending known dykes and mapping new dykes and vents, with distinct characteristics for dykes of different ages.

Resources

- Re-interpretation of linear magnetic anomalies in the Mauchline survey as dykes not faults implies a revision in the hypothesis for the gold mineralisation known within the area.
- The depth and width of concealed dykes are modelled from the regional magnetic data. Dykes of 1 m width at depths of 20 m should be detected. This is suitable for appraisal of the extent and volume of dyke rocks within areas of extraction of bedrock.
- There is a close spatial correspondence between low percentages of potassium radiometric data from the regional survey and the extent of peat and peaty soils at a scale of 1:25 000.

Former land use

- Magnetic anomalies from bedrock may be masked by man-made infrastructure and the effects of historical and current land use in industrial areas.
- Disturbed or man-made ground has a distinctively high regional radiometric signature. Areas of ground known to be disturbed but without a high radiometric may reflect a degree of restoration or revegetation.

Vacant and derelict land

- Bipolar magnetic anomalies are generated by the ferri-metallic content of known landfill sites, such as Nethermains near Irvine, and the presence of such anomalies near Muirkirk suggest unrecorded sites containing metallic refuse.
- Regional EM conductivity survey data indicate whether conductive fluids are present within a site. Comparison of high frequency (shallow penetration) and low frequency (deeper penetration) conductivity data for a site, as at Ballochmyle Quarry landfill near Mauchline, indicate the 3D subsurface extent of the conductive fluids.
- Conductivity anomalies are commonly associated with man-made features or structures. Conductive anomalies not associated with man-made ground or structures may be unrecorded landfill or waste disposal sites.
- An appraisal of all sites designated as Vacant and Derelict Land has been undertaken within the extent of the three infill survey areas and selected designated sites from the regional Hi-RES magnetic, radiometric and conductivity surveys
- A minority of Vacant and Derelict Land sites have high radiometric survey values, often related to previous land use, but the anomalies are often not uniformly high within a site.
- Most of the Vacant and Derelict Land sites within the regional survey are of sufficiently large size for the regional Hi-RES data set to indicate whether they should be flagged for specific attention during redevelopment.

Survey data

- Acquisition of EM conductivity survey data was not effective at the increased flying heights required over populated areas. Utility of the regional and infill magnetic and radiometric survey data was much less affected by increased survey height.
- High radiometric count anomalies do not indicate dangerous values or that the site is necessarily contaminated but areas with high counts are considered more likely to be contaminated than areas with low total radiometric counts.
- Ternary plots of the radiometric count data give an indication in the variation in the content of the three radioelements surveyed (K, Ur and Th) across a site.

Former mining

- Conductivity survey data was examined to consider contamination of groundwater due to previous industrial land use at Ardeer. Coincidence of shallow mining, an industrial site and conductivity anomalies at Longford suggests possible disposal of industrial waste into the mine workings. A similar scenario, but of unrecorded shallow mine working is inferred for conductive anomalies at Ladyha' Park.
- Comparsion of conductivity anomalies and underground mine plans in the valley of the River Ayr near Muirkirk suggests that conductive fluids from strata overlying the known worked coal seams may be causing reduced surface water quality.

Mapping of dykes and volcanic vent rocks directly from the Hi-RES geophysical data is recommended and outlines given for collaborative proposals to:

Test and verify differing methods to model concealed dykes and intrusions;
Model dyke width and depth in areas of potential opencast coal mining;
Investigate the use of potassium radiometric data to map peat and peaty soils;
Ground truth anomalies at landfill sites by ground geophysical observations;
Examine the anomalies at Longford and Ladyha' Park by water sampling and analysis;
Calibration of brownfield sites anomalies to establish 'threshold' values for regulators;
Appraise the success of opencast restoration by comparison with radiometric survey data;
Re-evaluate the hypothesis for gold mineralisation using all available data.

1 Introduction

This short report is an account of qualitative interpretation of selected data from the airborne High Resolution Resource and Environmental Survey (Hi-RES) that was acquired over part of Ayrshire in south-west Scotland. The geophysical data sets comprised magnetic, electromagnetic and radiometric data and were collected jointly by the Geological Survey of Finland (GTK) and the British Geological Survey (BGS). Interpretation is biased towards environmental issues and has therefore concentrated on the electromagnetic and radiometric data. A comprehensive interpretation of all the data sets has not been made, but representative examples are presented of the anomalies, selected because they appear to correspond to current issues of interest or concern such as the characterisation of ground thought to be contaminated, identification of possible sources for discoloured surface water and the mapping of soils, superficial deposits and bedrock geology. It should also be noted that these investigations are based on remotely sensed data and its comparison with existing geospatial information based on historical, land use, archaeological, mining/quarrying, soil, superficial deposits and bedrock geological data without additional field survey. Confirmation of the character of any anomalies of further interest would include follow up by ground survey.

The geophysical survey data are compared with geospatial data sets in a Geographical Information System (GIS). Superficial deposits, bedrock geology and boreholes are data sets of the British Geological Survey (BGS). Other data sets are used under licensed agreement with the originating organisation: 1:25 000 and 1:250 000 soil data (The Macaulay Institute); Land Cover of Scotland 1988 (The Macaulay Institute); digital coal mine plans for the Ardeer area (Coal Authority) PASTMAP archaeological data and industrial archaeological survey data (Royal Commission Ancient Historical Monuments Scotland); aerial photographic data (UKP/Getmapping); historical and modern geographical maps (Ordnance Survey). Areas of land designated as ‘vacant and derelict’, known landfill sites and other Local Authority waste facilities within the three counties of North, East and South Ayrshire have been provided by the Ayrshire Joint Structure Plan. Other data sets available to BGS through its role as a National Geoscience Data Centre are coal and non-coal mine plans.

1.1 SURVEY PARAMETERS

The main survey area was approximately rectangular and was located between the west coast and easting 271 km and northing 615 to 640 km (see Figure 1). Flight lines were in an east-west direction and were spaced at 200 m separation. This survey area is referred to as Ayr. In the west the terrain is at lower elevations and includes the conurbations of Kilmarnock, Irvine, Troon and Cumnock. Prestwick and Ayr were not included within the survey area. In the east there is higher ground that is mainly moorland. Three smaller infill areas were also flown at 50 m line separation. The first was over parts of Irvine and Stevenston and was selected to cover an area of industrial works that included a former explosives factory. Flight line direction was north-south and this area is referred to as Ardeer. The second infill area was to the south of the village of Mauchline and was selected because it is underlain by a groundwater aquifer within Permian sandstone bedrock and there are concerns regarding contamination from former sandstone quarries subsequently used as refuse landfill sites. Flight line direction was east-west and this area is referred to as Mauchline. The third infill area was over a region of active open cast coal mining that also includes many former coalmines and industrial works. Flight line direction was again east-west and this area is referred to by the village at the centre of the survey, Muirkirk.

The survey was flown with a fixed wing De Havilland Twin Otter (Registration sign OH-KOG) at a height above ground level of 56 m over rural areas and 250 m over urban centres at a normal flight speed of 220 km/h. Two sets of magnetic measurements were collected with Scintrex CS-2

Caesium magnetometers mounted in each of the wingtips. The electromagnetic system is also mounted in the wingtips and is operated in a vertical coplanar configuration at two frequencies (3,000 and 14,400 Hz). Radiometric measurements were taken with an Exploranium GR-820/3 spectrometer that comprises two sets of NaI crystals with a total volume of 42 litres. Full survey specifications are given in Appendix 1.

The total on-survey line km flown were 4,860.4 line km for Ayr. For each of the infill areas, to increase the coverage to 50 m line spacing, it was 510 line km for Ardeer, 422.8 line km for Mauchline and 593.8 line km for Muirkirk. The survey was flown between 29th September and 12th October 2004.

1.2 SELECTION OF SURVEY AREAS

The main Ayr geophysical survey was undertaken to prove the utility of Hi-RES survey methods in an area of recently completed and ongoing geological resurvey of bedrock and superficial deposits and 3D computer modelling of subsurface coal-bearing strata by the BGS. The three infill areas of more closely spaced survey lines, providing a much more detailed scale of resolution, were selected to address issues raised by structure plans for Ayrshire, provision of data suitable to meet implementation of the EU water framework directive and the needs of modern soil and geological resurvey. The areas selected for infill survey also avoided large urban areas and for logistical reasons were concomitant with the main survey area in order to maximise the return from the survey.

1.2.1 Ardeer

There has been an industrial site at Ardeer, Stevenston in North Ayrshire for more than one hundred years. Premises occupying the site have included the Nobel explosives works and Imperial Chemical Industries (ICI). The site is listed for industrial and business development in the Ayrshire Joint Structure Plan 1999 (AJSP, 2000) and detailed on maps in the North Ayrshire Local Plan (North Ayshire Council, 2005). A revised bedrock geological map spanning the Ardeer site has recently been published (BGS, 2005). The site also contains areas of ‘Derelict and Vacant Land’, as designated by Ayrshire planners and remains listed for business redevelopment in the Ayrshire Joint Structure Plan (2006). The objective of the Ardeer infill survey was to provide information to enable more cost-effective redevelopment of this industrial site by narrowing down areas within the site which may need to be investigated for contamination if subject to redevelopment. The Ardeer survey was also intended as an example of review of surplus industrial land from remotely sensed data to assess suitability for reallocation to other uses (AJSP, 2006).

1.2.2 Mauchline

Mauchline is known as a source of red sandstone for building stone although quarrying has for the most part ceased and the quarry sites reused. The sandstone and underlying volcanic rocks have been examined for potential gold mineralisation (Leake et al., 1997). The sandstone is also a subsurface groundwater aquifer and falls within the environmental safeguard of the Water Framework Directive. The infill survey at Mauchline aimed to locate quarry sites that have been reused and provide further information on the character of infilling materials and whether the influence of the fill materials is contained within the site. The Mauchline district remains to be completed for modern geological resurvey (Walton and Lee, 2001) and the geophysical survey data will inform future geological mapping.

1.2.3 Muirkirk

The valley of the River Ayr at Muirkirk has had a long history of exploitation of natural resources as evident from extensive industrial archaeological excavations (RCAHMS, 1995), scheduled ancient industrial monuments, subsurface coal and ironstone mine workings and sites of operational, restored and planned opencast coal abstraction (East Ayrshire Council, 2004.) Comparison with recently completed geological mapping (BGS, 1999) will enable the utility of the high-resolution geophysical data to inform strategic geological mapping to be assessed. Such methods would also be relevant to geological mapping for exploration and exploitation for coal and other mineral resources. The Ayrshire Joint Structure Plan 2025 consultation draft (AJSP, 2004) notes a concern regarding discharge of mine water from abandoned mine workings visibly affecting the quality of river water at Muirkirk. The detailed geophysical survey was intended to identify the location and potential source of contamination of surface waters.

2 Interpretational guidelines

2.1 ELECTROMAGNETIC SURVEY

Electromagnetic survey, or EM, maps the electrical properties of the ground. All EM systems generate a primary magnetic field due to an alternating current in a wire loop. This time-varying magnetic field generates electrical currents in the sub-surface. These in turn generate a secondary magnetic field and it is the ratio between the primary and secondary magnetic fields that is detected at the receiver of the EM system. Distinct conducting bodies at or near the ground surface will generate large anomalies, whilst distinct trends may be observed if the superficial deposits or bedrock geology has electrically conducting units within it. Conversely resistive areas of low electrical conductivity will generate low EM anomalies or trends.

The depth of investigation depends on the electrical conductivity of the ground, the frequency of the EM system and the height of the aircraft above ground level. An electrically conductive layer in the near surface leads to a reduction in the depth of penetration of the signal. Similarly, the higher the frequency of the EM signals the shallower is the depth of penetration. Hence for the two-frequency system used here, for average UK ground electrical conductivities and at a flying height of 56 m above ground level, it can be assumed that the maximum depth of penetration is about 100 m for the lower frequency of 3,000 Hz. The upper frequency of 14,400 Hz will be more responsive to conductive features at a shallower depth. It should be noted that when the aircraft flies high over urban centres there is no EM response and so the results are either highly resistive or have been removed from the data sets. The parameter calculated and presented in the plots is apparent electrical conductivity that has units of milliSiemens per metre (mS/m).

2.2 RADIOMETRIC SURVEY

The radiometric method measures the gamma ray radiation that is emitted from the decay of the naturally occurring isotopes ^{40}K (potassium), ^{238}U (uranium), ^{235}U (uranium) and ^{232}Th (thorium) and any anthropogenic derived radioactive isotopes. Average crustal abundances are K – 2%, U – 2.7ppm and Th – 8.5 ppm. ^{40}K is the only radioactive isotope of potassium and occurs as 0.012% of natural potassium and hence the gamma-ray flux of ^{40}K can be used to estimate the total potassium present. ^{235}U forms only 0.72 % of naturally occurring uranium and the gamma-ray energies in its decay series are too low to be useful in airborne gamma-ray surveying. ^{238}U does not emit gamma-rays, but it is detected by the decay of one its radioactive daughter products, ^{214}Bi (bismuth). Thorium occurs naturally as the radioisotope ^{232}Th and it too does not emit gamma-rays and so is detected by its radioactive daughter product ^{208}Tl (thallium).

Because the abundances of uranium and thorium have to be estimated from their decay series, which may not be in equilibrium, they are referred to as equivalent uranium and thorium (eU and eTh) and are presented in parts per million (ppm). Potassium, which is not estimated, is calculated as the percentage present. A fourth presentation that is sometimes used is the Total Count. This is the total number of scintillations received in the detector during the sampling time over the energy window measured. It is the lumped sum of all the gamma-ray energy received. It is presented as counts per second, sometimes referred to as Ur units meaning the sum of all counts received from 0.4 to 3.0 MeV. The gamma-ray flux is measured over the energy interval 0.4 to 3.0 MeV and so the main anthropogenic source that might be detected is ^{137}Cs (Caesium).

It should be noted that since earth materials absorb gamma radiation the radiation energy that is received at the detector of the spectrometer is emitted only from the top 0.3 m of the ground surface. In addition water is a very effective absorber of gamma rays and so no radiometric signal will be measured over saturated ground.

2.3 MAGNETIC SURVEY

The earth's magnetic field is dipolar with north and south poles. As a result the direction of the field at any point on the earth depends on the magnetic latitude. Magnetic minerals within rocks become magnetised by the earth's field in the direction of the field at that point. This type of magnetisation is known as induced magnetisation. The induced magnetic field of a rock unit is itself dipolar and the interaction of this small dipolar field with the earth's field leads to anomalies that have both positive and negative elements. The relative magnitudes of the positive and negative lobes and the shape of the anomaly are again dependent on magnetic latitude.

Some rock units, mainly igneous rocks, also have a remanent magnetisation, which is a magnetisation in the direction of the earth's magnetic field from when the rock unit was formed. This is usually different to the earth's present day magnetic field due to continental drift and periodic reversals in the earth's magnetic field. The resulting magnetisation of a rock unit is thus the vector sum of the induced and remanent components. Very often the remanent component is small, but occasionally it can dominate and in situations where the rock unit formed in the last few million years in a field that was reversed compared to the present day field, the rock unit will be reversely magnetised.

Ferrimagnetic minerals, particularly magnetite, are the main source of local magnetic anomalies. Rocks rich in ferrimagnetic minerals are ultramafic rocks (dunite, pyroxenite, peridotite etc.) basalt, dolerite, gabbro and some metamorphic rocks. Magnetic anomalies are also caused by ferrous material such as railway lines and some buildings and power lines also generate magnetic fields. Dumped ferrous material, as might be found in a landfill, can also generate substantial magnetic anomalies.

The measured quantity is total magnetic field strength, which has units of nanoTesla (nT).

3 Interpretation of features

This report is not a definitive interpretation of all the datasets and the interpretation was biased towards features that would be of interest to planners, environmental organisations and those interested in the sustainable development of the region. Definitive plots of each of the many datasets for all four areas are therefore not shown. No attempt was made to remove the anomalies generated by man-made features because such filtering can remove the subtle variations that assist in the interpretation of the geophysical results.

3.1 THE REGIONAL ISSUES

Issues arising from the regional Ayr survey with 200 m flight line spacing include peat mapping, landfill identification, brownfield site characterisation, opencast workings and mapping of dykes, faults and volcanic vents.

3.1.1 Peat mapping

Potassium radiometric data from the north-eastern part of the Ayr survey (Figure 2a) shows percentage potassium ranging from 2.8 to 0.02 % (red, yellow, green, light blue to dark blue). The mapped 1:50,000-scale superficial geology spanning the eastern part of the Ayr survey and including the Muirkirk area survey is illustrated in Figure 2b. Peat of >1.0 m thickness is shown in brown, alluvial deposits of clay, silt, sand and gravel are shown in yellow, glaciofluvial deposits of gravel, sand and silt are shown in pink and glacial till deposits of silty clay with stones are shown in blue. White polygons are areas of exposed bedrock without superficial deposits.

There is a close correlation between the areas of peat and the lower counts in the potassium plot. This reflects the composition of peat, which contains large quantities of humic material. The light blue and green in the potassium plot, reflecting low to moderate potassium percentages, picks out the drainage channels. The glaciofluvial deposits are characterised by moderate potassium percentages, shown in green and the till displays moderate to high potassium percentages, shown in green to yellow. Thus the potassium data, even at 200 m line spacing would appear to be a useful tool for mapping upland peat. In addition the airborne data show the peat distribution at a snapshot in time whereas the mapping data are acquired over many years. Hence, the regional management of peat over time could be greatly aided by repeated airborne radiometric surveys. It should be noted that for the purposes of geological survey of superficial deposits the threshold thickness for mapping is one metre thickness whereas the radiometric survey detects energy from the upper 0.3 m. The potassium survey data can therefore be used to provide information on the character of superficial deposits of 0.30 m (see 'Interpretational guidelines') to 1.0 m thickness.

Aspects of the 1:25,000 scale soil series data from the Macaulay Institute, which is available at this scale for the northern and western part of the Ayr survey area, are illustrated in Figure 3a. One Major Soil Sub-Group is shown: peat and peaty soil (peaty alluvial soil (undifferentiated), peaty gley, peaty podzol) as shades of blue and blanket peat (both > and < 1.0 m) as shades of dark brown. Comparison of the more detailed soil mapping with the potassium data (Figure 3b), re-emphasizes the close correlation between the distribution of peat and the low potassium percentages. The threshold between the light blue and green-coloured values on the potassium radiometric survey data appears as a close but not exact proxy to the mapped extent at 1:25 000 scale of peat and peaty soils. Areas of humic gley, non-calcareous gley and those designated as 'complex' soils adjacent to the mapped areas of peat and peaty soil also fall within the extent of low percentage potassium radiometric data. This is presumed to be due to the high water content of these soil types. Water bodies are characterised by low percentage potassium radiometric data as are small areas within the mapped extent of mineral alluvial soils. The relationship between the two data sets certainly merits more detailed comparison.

The relationship between this threshold and the extent of peat and peaty soils mapped at 1:250,000 scale in the south-eastern part of the survey area (not shown) is much more approximate, reflecting contrasting resolutions at different scales. The potassium radiometric survey data could be used to map the extent of peat in the absence of 1:25,000 soil series data, although of course not the genesis or other characteristics of the peaty deposit. The opportunity to investigate and examine the utility of radiometric potassium survey data to map peat and peaty deposits would be very welcome.

3.1.2 Landfill identification

Previous studies, based on flight data taken at 50 m line spacing,.have shown that landfills can sometimes be mapped with airborne EM surveys (Beamish, 2002; 2003; Lohva et al., 1999). In addition, if the landfill is leaking it may be possible to identify a conductive pollution plume in the sub-surface.

Many landfills, particularly old landfills whose locations have been lost, may produce EM anomalies that indicate their presence. However, where the sites have dimensions of 100 to 200 m they may be poorly sampled by 200 m spaced flight line data. Geological survey of an area south of the town of Mauchline records many quarries in sandstone bedrock for the period 1910 to 1959. Many of these quarries were subsequently used for landfill. The high frequency EM conductivity data illustrated in Figure 4a was collected along 200 m spaced flight lines from the southern outskirts of Mauchline. An apparent conductivity high shown in red lies within the extent of one former excavation, the eastern Ballochmyle Quarry, which is now a landfilled site [2501 6264]. This demonstrates the conductive nature of the landfill and indicates that there might be conductive leachate within the site. The anomaly appears to be extended to the west, suggesting that the landfill might be leaking. Figure 4b shows the low frequency EM conductivity data. In this case the anomaly, which is of deeper origin than that from the high frequency data, extends farther west into the site of the former western Ballochmyle Quarry site [2499 6265]. This may again suggest a leaking landfill. However, this anomaly is complicated by the railway line that would be expected to produce a conductive response and coincides with the interpreted 'landfill' anomaly. However, it should be noted that there are no other anomalies associated with this section of the railway line. Additionally, there are several other smaller quarries recorded by previous geological surveys that are not associated with conductivity anomalies. The resolution afforded by more closely spaced conductivity data would lead to improved anomaly separation.

3.1.3 Brownfield site characterisation

Radiometric survey, in contrast to electromagnetic survey, has a larger footprint; that is, the area of ground beneath the aircraft that is sampled is larger than for EM. Hence smaller targets will often still be sampled by several passages of the aircraft even when the line spacing is 200 m. Figure 5a shows total count radiometric survey data over a disused tip [2495 6296] to the north of Mauchline, adjacent to the A76 Kilmarnock Road. This is a known brownfield site, described as a colliery, and marked by East Ayrshire planners as Vacant and Derelict Land for redevelopment. The site is crossed by three of the east-west flight lines and produces a radiometric high (shown in red) indicating that the colliery tip has been enriched in the natural radioactive elements. There is an EM conductive anomaly in the high frequency data (Figure 5b) and a smaller anomaly in the low frequency data (Figure 5c) indicating that the conductive content of the tip may be relatively shallow and is unlikely to be leaking beyond the extent of the site.

Total count radiometric survey data from a small area north-east of Auchinleck [2551 6217] in East Ayrshire is shown in Figure 6. The area is underlain by coal-bearing strata and on the Ordnance Survey map there are two areas of former opencast workings at [2577 6233] and [2598 6236], and a large number of small raised areas of man-made ground are mapped. There are many radiometric total count anomalies (plotted in red) and most are known former workings or man-made ground. The largest total count anomalies in areal extent are sites of former opencast coal abstraction (Figure 6). The area illustrated includes six sites identified as 'Vacant and Derelict Land' (shown as polygons on Figure 6) by East Ayrshire Council. Two of these are sites at Roundshaw are described as 'bings', spoil heaps of waste from mining (Figure 6). The No 6 Bing [25663 62347] at Roundshaw is not associated with radiometric survey anomalies suggesting no concern regarding ground contamination from this data set. Whereas, No 15 Bing

[25706 62387], the largest designated site, is associated with a radiometric anomaly which extends farther south-west than the mapped site extent.

The two adjacent designated sites of Birnieknowe 1 [2577 6221] and Birnieknowe 2 [2575 6222] have a small radiometric anomaly but only in the northern or eastern part, respectively (Figure 6). The designated site at Happock [2582 6216] is also associated with a small radiometric anomaly which is mostly contained within the site. South of Auchinleck Burn the Dykes [2568 6218] derelict site is associated with a radiometric survey anomaly which spans the course of the burn. Field sampling would identify whether or not the cause of the anomaly would require remediation prior to redevelopment or affect surface water quality.

Virtually all of the radiometric anomalies shown in Figure 6 coincide with known areas of worked ground and they fall, for the most part, within that known extent. An anomaly that is not associated with an area of known worked ground is noted where water issues at the roadside north-west of Birnieknowe [2567 6230] (Figure 6).

3.1.4 Opencast workings

Opencast coal workings are a characteristic of the region, in particular within the county of East Ayrshire. Recent workings are commonly associated with older colliery sites and underground mines, worked in the 19th Century or before, creating a landscape with surface and subsurface workings and spoil heaps of several vintages. Quarrying of other rock types, such as limestone, is often associated with the mines. These activities lead to concentration of the naturally occurring radioelements as displayed by the total count radiometric survey data.

Total count radiometric survey values over a current area of opencast coal mining east of Muirkirk, at Glenbuck and Spireslack [2747 6295], are shown in Figure 7. There is a marked anomaly of high values in the vicinity of the opencast sites indicated by Ordnance Survey mapping but the relationship is not pronounced at the mapped former opencast workings west of Lightshaw [2706 6285] and total radiometric survey counts are low over opencast workings mapped at Muirkirk [2684 6275] in the south-west corner of Figure 7. This contrast may reflect the effects of restoration and remediation activities on former or inactive opencast sites.

Crawford Hill [2621 6181], south-east of Cumnock in East Ayrshire, is characterised by a large total count radiometric anomaly associated with opencast workings at High Garleffan [2624 6183] (Figure 8). The Ordnance Survey 1:10 000 scale topographic map shows the extent of the opencast workings and the anomaly shows good correspondence with the north and east edges of the mapped site. However, the extent of the anomaly extends much further west and south. In the East Ayrshire Opencast Coal Subject Plan the extent of potential coal extraction at Garleffan is shown as of much greater area. It seems highly likely that the current extent of opencasting activities at Crawford Hill are much greater than shown on the available topographical map and the anomaly probably reflects the actual extent of opencast coal mining activities at Garlaffan, as also noted at Glenbuck and Spireslack (Figure 7).

3.1.5 Mapping of dykes, faults and volcanic vents

Over geological time the Midland Valley has experienced a number of phases of volcanic activity creating lava bedrock formations that issued from volcanic vents and intrusion of near-vertical igneous dykes and near-horizontal igneous sills. Similarly, there is also a long history of geological faulting with distinct orientations of geological fault structures.

Magnetic data often contain a lot of information on the concealed geology, from shallow to often considerable depth. Magnetic anomalies sourced at shallow depth are characterised by short wavelength anomalies. Linear features in the magnetic anomaly data are usually associated with dykes and faults. Figure 9 is plot of the total magnetic field with the prominent, linear, magnetic features picked from the Ayr survey data, annotated in white. Many of these have a north-westerly trend and these are found in all parts of the image. Some east-trending features are also observed, but these occur mainly in the north-west part of the survey. Some of the picked lineations are due to the presence of underlying geological faults. Of interest is a prominent northerly oriented lineament (marked as feature A) that shows clear offsets at two localities corresponding with mapped faults. It is known that dykes can change course when coming to a crosscutting structure such as a fault or igneous intrusion. Hence, the most likely explanation of this feature is a minor Palaeogene dyke that has changed course at the crosscutting faults. Figure 10a shows the north-eastern region of the total magnetic field image (Figure 9) on which is superimposed a north-eastern-trending profile (in white) and the magnetic values along this profile are shown in Figure 10b. Mapped bedrock dykes are shown on Figure 10a as green linear features. The linear magnetic features are interpreted as dykes and shown on Figure 10b in blue, where the width of the blue column is equal to approximately half the width of the anomaly at half of its maximum amplitude. It should be noted that these blue column widths do not define the widths of the subsurface feature causing the anomaly. Techniques do exist for estimating the width and depth to the magnetic source, but these have not been applied here. Of the six interpreted dyke linear magnetic anomalies only three correspond with mapped dykes and two of these are displaced with respect to the position of the magnetic anomaly. This indicates the utility of the magnetic data for detecting dykes in the sub-surface. These dyke-related anomalies are all represented by minima (troughs on the magnetic profile) and range in value from 18 to 163 nT with anomaly half-widths from 84 to 164 m.

A similar pair of diagrams, from the centre of the Ayr survey (Figure 9), is shown in Figures 11a and 11b for a south-to-north orientated profile that crosses an east to west magnetic feature. A later phase of igneous dykes is again shown in green and other igneous rock intrusions are shown in mauve. Two interpreted dykes are shown in blue (Figure 11b) and these two dykes are probably continuations of the mapped dykes seen farther west (Figure 11a). These anomalies are maxima (peaks on the magnetic profile) with magnitudes of 92 and 36 nT with anomaly half-widths of 280 and 80 m.

Bedrock for much of the area of study is concealed beneath superficial deposits. However, using the Hi-RES magnetic data from the Ayr survey with a flight line spacing of 200 m the mapped presence of known igneous dykes can be extended and previously unknown dykes can be mapped in. The width of the dykes cannot be measured directly from the width of the magnetic anomaly but an appraisal of dyke width can be obtained by modelling of the anomaly.

3.1.5.1 Dyke modelling

The expected magnetic response from a dyke can be modelled and this aids the interpretation of observed linear features and demonstrates the limits of resolution possible in identifying dykes from an airborne magnetic survey. A dyke model is shown in Figure 12 that consists of a rectangular dyke of depth dimension 285 m. The profile along which the magnetic response was calculated is perpendicular and symmetrical to the profile and the dyke model extends 10 km each side of the profile. The magnetic response has been calculated at a height of 56 m above the ground and at a sample interval of 6 m, which replicates the magnetic profile that would be measured by an airborne geophysical survey. The variables in the sets of models run are the width and depth of the dyke. The background magnetic field was set to a value for the Midland Valley (declination –5.07º, inclination 69.6º and field value 39.4 Amperes per metre, A m^{-1}) and the modelling assumes that there is no remanence, i.e. the magnetisation of the dyke is by induction only. Two sets of models have been created; one for dykes of Permo-Carboniferous age that are generally east-west-trending and the other for the dykes of Palaeogene age that are generally north-west-trending. Rollin (in press) reports volume magnetic susceptibility values for the two suites of dykes based on around 300 measurements from all over Scotland and these are shown in Table 1. Magnetic susceptibility is a measure of the degree to which a substance may be magnetised. It is calculated as a ratio and is thus dimensionless, but there are two measurement systems (cgs and SI) that result in different values. SI refers to the Systèm International d'Unités, also referred to as the meter-kilogram-second-ampere system of units.

Dyke suite age	Volume magnetic susceptibility (SI)			No. of samples
	Minimum	Maximum	Mean	
Permo-Carboniferous	0.016	0.052	0.033	155
Palaeogene	0.001	0.073	0.025	136

Table 1 Volume magnetic susceptibility for Scottish dyke suites, measured in SI units from Rollin, in press.

From these measurements it can be seen that the Palaeogene dykes have the greatest range of magnetic susceptibilities, with a maximum value higher than that for the Permo-Carboniferous dykes, although the Permo-Carboniferous dykes have the higher mean magnetic susceptibility.

The results from the modelled Permo-Carboniferous dyke are shown in Figure 13 a – c. This dyke model was east-west-trending and assigned a magnetic susceptibility of 0.033 SI. The profile is at right angles to the dyke (south-north) and the three graphs refer to a dyke of width 10, 5 and 1 m, respectively. Within each graph the magnetic response is shown of the dyke at depths of 100, 20 and 5 m below the ground surface. The largest magnetic response is from the 10 m wide dyke at a depth of 5 m and this has a peak-to-peak response of 38 nT and an anomaly half-width of 75 m. As the depth to the top of the dyke increases the anomaly magnitude decreases and the wavelength (anomaly half-width) increases. As the width of the dyke is reduced the anomaly magnitude decreases. For the 1 m wide dyke the maximum peak-to-peak response is 4 nT. However, for modern high resolution airborne surveys the 1 m dyke at depths of 5 and 20 m should still be detectable although at 100 m depth the response is probably within the noise envelope of the survey.

A similar set of graphs is shown in Figure 14 a – c for the Palaeogene dyke model that strikes in a north-west direction. The profile is orientated north-east and the dyke was assigned a magnetic susceptibility of 0.025 SI. The results are very similar to those due to the Permo-Carboniferous dyke except that the anomaly magnitudes are less.

It is clear from an inspection of the total field magnetic anomaly data (Figure 9) and the 1:50,000 scale bedrock geology that many of the east-west striking igneous intrusions are not associated with magnetic anomalies. This may be because the magnetic survey was flown on east-west flight lines that would not resolve many east-west striking features. Equally it is quite likely that these dykes may have low magnetic susceptibilities. In contrast the north-west striking Palaeogene dykes (Figure 10) are characterised by pronounced anomalies of up to 163 nT that are local minima on the magnetic profile. This change in polarity of the magnetic anomaly compared to the modelled results demonstrates that the Palaeogene dykes have a large component of remanent magnetisation that is the approximate reverse of the present earth's magnetic field direction and dominates over the induced magnetisation component. The south-north profile in Figure 11 also crosses Palaeogene dykes, but in this case the anomalies are positive (as in the modelling). The anomaly magnitudes indicate that the dykes probably have a component of remanent magnetisation in the same approximate direction as the present earth's magnetic field that is combined with the induced component.

3.1.5.2 VOLCANIC VENTS

Figure 15 shows the total magnetic field data from around the town of Mauchline overlaid on the 1:50,000 scale bedrock geological map. This area is known to have a number of igneous intrusions (highlighted by a yellow circle) and volcanic vents (highlighted by red circles). The volcanic vents are characterised by dipolar magnetic anomalies. Other dipolar magnetic anomalies may correspond with vents that were previously unmapped and the blue circle indicates one of these in an area covered by superficial deposits of till and peat.

3.2 THE ARDEER REGION

The Ardeer infill survey was flown over the extensive industrial site at Ardeer and extended to the outskirts of Irvine in the east and to Stevenston in the north covering an approximate 5 x 5 km area (see Figure 16a). Flight lines were north to south in order to cross the geological strike at a high angle which has a mainly east to west orientation at this location. Flight line separation was 50 m. The Ardeer industrial works lies along the western banks of the River Garnock and is bounded to the west by the coast and to the north by a railway line, see Figure 16a.

3.2.1 Mapping of bedrock

The magnetic survey data records high values over much of the Ardeer survey area (Figure 16b). Many of the magnetic anomalies are coincident with man-made infrastructure (railways, roads, pipelines, power lines and buildings) and sites of industrial activity, e.g. Ayrshire Metal Products [2314 6388], which may mask any anomalies due to underlying bedrock geology. Igneous dykes mapped within the onshore part of the survey area are not associated with distinct magnetic anomalies (Figure 16b). However, linear anomalies noted in the shallow offshore area of west-north-west or north-north-west orientation [2276 6392] are parallel to known dyke orientations. An anomaly of westerly trend across the southern part of Bogside Race Course [2304 6396] may be a response to a sill or dyke, both of which are recorded within the area from subsurface mine and borehole information. Although the Annick Water Fault is mapped in this approximate position (BGS, 2005) and also modelled from data acquired by earlier aeromagnetic and gravity surveys (Monro, 1999), the magnetic anomaly in the Hi-RES data reveals the characteristics associated with a dyke.

3.2.2 Vacant and Derelict Land and Waste Facilities

The total count radiometric data for the Ardeer region is illustrated in Figure 17a. Raised values are observed within the extent of the industrial works but these are not uniformly very high. Distinctive highs are associated with a disused tip within the Bogside Race Course to the east of the River Garnock [2303 6400], an old workings further north on the east bank of the river [2299 6408] and near Dykehead [2312 6414]. Comparison of the total count radiometric data with sites designated as 'Vacant and Derelict Land' and also Waste Facilities (Figures 17b to 17e) illustrates that most of the designated sites have relatively low values (yellow and green colours). A minority of the sites have relatively high values (red colours); these sites might be anticipated as having high values as implied from previous or current land use but the anomalies are not uniformly high within each site (marked * in table). The high total count values do not indicate dangerous values or that the site is necessarily contaminated but areas with high counts are considered more likely to be contaminated than areas with low total radiometric counts.

Radiometric survey Total Count	**Designated Vacant and Derelict Land & Waste Facilities**
Low relative values (yellow and green)	Ardoch,; Ardeer Tavern; Ayrshire Central Hospital; Burnside House; Cunninghame Road; East Stevenston; Former Filling Station, Kilwinning Road; James Crescent, Irvine; Kilwinning Road, Stevenston; Garven Road; Harbour Street, Irvine; Hawkhill; Heather House, Irvine; Kyle Road; Landmark Building; Marine Drive; Moor Nursery; Nethermains x 2; Police Station Kilwinning Road, Irvine; Portland Place Irvine; Portland Place, Stevenston; Portland Road Irvine; Railway Sidings, Irvine; Land/buildings, Redburn Industrial

	Estate; Riverside Retail Park x 2; Sanderson Avenue; Watercut Road; West Byrehill.
High relative values (shades of red)	Ayrshire Metal Products Site*; Bartonholm Waste Facility; Byrehill Junction; Dykehead Bridge; Industrial Estate Stevenston; Lundholm; Lundholm Road; Matthew Wright Nephew*; Nobel Business Park*; Nethermains Landfill Site; Former Ravenspark Hospital; Redburn Brickworks*; Shooting Club Portland Road,

Table 2. Comparison of sites of designated Vacant and Derelict Land and Waste Facilities with their radiometric signature.

A ternary image of the radiometric data distinguishes the variation in the three radioelements surveyed (Figure 17f). In this plot each radioelement is assigned a colour range (red for high potassium, green for high thorium and blue for high uranium). Areas where the gamma-ray flux is due to more than one radioelement plots as a combined colour (see legend on Figure 17f). The image has been cropped to only display higher values. It can be seen that potassium (red) is dominant in the north of the industrial works [2280 6411] with some high values in the central region [2286 6401]. Uranium (blue) and thorium (green) are dominant across the main central and southern parts of the site. It is likely that these differences reflect former industrial usage and may be diagnostic of the activity carried out at that location. The Nobel Business Park Vacant and Derelict Land site is distinguished by low potassium and high uranium and thorium as shown by a distinctive cyan colour (Figures 17b and f). The adjacent Lundholm site (Figure 17b) is coloured yellow to blue indicating variations in low to high uranium, respectively (Figure 17f). The Ayrshire Metal Products site is also distinguished by a blue colour indicating high values of the uranium radioelement but restricted to the northern part (Figures 17e and f). Whereas part of the Matthew Wright nephew site to the south is characterised by high thorium (green) (Figures 17e and f). The site of the Redburn Brickworks (Figures 17d and f) is coloured yellow and green suggesting high thorium and low uranium although adjacent to areas of high potassium (red) and uranium (blue).

Figure 18a shows the high frequency EM conductivity data, measured in milliSiemens per metre, with a colour range restricted to 50 (dark blue) to 950 mS/m (red). The high frequency EM data is a response to shallow conductive features. There is a central core of high values over the site of the Ardeer industrial works that may be caused by buildings on the site, although industrial contamination is also a possible cause. For example, the anomaly at [2291 6401] is within the former detonator works of the explosives factory (PASTMAP data, RCAHMS). Figure 18b is a plot of the low frequency EM conductivity data with a colour range restricted to 50 (dark blue) to 1200 mS/m (red). Some very conductive values occur at several localities along the River Garnock e.g. [2296 6415] and a few occur towards the northern end of the Ardeer industrial site around [2284 6404] although these are probably due to buildings. None of these anomalies fall within the extent of designated Vacant and Derelict Land sites. Anomalies noted in the high frequency EM data in the vicinity of the detonator works at [2291 6401], are much diminished in the low frequency data that responds to conductive features at greater depth. Conversely, anomalies noted in the shallow high frequency data (Figure 18a) at [2278 6405], between the Nobel Business Park and Lundholm Vacant and Derelict Land sites (Figure 17b), are much more marked in the deeper low frequency EM data (Figure 18b).

The Nethermains Landfill Site [2309 6415] west of Dykehead (Figure 17d), a designated waste facility, is distinguished by a marked bipolar anomaly of adjacent very high and low values in the magnetic survey data (Figure 16b). This feature is probably due to the high proportion of ferri-magnetic metal contained within the landfill and there is a corresponding high anomaly in the radiometric survey data (Figure 17a and d). There is a moderate anomaly within the shallow, high frequency EM survey data (Figure 18a) for Nethermains, but not in the deeper low frequency data (Figure 18b), which again may be due to the presence of metal within the relatively shallow refuse fill.

Some very conductive values do occur at the mouth of the River Garnock as adjacent to the 'The Big Idea' [2303 6383]. These are probably due to conductive seawater on the beach (the rest of the marine area and the tidal region of the River Garnock have been masked in the plot due to very high conductivities measured over salt water).

3.2.3 Anomalies related to industrial land use

Ayrshire is a region with a long history of subsurface mining of coal and there are many mine shafts and collieries marked on historical and recent maps within the extent of the Ardeer survey. With a few notable exceptions, described below, the mapped presence of outcrops of coal seams, shallow and deep mine shafts and colliery sites do not generally appear to co-incide with distinct anomalies in the geophysical data.

Two shafts marked at the site of the Ardeer colliery on the coast at [2273 6403] are associated with marked magnetic and radiometric anomalies (Figures 16b, 17a and b) but there is not a coincident feature in the EM data. However, there is an adjacent anomaly in both the high frequency and low frequency EM data (Figure 18a and 18b). By contrast there are neither marked radioactivity nor EM anomalies at the site of the nearby Prince of Wales colliery at [2270 6407] which is now playing fields (Figures 17a, f, 18a and b).

Distinctive high magnetic and radiometric anomalies correlate with the site of Bogside (No.1) colliery in the centre of the Bogside race course [2304 6400] (Figures 16b and 17a). The presence of the Five Quarter, Parrot and Turf coals is recorded in the pit to depths of more than 53 fathoms (105 m). The yellow colour on the ternary radioelement plot indicates high potassium and thorium and low uranium (Figure 17f). There are no coincident anomalies at the site of the Bogside colliery in the high or low frequency EM data (Figures 18a and b). On current topographical maps the Bogside colliery is marked as a disused tip.

The vicinity of Bartonholm on the east bank of the River Garnock [2306 6411] has been a site of refuse disposal for more than 35 years (Irvine Development Corporation, 1971) and remains a waste facility (Figure 17d). It is marked by high magnetic and moderate radiometric anomalies (Figures 16b, 17a and d) but is not characterised by either high or low frequency EM anomalies (Figures 18a and b). Whereas the site of the Bartonholm colliery at [2299 6409], within the Bartonholm area, remains as a distinct discrete anomaly in magnetic and radiometric survey data (Figures 16b, 17a and d). The cyan colour of the ternary radioelement plot indicates high thorium and uranium and low potassium content (Figures 17a and f).

3.2.3.1 Near the Longford Chemical Works

The largest anomaly in the low frequency EM data (Figure 18b) occurs to either side of the River Garnock where it is marked with 'Weirs' around [2295 6415] and compared with the high frequency data (Figure 18a) represents a considerable spreading out of the conductive values with increasing depth. It is possible to speculate on the cause of the large anomaly from an examination of historical maps. On the 1860 map a number of points are marked as having been old coal pits, but otherwise the area around the anomaly comprises open fields. However, on the 1897 map a chlorine works is shown adjacent to the river at a point that corresponds with the western end of the anomaly (see Figure 19a) and the position of a borehole drilled within the extent of those works in 1887 is described as lying 'east of old Oil Work'. On subsequent maps from 1911 and 1938 the site of the chlorine works is now shown as Longford Chemical Works and on geological maps published in 1924 two coal shafts are recorded, in the north-west and north-east of the works, with coal at 44 to 55 fathoms (86 -108 m). The coal-bearing strata are concealed beneath 11 to 16 m of superficial deposits of soil, sand, gravel and glacial till. Coal seams were also recorded from the Bogend colliery 600 m upstream on the north bank of the river. The croplines of the Kilmarnock Parrot (KPT), Kilmarnock Turf (KTU) and Upper Wee coals (UPWC) are mapped from the chemical works north-north-eastwards and underlying the River Garnock, (Figure 19b).

Early plans of coal extraction, dated 1841 and worked from the Snodgrass colliery on the east bank of the River Garnock, show the mapped ‘Termination of Coal Working’ in the Kilmarnock Parrot Coal up to the bank of the river (Figure 19c). North of the mapped boundary of workings ‘Depressions’ are noted (Figure 19c) indicating collapses associated with recorded and unrecorded workings beyond the surveyed extent of mining and at the mapped outcrop of the Parrot Coal (Figure 19b). There is no information as to the depth of the workings but a ‘Place of Irruption’ (Figure 19c) is recorded within the former course of the river (shown as a dotted line on Figure 19a) marking a point of ingress of water. The workings beneath the former position of the river were likely to be at shallow depth below rockhead for water to ingress from the surface. The Parrot Coal is underlain by the Kilmarnock Turf and Upper Wee coals, although there are no available plans of workings of these seams it is reasonable to consider that they have also been worked. The marked anomaly in the high frequency conductivity data along the River Garnock shows a close spatial correspondence with the shallow workings of the Kilmarnock Parrot Coal and conductive fluids within these workings, and any workings in the underlying Turf and Upper Wee coals, appear to have generated the anomaly.

Coal mine plans from the Bogend colliery, on the north bank of the river (Figures 19a and c), Stevenston No 7 colliery within the Longford Chemical Works and Stevenston No 6 colliery (Figures 19a and b) show worked coals that are deeper in the geological sequence and lie to the north of the westward-trending geological fault shown in Figure 19b. Waters in these workings are considered unlikely to contribute to observed conductivity anomalies.

Although there are no available records of mining of the Upper Wee, Kilmarnock Parrot and Kilmarnock Turf coals shallow unrecorded workings should be expected where they crop-out within the extent of the chemical works at Longford (Figure 19b), as is the case on the eastern river bank. It is of note that there are many coal seams at outcrop and 143 records available of coal mine workings within the extent of the Ardeer survey but few are associated with conductivity anomalies in the Hi-RES survey data. However, the site at Longford has had a long history of industrial usage as a chemical, oil and chlorine works and, more recently, premises of an explosives factory established on both banks of the river. It was common practice in the past to dispose of unwanted materials in old mine shafts and such disposal has only been regulated in recent years to protect surface and groundwater bodies. The very marked anomalies in the conductivity data where underground coal workings come to surface and near the site of the former Longford Chemical Works may be due to the disposal of industrial waste in the mine cavities at sometime during the lifetime of the site.

3.2.3.2 LADYHA’ PARK

Two conductivity anomalies at the north-eastern edge of the Ardeer survey in Ladyha’Park [2318 6424] also show a marked spreading out of the conductive values with increasing depth (Figures 18a and b). Four coal seams are mapped at rockhead, beneath approximately 15 to 18 m of sand and gravel and glacial till; Upper Wee, Kilmarnock Turf, Kilmarnock Parrot and Linn Bed coals. The 1897 map illustrates the Ladyha’ colliery at [2315 6424] that lies to the west of the two conductivity anomalies in Ladyha’ Park (Figure 19d). However, mine plans for Ladyha’ No 2 colliery show working coals deeper within the geological sequence at more than 31½ fathoms (>60 m) below ground level. The eastern anomaly underlies an area of ponded water and extends southwards in the deeper low frequency conductivity data (Figures 18a and b). A borehole in the immediate vicinity of the pond describes coal 18 m below surface. Here unrecorded shallow workings are expected along the line of outcrop although there are no available plans of mine workings. Hence it is likely that the conductive anomalies at surface and at depth in Ladyha’ Park could be due to polluted mine waters within old unrecorded workings.

3.3 THE MAUCHLINE REGION

Extra flight lines were flown in a block to the south of Mauchline (Figure 20) to increase the density of the west to east flight lines to a line spacing of 50 m. The region was chosen for geological, land use and hydrogeological reasons. The area includes distinctive formations of red sandstone, which has been quarried for building stone, and underlying volcanic rocks (Figure 21a). Geological mapping was last undertaken in the 1950s and the area remains to be completed for modern geological survey (Walton and Lee, 2001). The red sandstone is an important groundwater aquifer and hydrogeological investigations by BGS include the drilling and geophysical logging of groundwater in three boreholes, including one production borehole, within the sandstones (Buckley, Perkins and Shedlock, 1986). These boreholes lie immediately north of the Mauchline survey. The sandstone quarries were abandoned and have subsequently been used as landfill sites for refuse and the survey is intended to indicate whether the influence of the fill is retained within the site. The survey covers an approximate 8 x 4 km area and is shown in Figure 20.

3.3.1 Mapping of bedrock

The western and northern part of the Mauchline survey is underlain by Permian sandstones of the Mauchline Sandstone Formation and Carboniferous sedimentary rocks underlie the eastern margin of the survey area (Figure 21a). Over the Permian sandstone there are a number of ‘bulls eye’, high amplitude magnetic anomalies that correspond with buildings (Figures 21a and b). However, the most distinctive anomalies within the area of sandstone are linear features that coincide or are extensions of mapped igneous dykes (compare Figures 21a and b). Using these new data it will be possible to map extensions to known dykes of north-westerly and easterly trend (Figure 21a). Additionally, a linear feature trending north-north-west from Burnbrae Lodge [2478 6244] may reflect the presence of a previously unmapped fault or dyke (Figure 21b). Mineral reconnaissance activities in this area have concluded there are notably high values of gold within the Mauchline Basin and that mineralisation may be associated with magnetic lineaments of north-west trend (Leake et al., 1997). The magnetic lineaments are suggested by Leake et al. (1997) to indicate deep-seated faults and any new data that supports the presence of faults would be of great interest. However, the character of the linear anomalies from this more highly resolved magnetic data suggests they are due to the presence of dykes rather than faults.

Permian basaltic lava of the Mauchline Volcanic Formation (Figure 21a) underlies the sandstone and beds of eroded lava fragments are interbedded within the base of the sandstone formation. The volcanic rocks curve around from the south-west then strike northward through the centre of Figure 21a. The pattern of adjacent high and low values in the magnetic survey data marks both the extent of the volcanic rocks at rockhead and where they are overlain by relatively thin sandstone formation rocks (at least 164 m of sandstone proven in boreholes) (Figure 21b).

The high frequency EM conductivity data (Figure 21c) also show linear features that correlate with railway lines, some roads and power lines. There is also a distinct linear conductivity low extending to north and south from High Clews [2515 6243] that is within the volcanic rocks toward the top of that sequence (compare Figures 21a and c).

The range of radiometric total count values in the Mauchline survey (Figure 21d) appear narrow, compare scales on Figure 21d with Figures 6, 7, 8 and 17a.

3.3.2 Mapping of superficial deposits

Most of the Mauchline survey area is covered with superficial deposits. The only mapped extent of peat is very clearly picked out by low values (blue colour) of total radiometric count underlying Kipplemoss Plantation [2484 6260], at the northern edge of the survey area near Mosshead (Figure 21d), which is also distinguished by high EM anomaly values (Figure 21c).

3.3.3 Vacant and Derelict Land and Waste Facilities

There are only five sites designated as Vacant and Derelict Land within the Mauchline survey area at St Cuthbert Street, Blackwood Avenue, Somerville Street, Newton Terrace in Catrine and the disused Catrine Branch Railway Line. There are no anomalies in the magnetic survey, the total radiometric count is similar to all the surrounding buildings within Catrine and the EM survey data show uniform values within the town. The latter is probably associated with the greater height of survey required over populated areas. There is no indication of the presence of contaminated land within the designated sites from the airborne geophysical survey data.

3.3.4 Anomalies related to industrial land use

The sandstone quarries that have subsequently been used for the purposes of landfill are mostly within the immediate vicinity of the town of Mauchline. They were not included within the extent of the Mauchline survey for the operational reasons that require higher survey flight over buildings. The anomalies associated with disused sandstone quarries are examined in the interpretation of the regional survey data.

3.4 THE MUIRKIRK REGION

Muirkirk is situated at the eastern extremity of the surveyed region and extra flights were made to increase the density of the west to east flight lines to a line spacing of 50 m. The region has a history of ironstone and deep coal mining, from 1787 to 1968, and quarrying of limestone. The southern side of the Murkirk valley was occupied by miner's houses, an ironworks and blast furnaces, tarmacadam works, spoil heaps, roads, railways and tramways (RCAHMS, 1995). The floor of the valley is underlain by subsurface mine workings in bedrock. Open cast mining of coal continues on the northern side of the valley. The area of historical industrial landscape and modern abstraction of natural resources was the focus of the infill geophysical survey. The survey covers an approximate area of 38 km^2 and is shown in Figure 22a.

3.4.1 Mapping of bedrock

The detailed magnetic survey of the Muirkirk area is dominated by negative (blue) and positive (red) linear anomalies generated by dykes of Palaeogene and Permo-Carboniferous age, respectively (Figure 22b). Where the north-west-oriented negative (blue) and positive (red) linear anomalies along the northern margin of the survey coincide with already mapped dykes they can be extended and made more continuous (see also section 3.1.5 and Figures 10 and 11). In places, concealed dykes will be newly mapped using the new Hi-RES magnetic data. A marked positive (red) linear anomaly in the south-eastern part of the Muirkirk survey area is aligned east-north-east (Figure 22b). The anomaly coincides with two mapped exposures of basic dyke rocks on the north side [2735 6268] and to the north-west [2727 6268] of Hawlk Hill. The anomaly indicates it is a single dyke, offset by faulting, that extends much further toward the south-west (Figure 22b). A dyke is not mapped at outcrop along a positive linear anomaly of west-north-west orientation in the south-west of the survey area but coincides with a basic dyke mapped in underground workings at Kames colliery, proven at depth by workings in the 7 Foot Coal seam at [2683 6262].

Broad, less pronounced linear anomalies of north-east trend extend across the north-western part of the Muirkirk survey area (Figure 22b). The southern boundary of high magnetic anomaly values at Shaw Knowe [2674 6275] is marked by a geological fault that divides the older rocks to the north from coal-bearing strata of the Muirkirk valley to the south (Figure 22b). The magnetic high underlying Black Hill [2703 6291] corresponds to igneous felsite bedrock geology. The marked linear magnetic anomaly trending east-north-east along the valley floor of the Greenock Water [2690 6290] coincides with a dyke (Figure 22b). The dyke is likely to be much more extensive than mapped on the basis of this new magnetic survey data.

3.4.2 Anomalies related to former industrial land use

Archaeological survey of the industrial landscape at Muirkirk was undertaken during 1991-92 (RCAHMS, 1995) (Figure 22a). Anomalies in the total count radiometric data (Figure 23a) coincide with surveyed industrial archaeological features on the south side of the Muirkirk valley; Wellwood Pit [6868 2564] and spoil heaps at the end of a trackway from Wellwood to the south [26869 62543] (Figure 23b); areas of many shallow mine workings north of Colt Burn [2693 6256] (Figure 23b); mine workings east of Catchyburn Rows [2275 6264] (Figure 23c); and an anomaly centred at [26974 2629] which now includes a football pitch (Figure 23c). A ternary image of the radiometric data (Figure 24) shows the relative abundance of each radioelement by assigning a colour in the range red to cyan for high to low potassium, green to magenta for high to low thorium and blue to yellow for high to low uranium. High values for all three elements will appear white. The image has been cropped to only display higher values. The ternary plot of the three radioelements (Figure 24) shows blue, green and cyan colours in the areas of historical mineworkings that indicate high thorium and uranium composition but low potassium in these areas. However, not all of the areas of mapped shallow mine workings are associated with anomalies in the radiometric survey data (Figures 23b and c).

There are three marked anomalies in the magnetic survey data north of Kames (Figures 22b and 27) within the site of the former Muirkirk Ironworks (RCAHMS, 1995); adjacent to Furnace Road [2696 6266], in the centre of the site [2697 6267] and adjacent to the former canal basin in the north-east part of the site [2698 6269] (Figure 27).

Overall, the extensive industrial archaeological works and workings coincide with the very broad high in both the high and low frequency EM conductivity data (Figures 25 and 26, respectively). These correspond with the outcrop of coal-bearing Limestone Coal Formation rocks and where they dip northwards into subsurface workings. There was no coincidence of conductivity anomalies with either the mapped limestone quarries or the MacAdam’s tar works.

3.4.3 Anomalies related to coal and ironstone mining

High counts in the total count radiometric data are seen over the current area of opencast coal working and former workings at Glenbuck and Spireslack [2748 6293] (Figure 23a), and along the access road and some of the drainage channels leading to the workings from the north [2745 6297]. High counts are also recorded north of the village over former opencast workings mapped west of Lightshaw [2706 6284] and surrounding the minewater treatment system [2684 6262] at the south-western end of the village (Figure 23a).

White anomalies on the ternary image of the radiometric data (Figure 24) in the area of current opencast workings demonstrates high concentrations of all three radioelements. However, there are also concentrations of each of the radioelements across other parts of the survey. In a central region just north of the A70 and including the area of former opencast workings west of Lightshaw [2706 6284] there is an increased concentration of thorium (green). Uranium is more dominant at the south-western end of the village (blue). North of Muirkirk village, on the southern and western flanks of Black Hill [2701 6288], and also in Ponesk Burn [2722 6300] red anomalies indicate high potassium values (Figure 24) that reflect a change in the underlying bedrock. A fault of north-west trend juxtaposes Carboniferous coal-bearing rocks to the south against older, Siluro-Devonian igneous rocks to the north. The high potassium composition of both igneous and sedimentary rocks of this age can be seen as red anomlies at Linburn [2694 6297] and in the valley of the Greenock Water [2664 6282] (Figure 24).

Figure 25 is a plot of the high frequency EM conductivity data with a colour range restricted to 20 (dark blue) to 200 mS/m (red). Higher values occur in a south-westerly trending belt to the south of the village [2705 6265] and in an anomaly at the south-western end of the village, near Midwellwood Farm [2667 6265] and Upper Wellwood [2674 6256]. These anomalies correspond in part with the locations of old workings marked on historical maps (Figures 22a, 23b and c), with mapped subsurface mine workings (Figure 26) but not the mine water treatment plant at [2684 6262]. Figure 26 is a plot of the deeper sensing low frequency EM conductivity data with a colour range also restricted to 20 (dark blue) to 200 mS/m (red). Of note are the large anomalies near Midwellwood Farm [2667 6265] and Upper Wellwood [2674 6256] at the south-western end of the village and the large anomaly near Kames [2703 6266]. Comparison of these anomalies in the shallow high frequency and deeper low frequency data indicate an increase in conductivity and size with depth. Figure 26 also includes the surveyed extent, shown as light green polygons, of the subsurface workings of the Gaswater Coal seam and in purple, the Muirkirk 6 Foot Coal seam. The coal-bearing strata are cut across by north-west-oriented geological faults. There is a reasonable correspondence between the conductivity anomalies and subsurface workings within fault-defined blocks. The closest correspondence is between the conductivity anomalies and workings in the Gaswater Coal in the vicinity of Upper Wellwood [2677 6258] and east of the sewage works at [2680 6263]. The spatial association of the deep, low frequency conductivity anomalies in the vicinity of Upper Wellwood and the mapped underground workings in the Gaswater Coal suggest that polluted mine waters may be the cause. Here the Gaswater Coal workings lie in the centre of a synclinal fold and at heights between -30 m and Ordnance Datum (200 to 230 m below ground level). The anomaly would be a response to conductive waters at shallower depth than the Gaswater Coal and indicate the presence of conductive groundwater in the overlying strata and in any other shallow unrecorded coal workings there.

The association between the low frequency conductivity anomaly near Kames (Figure 26) and surveyed subsurface mine workings in the Gaswater and Muirkirk 6 Foot coals is sufficient to also suggest mine water as the source cause. The correspondence is not as close as at Upper Wellwood but the Gaswater and Muirkirk 6 Foot seams crop out along the valley and there will be unrecorded shallow workings as illustrated by the archaeological survey (Figures 23b and c).

3.4.4 Vacant and Derelict Land and Waste Facilities

There are eight designated Vacant and Derelict Land sites within the Muirkirk survey area and they are all within the immediate vicinity of the town (Figure 27).

The largest Vacant and Derelict site, Main Street, lies south of Smallburn Road and extends to the River Ayr. It is marked as a disused tip on the Ordnance Survey topographical map and a waste tip (bing) from the mining of ironstone that formerly occupied the site although it is now landscaped. There is a gradual increase in the magnetic anomaly values from low in the north-east to high in the south-west due to two pronounced high and low, bipolar magnetic anomalies south of the River Ayr, centred at [2690 6266] and also near the centre of Muirkirk village at [2696 6272] (Figure 27). These two anomalies may have a geological origin but given the close proximity of old ironworks and mines a source from buried industrial metallic refuse cannot be completely discounted. The total count radiometric survey reveals lowest values in the south-west of the Main Street site, increasing eastward to high values in the south and east (Figure 23a). The ternary plot of radioelements illustrates blue and cyan colours indicating high uranium content associated within the anomaly (Figure 24). However, the EM survey lines are at a change in altitude of the survey aircraft which will produce spurious conductivity results.

At Torhill (Figure 27) the second largest Vacant and Derelict site is the former Crossflat aqueduct (PASTMAP data from RCAHMS). The magnetic survey records low values. Radiometric survey values are moderate and the ternary radioelement plot (Figure 24) indicates high uranium content. The high and low frequency EM conductivity values are moderate to low at the aqueduct site.

A designated site at Furnace Road spans one of the bipolar magnetic anomalies (Figure 27). Very high magnetic survey values are recorded at the eastern edge of this Vacant and Derelict site and this anomaly has the characteristics of an anthropogenic source. Total count radiometric survey values are high (Figure 23a) and the green and blue colours in Figure 24 imply high thorium and uranium content.

Vacant and Derelict sites within Muirkirk on Main Street, off Furness Road, Wellwood Street and Bridge Street are all characterised by moderate or low values for both the magnetic (Figure 27) and radiometric surveys (Figure 23a). The increased height needed to fly over the town does not provide useful EM conductivity data for these sites.

4 Conclusions

4.1 REGIONAL AYR HI-RES SURVEY

The regional Hi-RES magnetic survey data at 200 m line spacing can be used to map igneous rocks; dykes, volcanic vents and other minor intrusions. The mapped extent of known igneous dykes can be extended and previously unknown dykes can be mapped by inference.

Dykes of differing geological age can be distinguished by their contrasting magnetic character. The width of the dykes cannot be measured directly from the width of the magnetic anomaly but an appraisal of dyke width can be obtained by modelling of the induced magnetic anomaly. Recognition of the dykes depends upon width, depth and magnetic characteristics. Dykes of Permo-Carboniferous age 10 m wide and at a depth of only 5 m will be more readily identified than narrower dykes at greater depths. However, a Permo-Carboniferous dyke of 1 m width at depths of 5 m and 20 m should be detectable although probably not distinguishable at 100 m depth. Detection of dykes of Palaeogene age would be similar although the induced anomaly magnitudes would be less. However, due to the remanent magnetisation, often of a reversed magnetic polarity, the characteristics of these intrusions are very distinctive. Dykes that are oriented near-parallel to the survey flight lines may not produce resolvable magnetic anomalies.

Volcanic vent rocks have a distinctive bipolar magnetic character that indicates their presence where previously they have not been mapped in areas where bedrock is concealed beneath superficial deposits.

Geological faults in bedrock can be mapped from the regional magnetic survey where an offset occurs in magnetic host rocks.

Regional radiometric survey data show a close correspondence with the extent of peat and peaty soils at 1:25,000 scale where within 0.3 m of the ground surface. The regional potassium radioelement data could be used to assist in the mapping of the extent of peat and peaty soils at 1:25,000 where soil series data does not exist at that scale.

Geophysical anomalies generated at any given point are mostly site specific. With the exception of the magnetic anomalies caused by igneous dykes and radiometric signature associated with peat and peaty deposits the possible influences on each anomaly need to be individually considered. Anomalies at each site are a response to bedrock, superficial geology, previous and current land use and man-made infrastructure.

Regional EM conductivity survey data can indicate if the content of known landfill sites has a conductive character or not and whether any conductive fluids are retained within the extent of the site. Comparison of anomalies in the high and low frequency conductivity data allows an appraisal of the depth, as well as the extent, of the conductive fluids. The character and extent of small landfill sites may only be resolved by more closely spaced flight lines. Conductivity anomalies are commonly associated with man-made features or structures mapped at the time of the latest available topographical survey. Conductive features not associated with mapped deposits of man-made ground may represent old, unrecorded landfill sites or very recent sources of conductive fluids.

Sites of opencast mining that were active or recently disused at the date of the Ayrshire Hi-RES survey are associated with marked and distinct anomalies in the total count radiometric survey data. For older, disused opencast mining sites the anomalies are less marked and more diffuse. The Hi-RES data appears to reflect the degree of restoration and vegetation of the disused sites and might be used to measure the success of remediation activities.

An appraisal of sites designated as Vacant and Derelict Land has been undertaken using the regional airborne Hi-RES radiometric and conductivity data for selected parts of the Ayrshire survey. Most of the designated Vacant and Derelict sites within the Ayrshire survey are of a sufficient size that the regional Hi-RES data set can be used to indicate whether or not sites should be flagged for additional attention when ground investigations are undertaken prior to redevelopment. However, at a line spacing of 200 m it is not possible to define the exact form of the anomalies for some of the smaller sites.

An operational requirement of safe flying height over populated areas produces spurious results in the EM conductivity survey data where survey height was increased over built up areas. It is not possible to appraise the conductive nature of Vacant and Derelict Sites where the survey was required at this greater height.

4.2 DETAILED HI-RES SURVEYS OF ARDEER, MAUCHLINE AND MUIRKIRK

Interpretation of concealed bedrock from the detailed magnetic survey data was greatly enhanced in rural areas but masked by infrastructure and the effects of former and current land use in industrial areas. Where anthropogenic influences within the Ardeer industrial area obscured anomalies due to bedrock geology the Hi-RES magnetic survey spanning the coast and shallow offshore area was used to clarify interpretation of the onshore bedrock geology.

Igneous rocks, especially dykes, can be readily mapped from the detailed survey data, for example across the aquifer sandstones at Mauchline and coal-bearing strata at Muirkirk. The magnetic character of dykes is more difficult to distinguish in areas of abundant historical and modern industrial influences, as at Ardeer.

Interpretation of geophysical anomalies from detailed surveys in areas with a long history of exploitation of natural resources and industrial activities at Muirkirk and Ardeer, respectively, was greatly assisted by archaeological surveys and PASTMAP archaeological and architectural data from Royal Commission of Ancient and Historical Monuments Scotland.

The legacy of subsurface coal mining on ground conditions, inferred from geophysical surveys, differs between the survey areas examined. At Ardeer the position of coal seams at rockhead, shallow and deep mine shafts and colliery sites do not generally appear to coincide with distinct anomalies in the geophysical data although with a few notable exceptions. At Muirkirk detailed survey of industrial archaeological workings and buildings show a good correspondance between areas of shallow coal mining, the Wellwood Colliery, spoil heaps and disturbed ground with anomalies in the radiometric survey data. There are no radiometric anomalies solely associated with limestone quarries or the MacAdam’s tar works. The source for pronounced bipolar magnetic anomalies within and adjacent to Muirkirk is not known but may be due to the presence of buried, ferri-magnetic industrial waste.

Very marked anomalies in the EM conductivity data where underground coal workings come to surface near the site of the former Longford Chemical Works, Ardeer, may be due to the disposal of industrial waste in the mine workings during the lifetime of the site.

Ayrshire Joint Structure Plan states that the discharge of mine water from abandoned deep coal mines has visibly affected river water quality in Muirkirk. High values in both the high (shallow) and low frequency (deep) conductivity surveys across the course of the River Ayr are noted at the south-western end of the village of Muirkirk. The anomalies are more marked and extensive in the low frequency survey indicating the source is more conductive and larger at depth. There are two separate anomalies downstream from the minewater treatment plant that cut across the course of the river from south-east to north-west. There is a spatial correspondence between the conductivity anomalies and fault-defined blocks, evident from the extent of subsurface mine workings of the Gaswater Coal. At the centres of the two anomalies the strata lie within the axis of a synclinal fold. The geophysical anomalies are shallower than the workings in the Gaswater Coal, which lie at depths of 200 m to 230 m below surface, suggesting the inferred presence of conductive waters that lie within the overlying strata within the centre of the fold and may be due to unrecorded shallow workings there. A marked conductive anomaly at depth in the vicinity of Kames may also be due to conductive mine waters but this does not appear to impinge on the course of the River Ayr.

Appraisal of Vacant and Derelict Land sites from the detailed radiometric and EM conductivity surveys resolves anomalies as little as 50 m in diameter. Additionally, it reveals more subtle anomalies inferred to be a variation in the character of ground conditions from the variation in survey data within a designated site. The relative contribution of the three different radioelements to the total count radiometric survey data can also provide an indication of variation in ground conditions within a designated site. The presence of a geophysical anomaly does not indicate dangerous conditions or that the site is necessarily contaminated but that it is considered more likely to be contaminated than areas without an anomaly.

The magnetic and radiometric survey results are little affected by the variations in survey height over the populated areas examined. However, conductivity is adversely affected by increased altitude and can not be used where higher survey flights are needed.

Linear anomalies from the detailed magnetic survey of the Mauchline area, interpreted from earlier geophysical data sets as attributed to faults, are considered more likely to be igneous dykes from this more highly resolved survey data. The relatively high numbers of gold grains in stream sediments from the Mauchline area (Leake et al., 1997) has been attributed to the possible presence of deep-seated geological faults inferred from previous magnetic survey data. The detailed Hi-RES data of the Mauchline area does not support faults as the source of the linear magnetic anomalies. Consideration of the concentration of arsenic, antimony and tin values from analysis of stream sediments from the Mauchline area (BGS, 1997) led Breward et al. (2004) to conclude the gold concentrations were reworked ‘placer’ deposits not mineralisation within fractures.

5 Recommendations

5.1 MAPPING AND MODELLING OF DYKE ROCKS

Regional Hi-RES data, where available, should be reviewed and interpreted at an early stage in BGS geological resurvey for previously unknown dykes using the latest methodologies for digital geological mapping and 3D modelling. Where industrial areas are present in a coastal setting the Hi-RES survey should span the coast and shallow offshore area sufficient to clarify anomalies due to onshore bedrock geology from the magnetic survey data.

Mapping of previously unknown dykes and extension of already mapped dykes inferred from the Ayr Hi-RES survey within recently published map sheets (since 1995) should be captured and presented in DigMap format.

Proposals to test and verify differing methods for modelling of dykes by provision of geological map data from an existing opencast mine site within the existing Hi-RES survey area would be welcomed. The site must provide data on the extent, depth, thickness and lithology of the dyke rocks. Testing and verifying of the modelling methods would be undertaken as a university collaborative research project with BGS and the mining company.

Many areas of potential opencast coal abstraction identified by the East Ayrshire opencast coal subject plan (East Ayrshire Council, 2004) north of National Grid northing 615 lie within the extent of the Ayrshire Hi-RES survey. Commissions to model the thickness and depth of dyke rocks and volcanic vents from the Hi-RES data by mining companies or consortia would be well received.

5.2 MAPPING OF PEAT DEPOSITS

Undertake investigation of the potassium radiometric survey data, by BGS and in conjunction with soil scientists at the Macaulay Institute, as a tool to assist in the mapping at 1:25,000 scale of peat and peaty soils. This research may be enhanced by collaboration with university scientists and incorporate the findings of research on Hi-RES data that is in progress within the UK. The objective would be distinction of small areas of peat, more detailed than at 1:25,000 scale, to quantify the extent of carbon 'sink' deposits.

5.3 ASSESSING POTENTIAL TO MAP CONTAMINATED GROUNDWATER

Ground geophysical observations should be undertaken of the landfill site occupying the former eastern Ballochmyle Quarry [2501 6264] near Mauchline to investigate and verify the character of the anomaly identified by the conductivity survey and model the extent of that anomaly. Further investigations would appraise whether the anomaly presents a threat to the groundwater aquifer and/or the landfill contents would generate landfill gases. Collaboration has already been initiated with the NERC Airborne Remote Sensing Facility and the University of Hull.

Sampling and analysis of groundwater in the vicinity of the River Garnock at Longford, Ardeer, would examine the possible disposal of industrial waste within shallow mine workings inferred from their close association with conductivity anomalies and an industrial site at Longford. Proposals to investigate the conductivity anomaly at Longford would be of interest to BGS to test the hypothesis that shallow mine workings have been used for industrial waste disposal. Environmental regulators and planners may also participate if the area is to be identified for redevelopment.

Conductivity surveys indicate large bodies of highly conductive fluids in the subsurface south-west of Muirkirk that have a spatial association with underground mine workings. Further research into these anomalies, including comparison with known points of mine water discharge into the river, could more closely indicate the source of minewater considered to affect river water quality in the vicinity of Muirkirk. Sampling and analysis by BGS is planned and collaboration with the Scottish Environmental Protection Agency (SEPA) is envisaged to appraise how safeguarding of both surface and groundwater bodies may be informed by research based on the interpretation of Hi-RES and ground observational data.

5.4 ASSESSING POTENTIAL TO MAP CONTAMINATED OR REMEDIATED GROUND

Many Hi-RES anomalies from the Ayr survey can be directly related to previous industrial or mining land use. Ground investigation of anomalies that are **not** associated with man-made features in historical or recent geographical and aerial survey data, would inform identification of the possible source of the anomalies. Field investigations should be undertaken at sites with magnetic, radiometric or conductive anomalies that have neither a direct spatial association nor obvious link to recorded land use, as at Ladyha' Park and near Birnieknowe, respectively. The possible sources would include sites of unrecorded liquid waste disposal or landfill that could present a threat to the environment or public health. Calibration of the anomalies by field analysis would enable threshold values to be set by planning authorities. Above these thresholds developers could be expected to demonstrate particular attention to ground investigations prior to redevelopment. Analysis of field results to calibrate the Hi-RES results would also inform environmental regulators of a previously unrecorded contaminated site and collaboration with SEPA or other environmental organisations is invited.

Comparison of the Hi-RES total count radiometric survey data with mining company data on the extent of disused opencast mine workings and remedial activities undertaken to promote site restoration would 'calibrate' interpretation of the Hi-RES radiometric data. BGS should ask mining companies to provide data on the extent and timing of extraction, restoration and remediation activities of opencast sites within the extent of the Ayr survey. BGS would compare it with the Hi-RES results to assess the data set for appraisal of the success of restoration activities for opencast mine sites but relevant to all areas of disturbed ground.

5.5 FORMATION OF MINERAL DEPOSITS

The genesis of the widespread occurrence of gold in stream sediments samples from the Mauchline Basin should be investigated by integrated interpretation of Hi-RES magnetic survey data, mineral reconnaissance (Leake et al, 1997), regional geochemical (BGS, 1993) and other available datasets. The hypothesis of mineralisation in fractures was based on an earlier magnetic survey which is now superseded by the Ayr Hi-RES results.

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

AYRSHIRE JOINT STRUCTURE PLAN. 2000. *Ayrshire Joint Structure Plan 1999, a framework for the 21st century*. (Prestwick, Ayrshire: Ayrshire Joint Structure Plan Committee.)

AYRSHIRE JOINT STRUCTURE PLAN. 2004. *Ayrshire Joint Structure Plan 2025 Consultation draft,* (Prestwick, Ayrshire: Ayrshire Joint Structure Plan Committee.)

BEAMISH,D. 2002. Airborne EM applied to environmental geoscience in the UK. First Break, Vol. 20, October 2002, 618-622.

BEAMISH,D. 2003. Characterising landfills from the air. First Break, Vol. 21, October 2003, 36-41.

Breward, N, Akhurst, M C, and Stone, P. 2004. Cryptogeology. Regional geochemistry as an aid to geological mapping. *Earthwise* issue 20, British Geological Survey.

BRITISH GEOLOGICAL SURVEY. 1993. Regional geochemistry of southern Scotland and part of northern England. (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY. 1999. New Cumnock, Scotland Sheet 15W. Solid Geology, 1:50 000 Geology Series (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY. 2005. Irvine. Scotland Sheet 22W and part of 21E. Bedrock. . 1:50 000 Geology Series. (Keyworth, Nottingham: British Geological Survey.)

Buckley, D K, Perkins, M A, and Shedlock, S L. (1986). Geophysical logging of trial water boreholes in sandstone basins of Dumfries and Galloway, and the Mauchline Basin.

EAST AYRSHIRE COUNCIL. 2004. *East Ayrshire Opencast Coal Subject Plan. (*Kilmarnock, East Ayrshire: East Ayrshire Council.)

IRVINE DEVELOPMENT CORPORATION. 1971. Irvine new town plan. (Irvine Development Corporation: Irvine, Ayrshire.)

LEAKE, R C, CAMERON, D G, BLAND, D J, STYLES, M T, AND FORTEY, N J. 1997. The potential for gold mineralisation in the British Permian and Triassic red beds and their contacts with underlying rocks. *Mineral Reconnaissance Programme Report,* British Geological Survey, No. 144.

LOHVA, J., JOKINEN, T., VANHALA, H. AND LAHTI, M. 1999. Landfill monitoring by airborne EM and ground resistivity measurements. In *5th meeting of the Environmental and Engineering Geophysical Society, European section*. VERÖ, L. (editor). September 6-9,1999, Budapest, Hungary: proceedings. Budapest: Environmental and Engineering Geophysical Society.

MONRO, S K, 1999. Geology of the Irvine district. *Memoir of the British Geological Survey*, Sheet 22W and part of Sheet21E (Scotland). ISBN 11 884550 0

NORTH AYRSHIRE COUNCIL. 2004. *North Ayrshire Local Plan. (*Irvine, North Ayrshire: North Ayrshire Council.)

Rollin, K E. In press. *Regional geophysics of Northern Scotland.* Version 1.0 on CD-ROM. (Keyworth, Nottingham: British Geological Survey.)

ROYAL COMMISSION ON THE ANCIENT AND HISTORIC MONUMENTS OF SCOTLAND. 1995. Muirkirk, Ayrshire; an industrical landscape. RCAHMS Broadsheet, 1,

WALTON, G AND LEE, M K. 2001. Geology for our diverse economy: *report of the Programme Development Group for Onshore Geological Surveys*. (Keyworth, Nottingham; British Geological Survey,)

Appendix 1 Technical details

Aircraft

The aircraft used in the survey was a fixed-wing, twin-engine DHC-6/300 Twin Otter (registration sign OH-KOG, registered in Finland). The aircraft is owned by the Natural Environment Research Council / British Geological Survey (NERC / BGS). Flying and maintenance are operated by the Finnish Aviation Academy (FAA) and the geophysical equipment monitoring on flights was operated by the Geological Survey of Finland (GTK).

The specifications of the aircraft are as follows;

Normal flight speed	220 km/h
Flight speed on survey flights	160 – 220 km/h (50 – 60 m/s)
Rate of climb	7.5 m/s

This aircraft was build in Canada in 1979 and has been in use since 1980 for aerogeophysical measurements. During the manufacturing of the Twin Otter several modifications were made to its electrical systems in order to reduce the electrical noise levels. Condition of the aircraft is good.

The aircraft offers several major advantages in terms of utility and cost, including excellent performance reserves, low-speed handling characteristics and operational flexibility allowing the use of unsupervised and unpaved air strips.. Twin Otter was selected for the measuring platform as the most suitable fixed-wing aircraft for low altitude STOL (short take-off and landing) operations.

Equipment

Outline specifications of geophysical and ancillary equipment

Electromagnetic system:	GTK EM95 dual frequency (3.125 and 14.368kHz)
Aircraft Magnetometer:	2 Scintrex CS-2 caesium vapour sensors, located in opposite wing tips
Magnetic Compensator	RMS Instruments Automatic Aeromagnetic Digital Compensator (AADCII)
Gamma-ray spectrometer	Exploranium GR-820/3 gamma-ray spectrometer 256-channels, self-calibrating
Altimeter	Collins radar altimeter
Data location system	Real time DGPS based on Ashtech GG-24 GPS+GLONASS receivers in aircraft and at base station
Data acquisition system	GTK proprietary: control unit including server, power unit, alarm box, Local Area Network

Detailed Specification of Equipment

Two frequency EM system (GTK EM95):

Coil configuration	Vertical-coplanar
Frequencies (kHz)	3.125 and 14.368
Coil separation (m)	21.36
Magnetic dipole moment (Am^2)	115 (LF) and 55 (HF)
Measuring range (ppm)	0- 40,000
Noise (STD) In-phase ppm	4 (LF) and 8 (HF)
Noise (STD) Out-of-phase ppm	3 (LF) and 8 (HF)
Sampling interval (samples/s)	4

Aircraft Magnetometer & AADCII (Automatic compensator) :

• Magnetometer configuration	Dual sensor, wing-tip mounted to facilitate horizontal gradiometry
• Sampling interval	0.1 second (10 Hz)
• Resolution	0.001 nT
• Gradient tolerance	10,000 nTm^{-1}
• System noise envelope	< 0.1 nT
• Manoeuvre noise	< 0.2 nT peak-to-peak (for each of 10° rolls, 5º pitches & 5º yaws). The sum of these for the 12 manoeuvres not to exceed 3 nT.
• Heading error	Typically ± 2 nT
• Total noise envelope	< 0.2 nT peak-to-peak after compensation.

Gamma-ray Spectrometer **:**

• Gamma-ray detector	2 Sets of NaI(Tl)-crystals: 32L downward looking and 8L upward looking

• Sampling interval	1 second
• Number of channels	256
• Overall system resolution	< 12% (fwhm of ^{137}Cs peak at 662 keV) (IAEA[1])
• Potassium window limits	1370 - 1570 keV (to nearest whole no. of channels)
• Uranium window limits	1660 - 1860 keV (to nearest whole no. of channels)
• Thorium window limits	2410 - 2810 keV (to nearest whole no. of channels)
• Total count window limits	400 - 2810 keV (to nearest whole no. of channels)
• Cosmic limits	3000 keV - ∞ (to nearest whole no. of channels)
• Upward crystal U window	1660 – 1860 keV
• System deadtime	± 0.1% measurement accuracy

Ancillary equipment **:**

• DGPS	AshtecGG24, 12-channel L1 GPS + 12-channel L1 GLONASS, updates to 2Hz, Post processing accuracy (95%) to 75 cm (GPS+GLONASS), 1 m (GPS only).
• Radar altimeter	Range: 0- 300 m; Precision: 0.3 m; Accuracy: ±4%
• Temperature sensor	Precision: 0.1 degree Celsius outside, 1 degree inside
• Power line monitor	3 orthogonal fluxbars summed to give total field across a bandwidth centred on 50-60 Hz. Uncalibrated units.
• Barometric height sensor	Precision: 0.1%
• Video tracking system	Digital video coverage of flight path
• Monitor	No overlap; corrected for Compton Scattering before display
• Sampling interval	Typically 1 second or less

[1] International Atomic Energy Agency, 1991 - Airborne Gamma Ray Spectrometer Surveying. Section 2.2.3 p12) *International Atomic Energy Agency Technical Reports Series Number 323*, IAEA Vienna. (

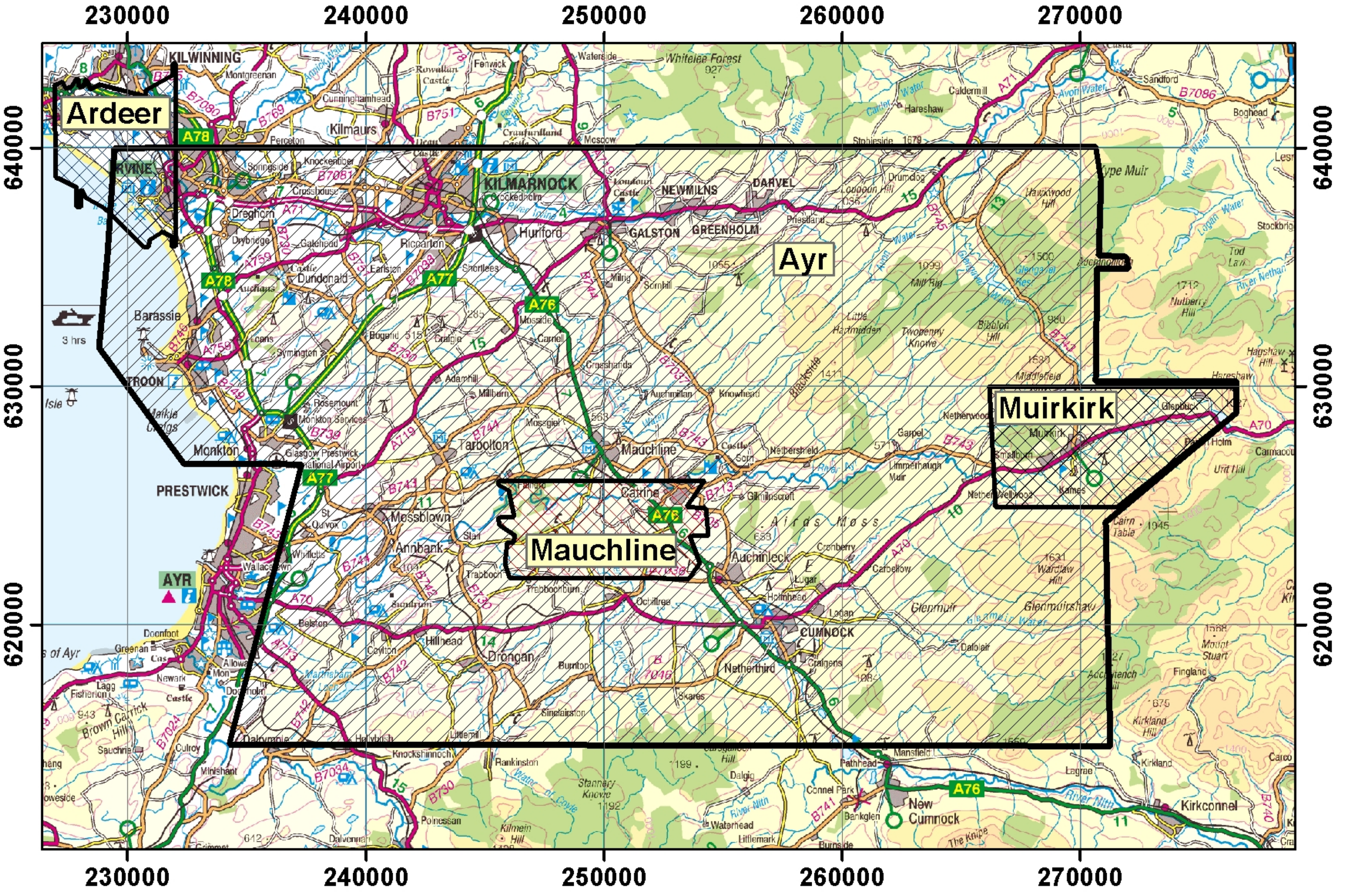


Figure 1. Location diagram of the Ayrshire airborne geophysical survey. The main survey is enclosed by the large polygon and is referred to as Ayr. Flight line spacing was 200 m and flight lines were orientated east to west. Three smaller polygons were infilled with 50 m spaced flight lines and these are shown as the cross-hatched polygons Ardeer, Mauchline and Muirkirk. Mauchline and Muirkirk were flown in an east to west orientation and Ardeer was flown north to south.

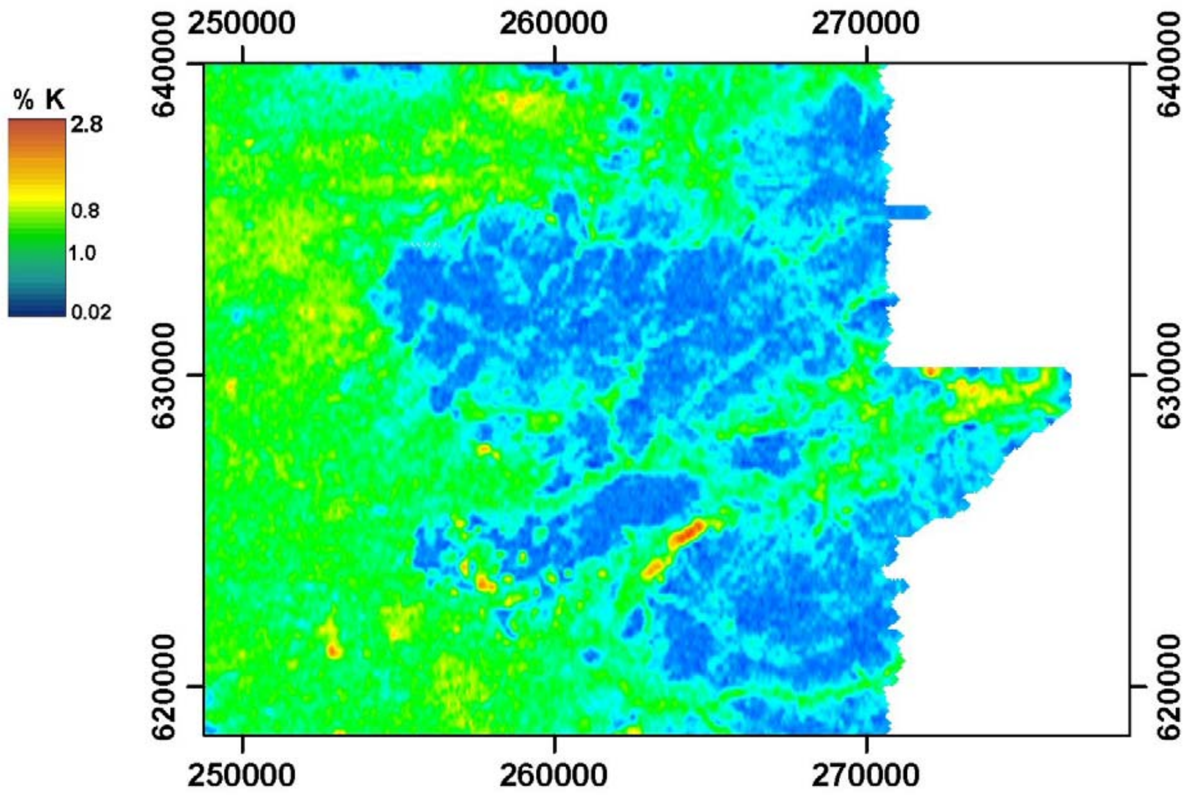


Figure 2a. Potassium radiometric data from the north-eastern part of the Ayr survey area. Data are plotted as percentages and range from 0.02 to 2.8% in a colour scale from dark blue to red.

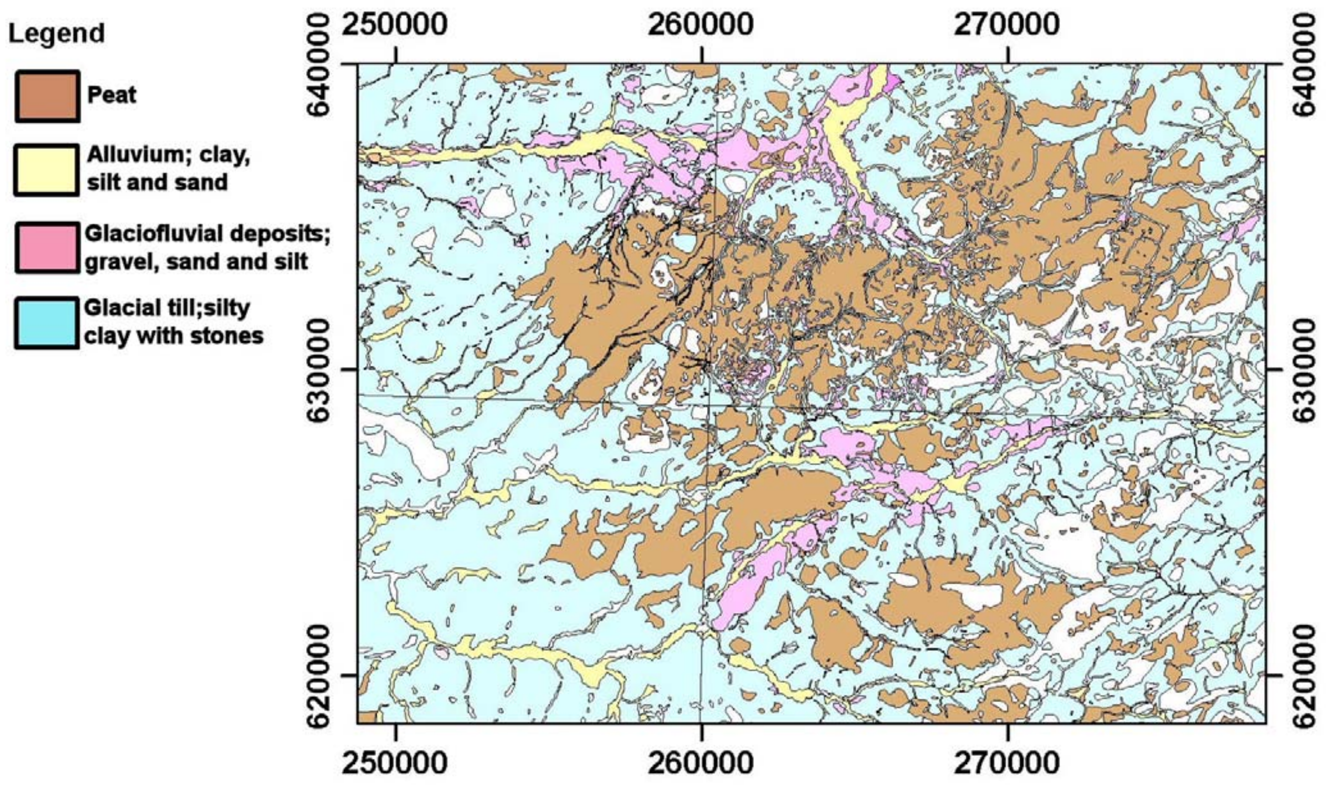


Figure 2b. Superficial geology mapped at a scale of 1:50,000 from the same area as the potassium data shown in Figure 2a. There is a close correspondence between the areas of peat and low percentages of potassium shown in Figure 2a.

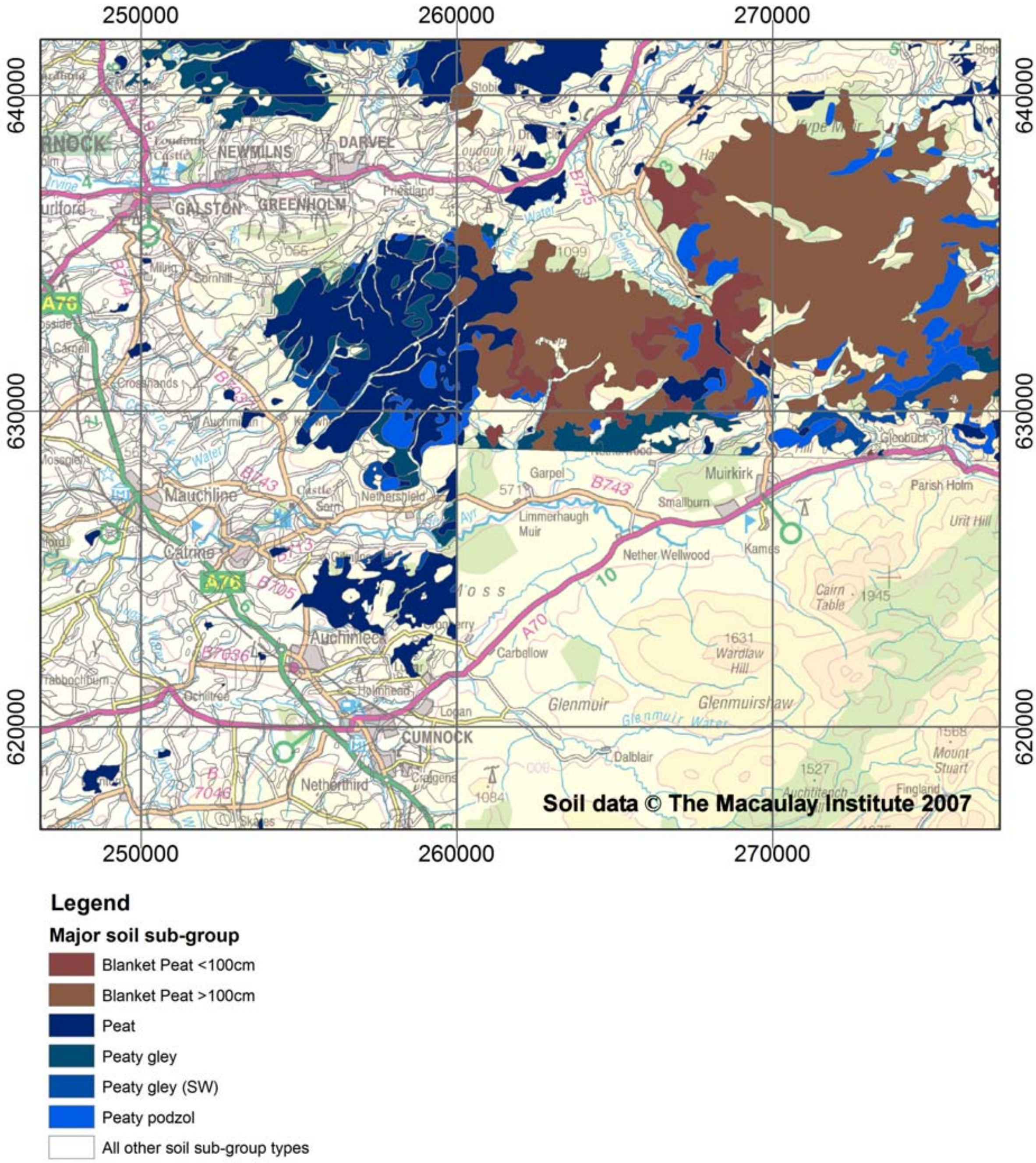


Figure 3a. Major Soil Sub-Group from the soil series data, mapped at a scale of 1:25,000, from the Macaulay Institute © The Macaulay Institute 2007. The area includes the extent of Figure 2. Peat and peaty soils (peaty alluvial soil (undifferentiated), peaty gley and peaty podzol) shown in shades of blue. Blanket peat shown in shown in shades of brown. All other soil sub-group types uncoloured. Soil series data at 1;25,000 scale not available for the south-eastern part of the area shown. Soil data underlain by Ordnance Survery 1:250,000 scale map.

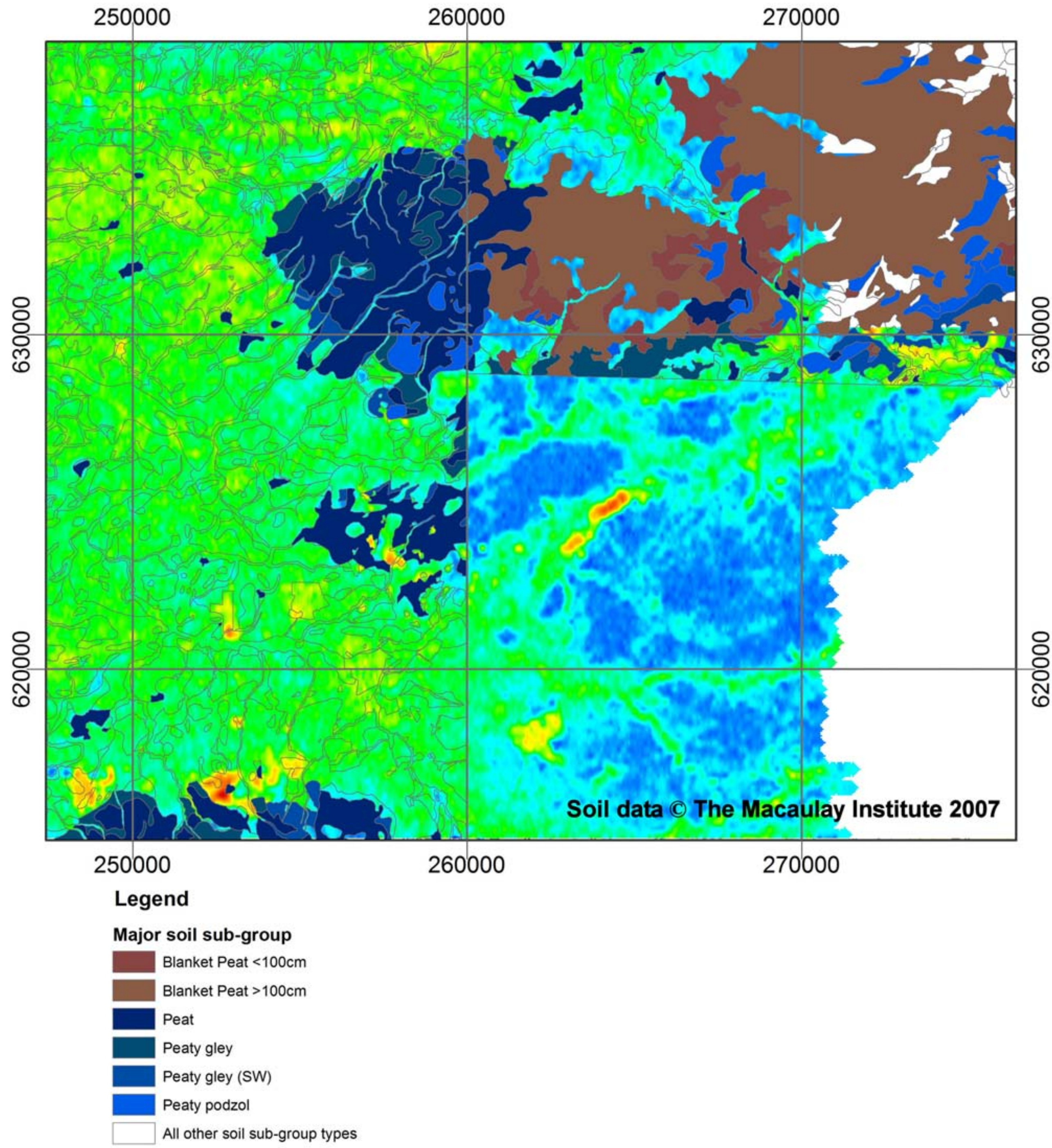


Figure 3b. Major Soil Sub-Group from the soil series data, shown in Figure 3a overlying potassium radiometric data, shown in Figure 2a. Soil series data at 1;25,000 scale © The Macaulay Institute 2007.

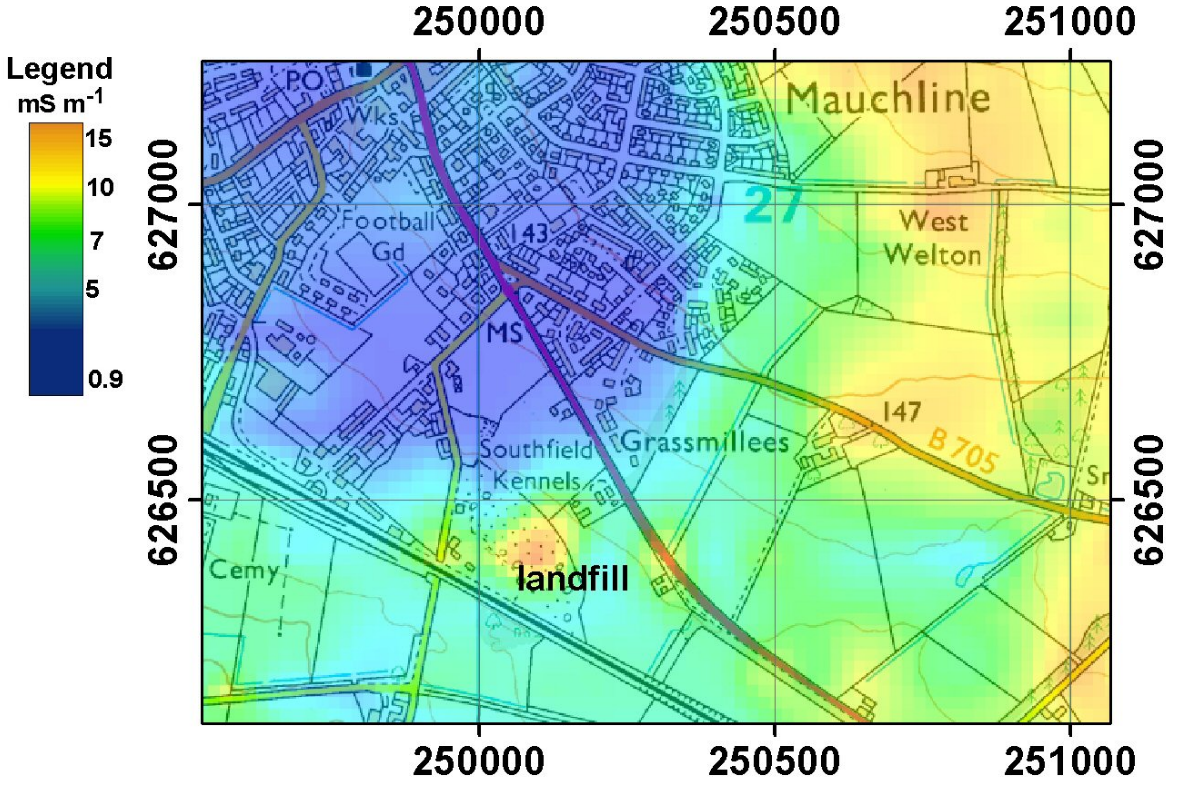


Figure 4a. High frequency EM conductivity data from the Ayr survey on the southern outskirts of Mauchline. A disused sandstone quarry, eastern Ballochmyle Quarry, that was subsequently used for landfill has been marked. The data ranges from 0.9 mS m^{-1}, dark blue in the high fly zone over the town, to 15 mS m^{-1} shown in red.

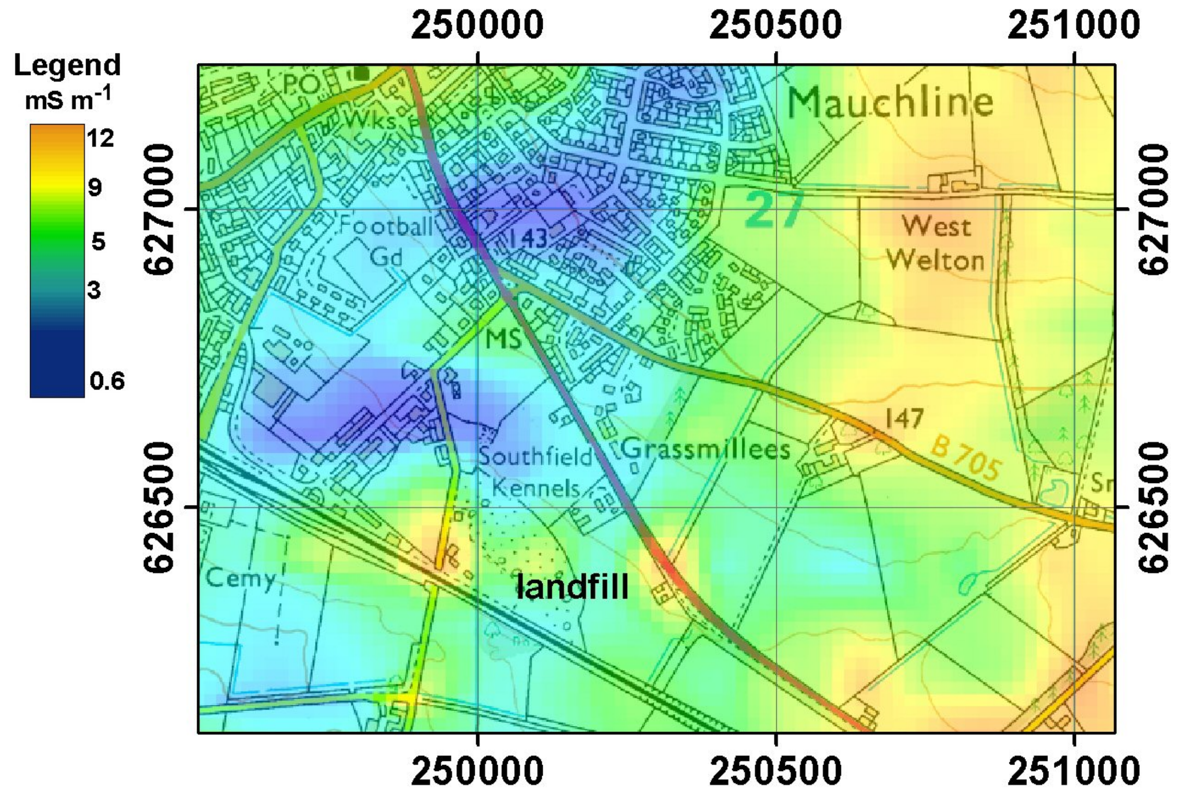


Figure 4b. Low frequency EM conductivity from the Ayr survey on the southern outskirts of Mauchline. The conductivity anomaly associated with the landfilled Ballochmyle Quarry extends farther west at greater depth, see Figure 4a. The data ranges from 0.6 mS m^{-1}, dark blue in the high fly zone over the town, to 12 mS m^{-1} shown in orange.

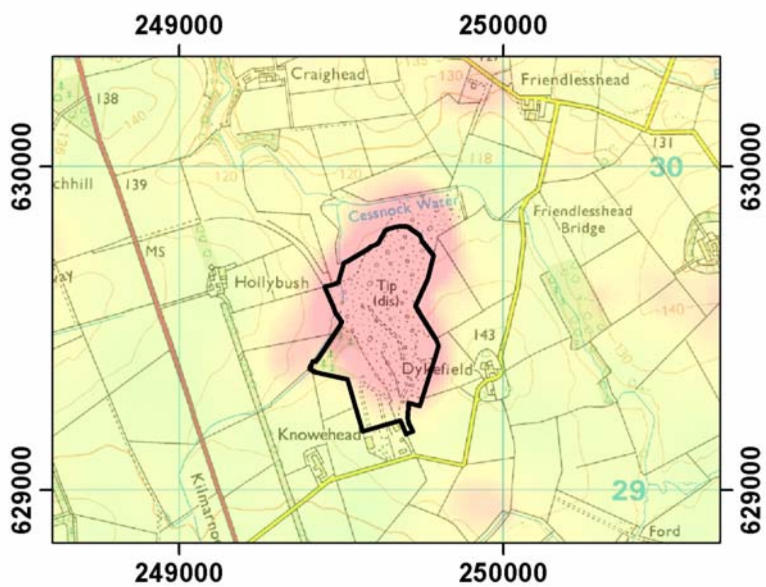


Figure 5a. Total count radiometric data from the Ayr survey to the north of Mauchline. The bold line shows the extent of a disused tip (brownfield site), designated as ‘Vacant and Derelict Land’. The data range from 5 cps, shown in green, to 10 cps, shown in red.

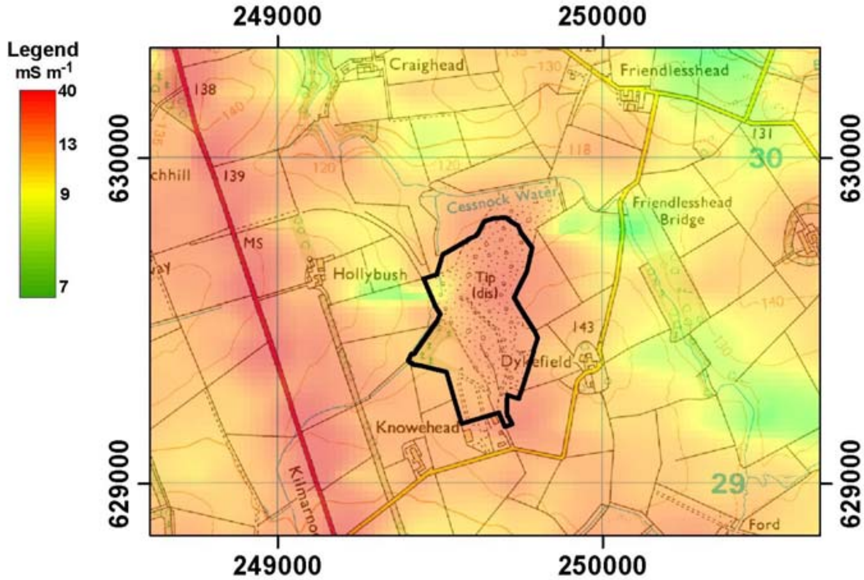


Figure 5b. High frequency EM conductivity data from the Ayr survey to the north of Mauchline. The bold line shows the extent of a disused tip (brownfield site), designated as ‘Vacant and Derelict Land’. The data range from 7 mS m^{-1}, shown in green, to 40 mS m^{-1}over the main road, shown in red. Maximum values over the tip site are around 20 mS m^{-1}.

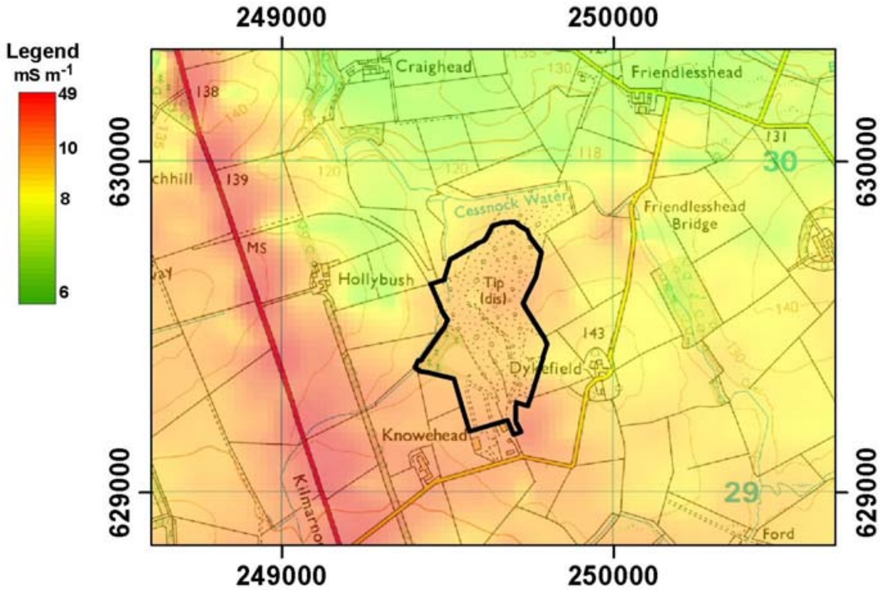


Figure 5c. Low frequency EM conductivity data from the Ayr survey to the north of Mauchline. The bold line shows the extent of a disused tip (brownfield site), designated as ‘Vacant and Derelict Land’. The data range from 6 mS m^{-1}, shown in green, to 49 mS m^{-1}over the main road, shown in red. Maximum values over the tip site are around 12 mS m^{-1}.

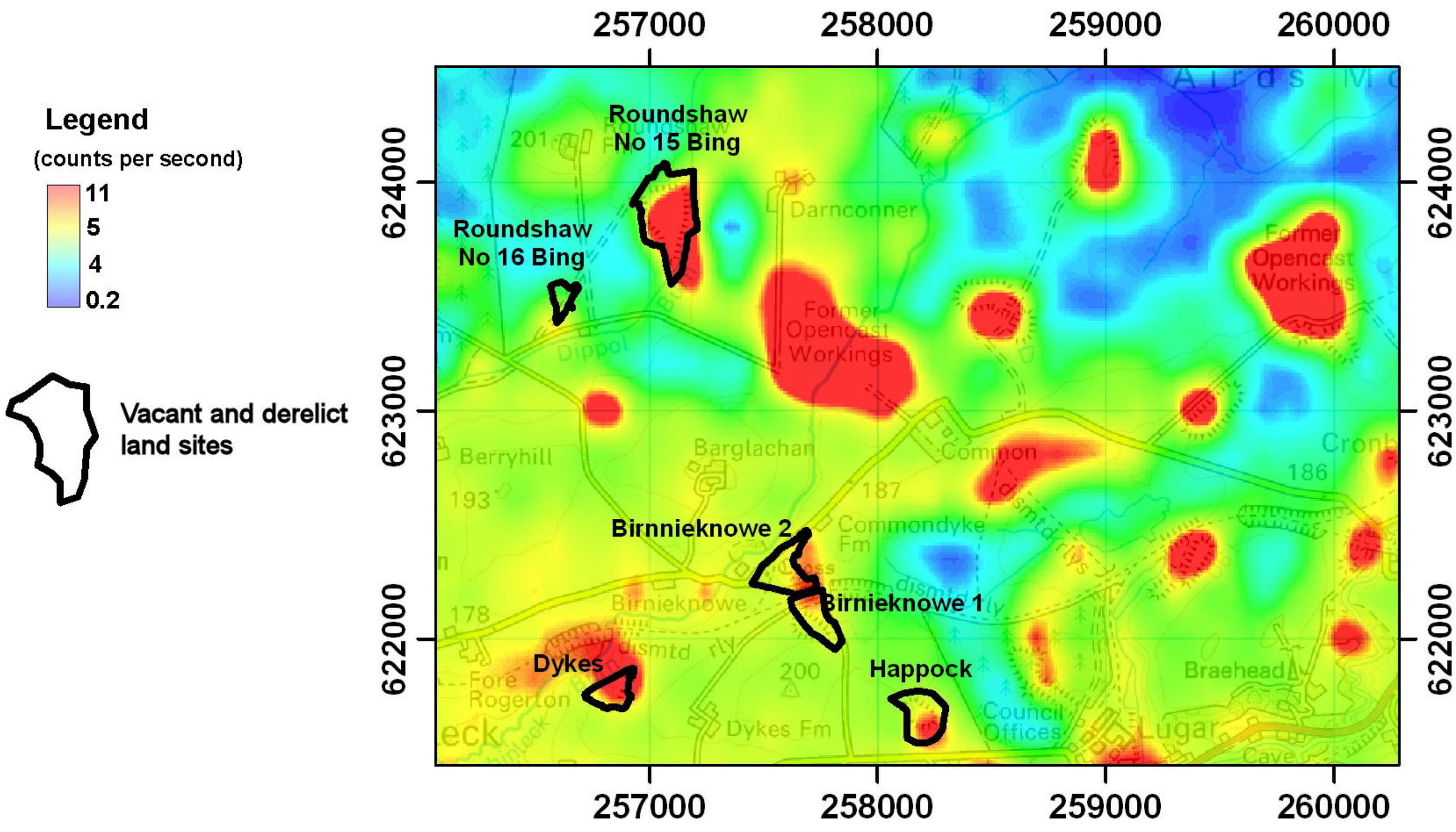


Figure 6. Total count radiometric data, recorded in counts per second (cps), from the Ayr survey to the north-east of Auchinleck showing the high correlation between known disused waste tips, former opencast mine workings, 'Vacant and Derelict Land' sites and total count radiometric highs. The data range from 0.2 cps (dark blue) to 11 cps (red).

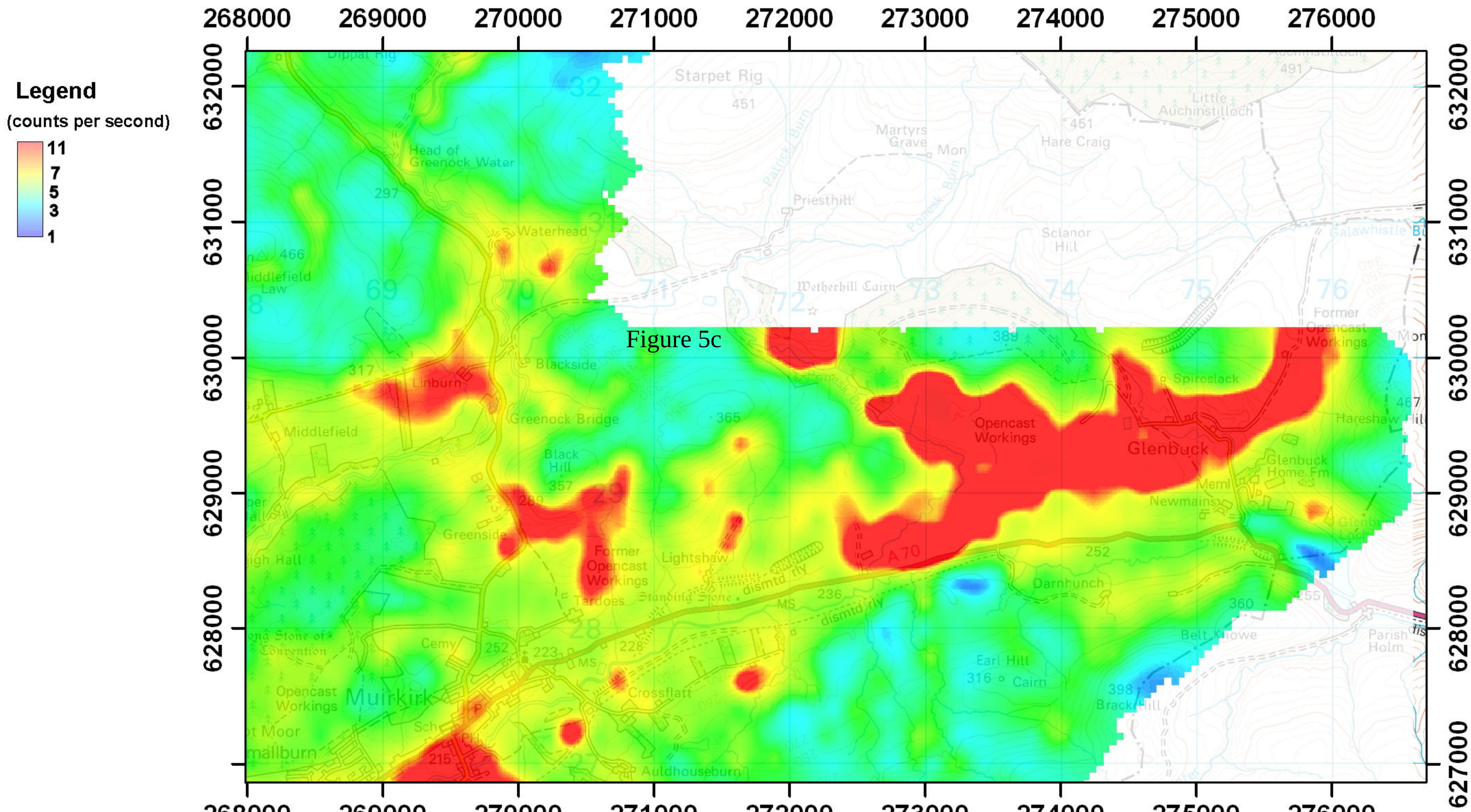


Figure 7. Correlation between opencast coal workings and total count radiometric highs from the Muirkirk – Cumnock area. The data are from the Ayr survey and are recorded in counts per second (cps) and range from 1 cps (blue) to 11 cps (red).

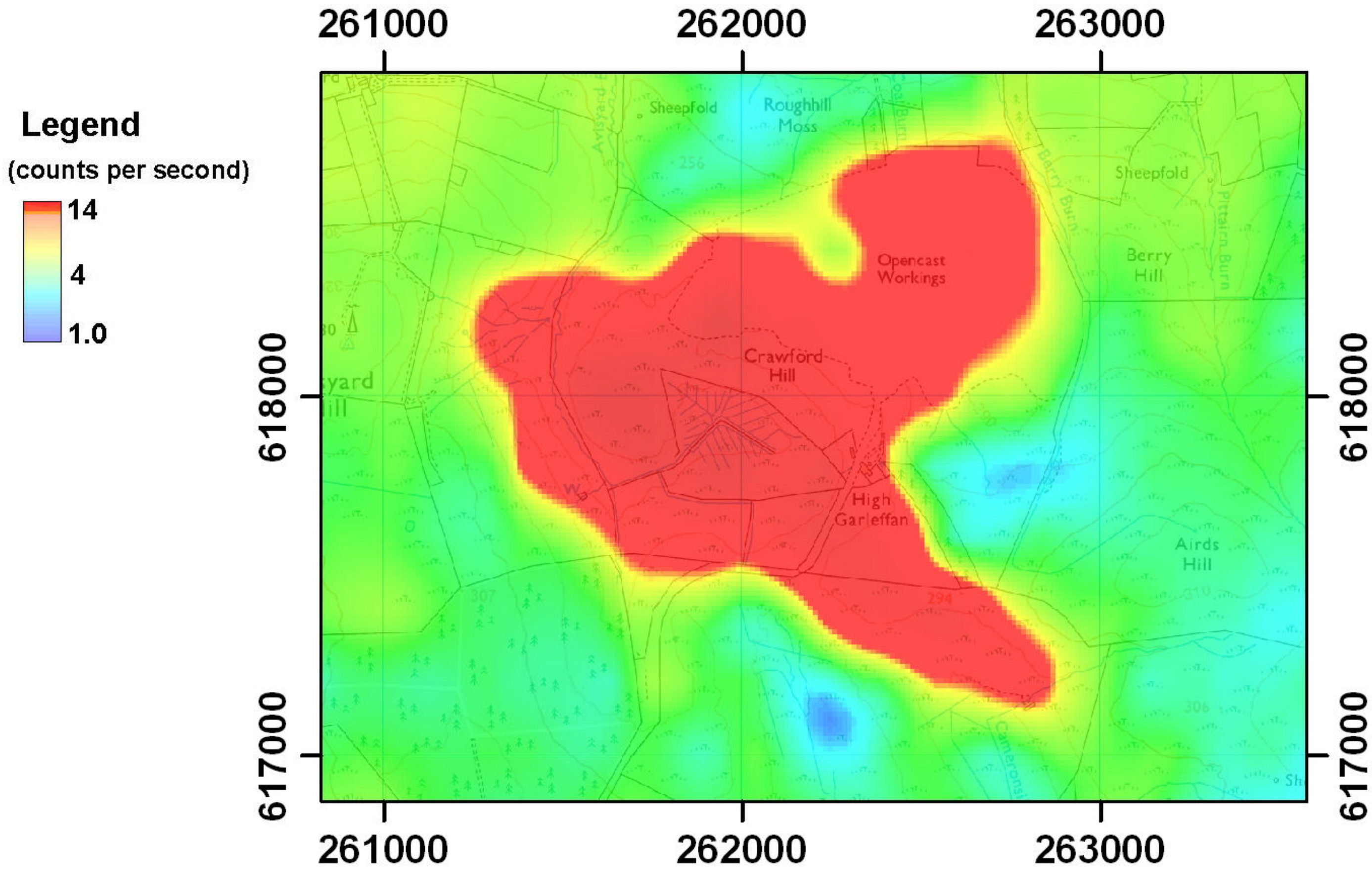
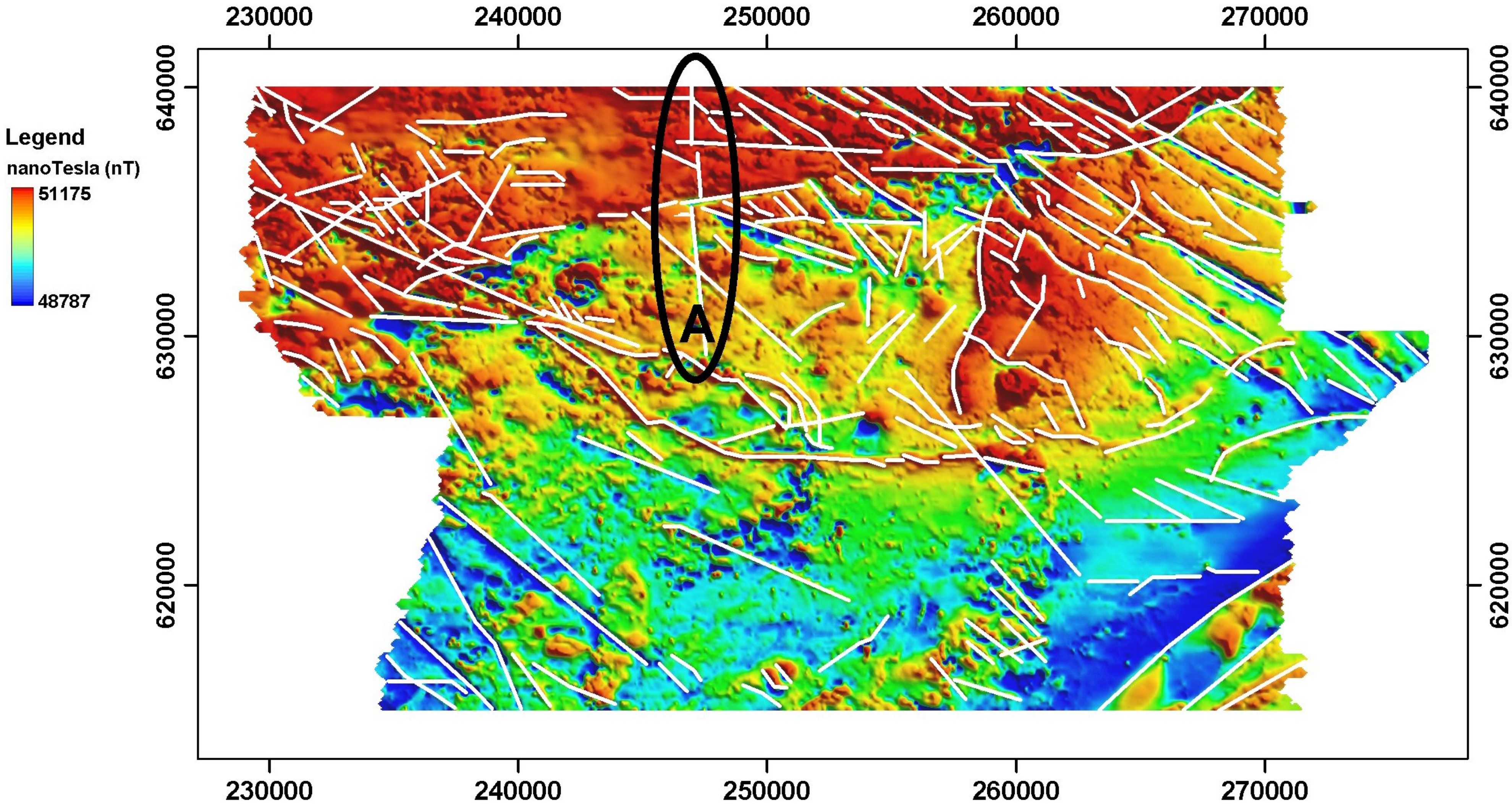


Figure 8. Correlation between the Garleffan opencast coal workings and total count radiometric highs from Crawford Hill, south-east of Cumnock. The data are from the Ayr survey and are recorded in counts per second (cps) and range from 1.0 cps (dark blue) to 14.0 cps (red).


230000
240000
250000
260000
270000
640000
630000
620000
Legend
nanoTesla (nT)
51175
48787
A

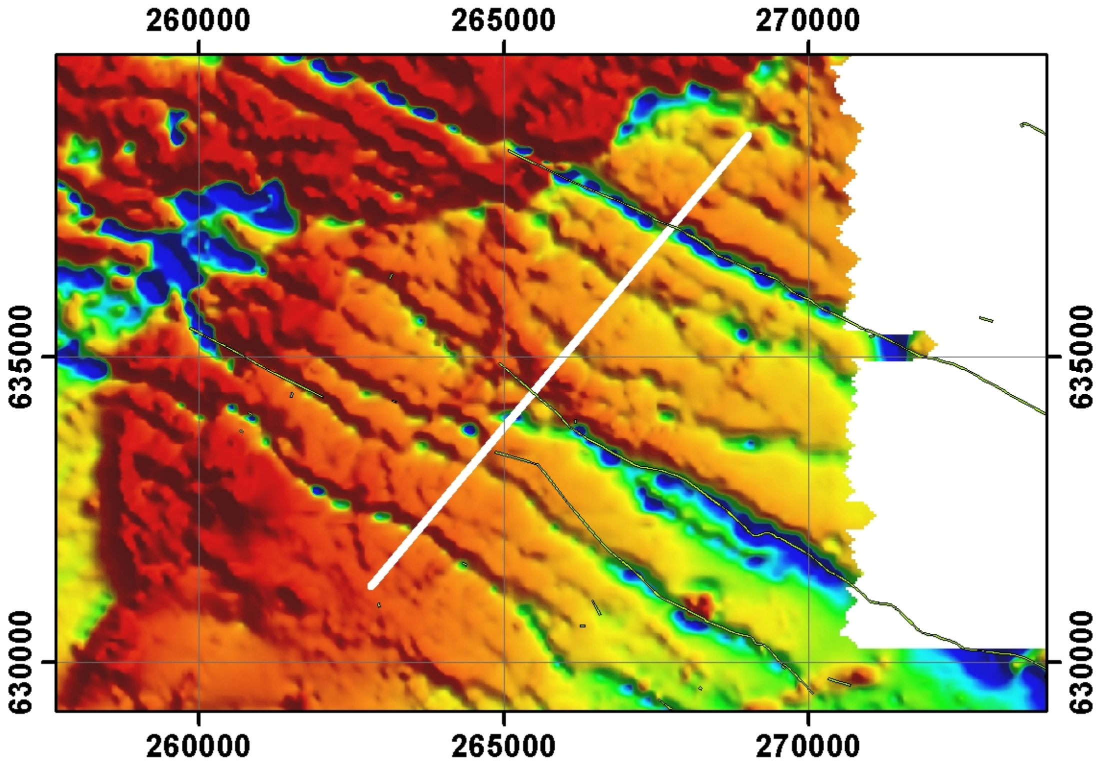


Figure 10a. Total field magnetic data in nannoTeslas (nT) from the north-eastern region of the Ayr survey. The position of the profile along which airborne magnetic data have been extracted (illustrated in Figure 10b) is shown in white. The profile is orientated from south-west to north-east. Mapped Palaeogene dykes are shown in olive green.

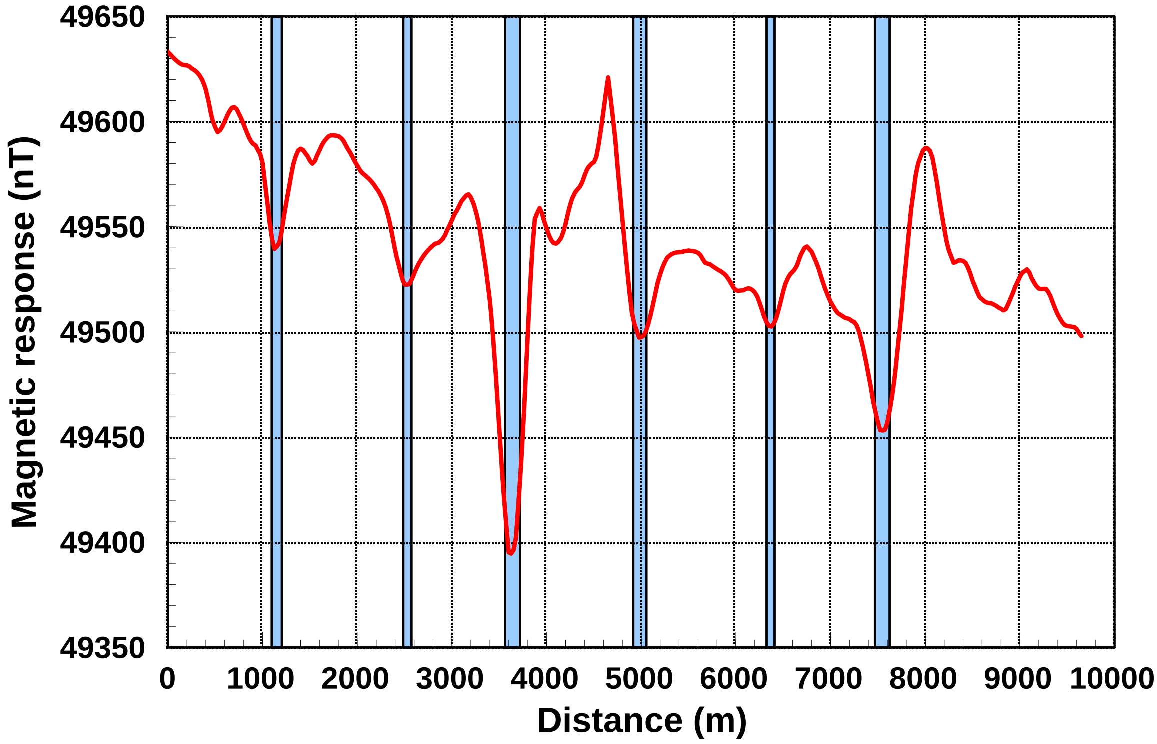


Figure 10b. Total field magnetic data in nanoTeslas (nT), displayed in red, along the profile shown in Figure 10a, orientated from south-west to north-east. The interpreted locations of dykes are shown by the blue columns. The widths of the columns are equal to approximately half the width of the anomaly at half its maximum amplitude and do not refer to the width of the dykes.

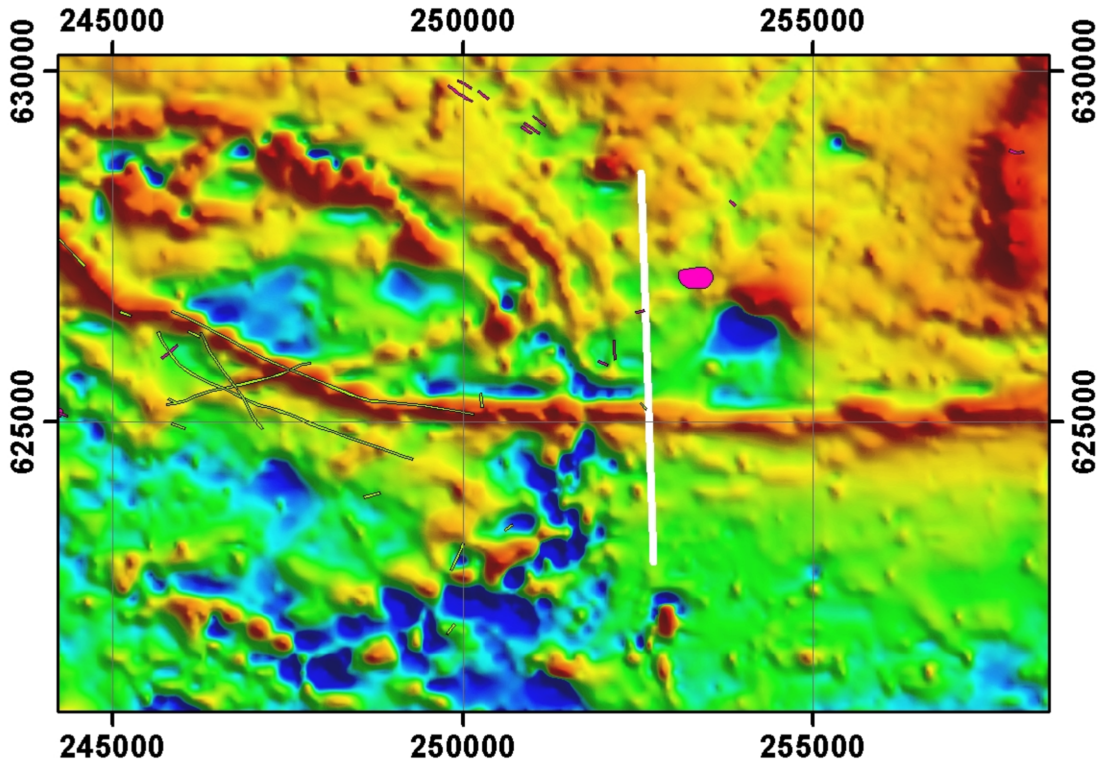


Figure 11a. Total field magnetic data in nannoTeslas (nT) from a central region of the Ayr survey near Mauchline. The position of the profile along which airborne magnetic data have been extracted (illustrated in Figure 11b) is shown in white. The profile is orientated from south to north. Mapped Palaeogene dykes are shown in olive green.

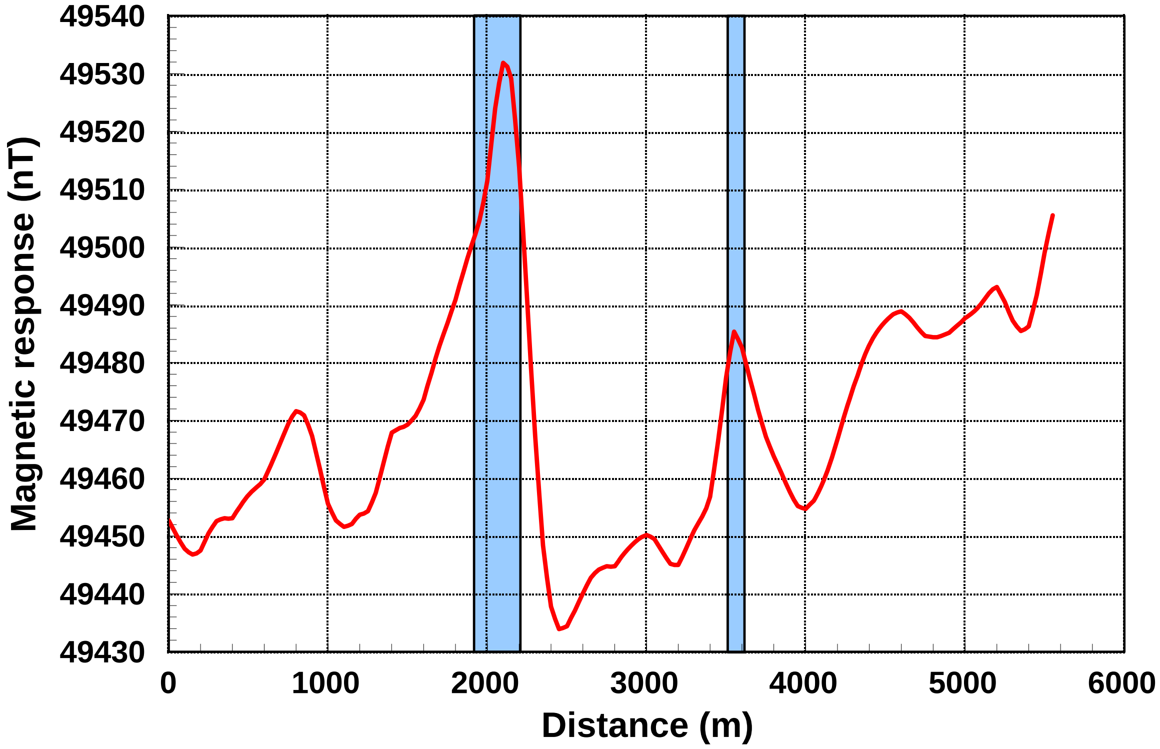


Figure 11b. Total field magnetic data in nanoTeslas (nT), displayed in red, along the profile shown in Figure 11a, orientated from south to north. The interpreted locations of dykes are shown by the blue columns. The widths of the columns are equal to approximately half the width of the anomaly at half its maximum amplitude and do not refer to the width of the dykes.

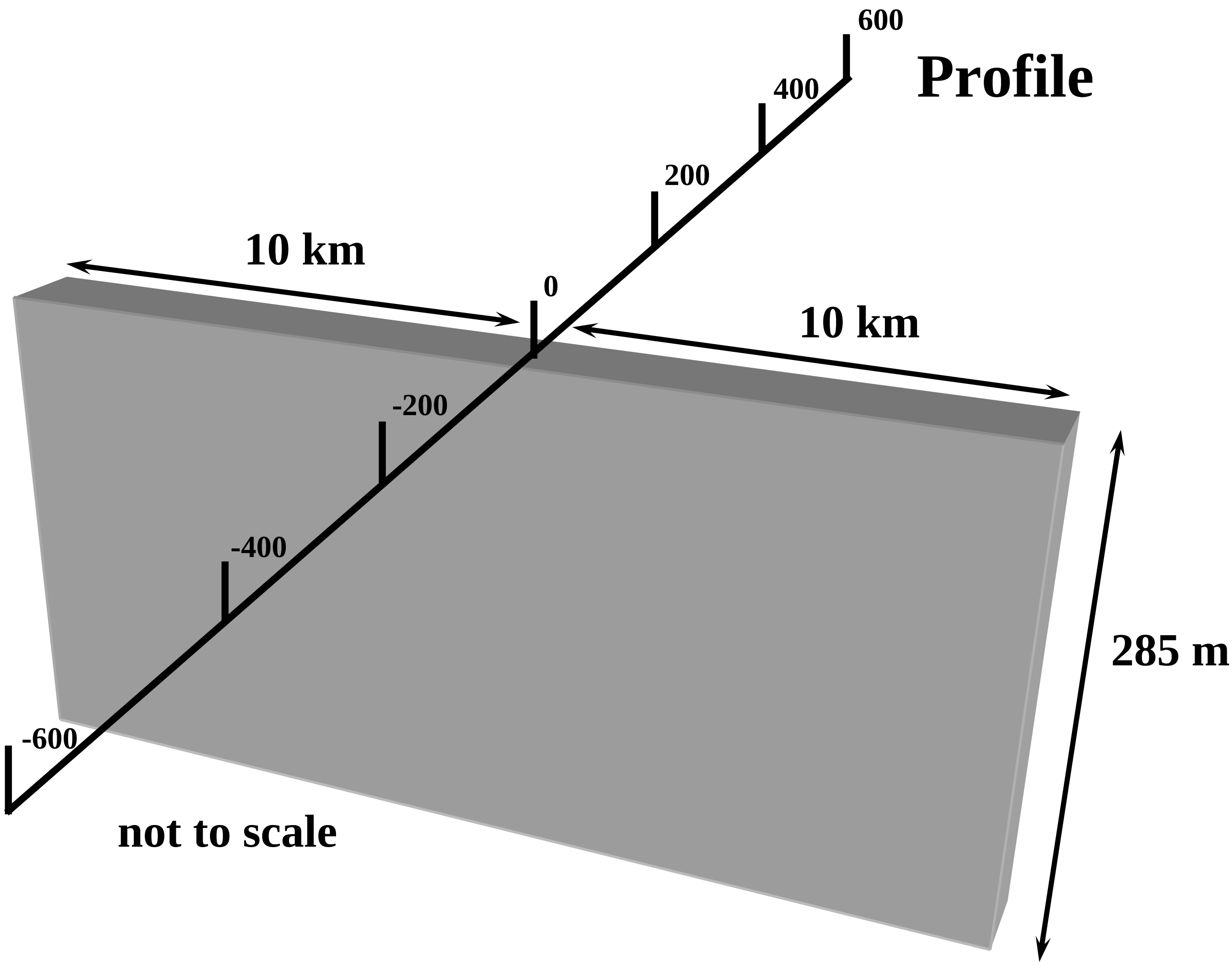


Figure 12. Dyke model for magnetic modelling comprising a rectangular block of width 20 km and depth extent 285 m and a variable width and depth. The magnetic response was calculated at a height of 56 m above ground level at a sampling interval of 6 m.

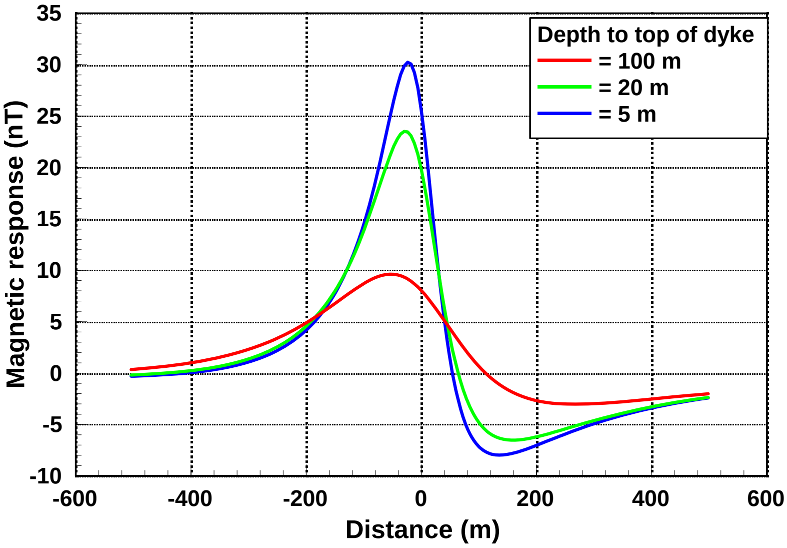


Figure 13a. Modelled magnetic response of a Permo-Carboniferous east-west-trending dyke of width 10 m at depths of 100 m, 20 m and 5 m and magnetic susceptibility 0.033 SI.

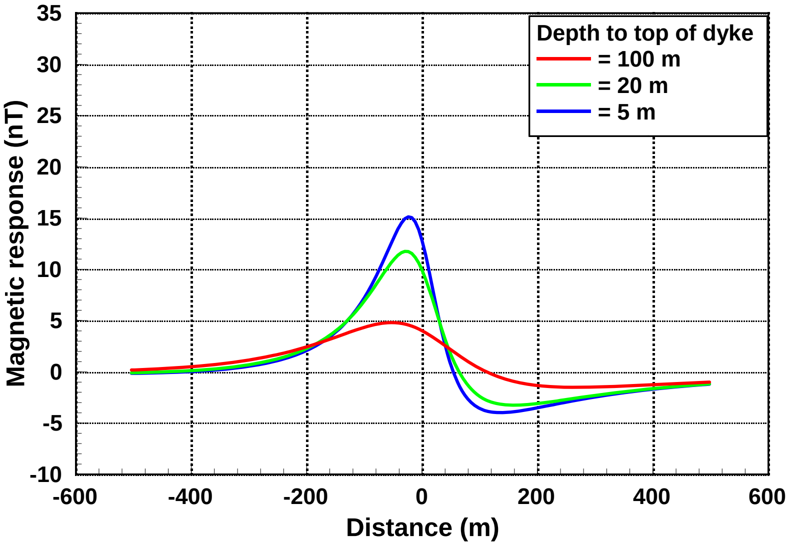


Figure 13b. Modelled magnetic response of a Permo-Carboniferous east-west-trending dyke of width 5 m at depths of 100 m, 20 m and 5 m and magnetic susceptibility 0.033 SI.

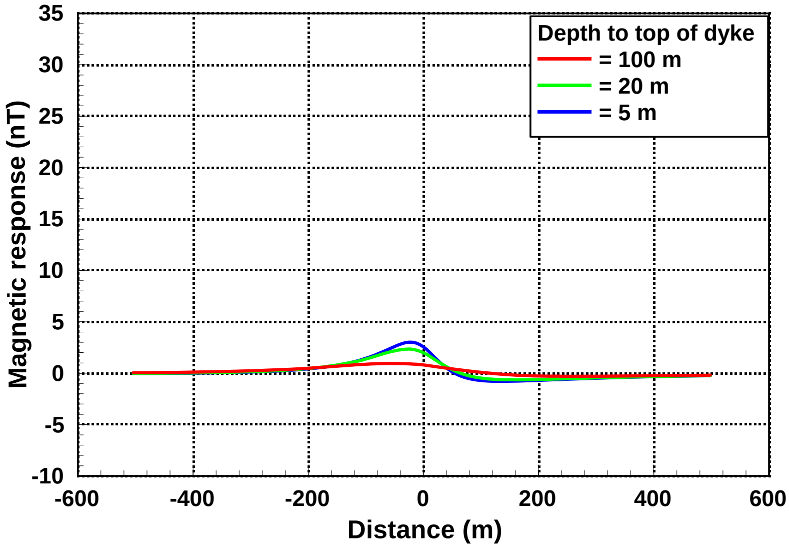


Figure 13c. Modelled magnetic response of a Permo-Carboniferous east-west-trending dyke of width 1 m at depths of 100 m, 20 m and 5 m and magnetic susceptibility 0.033 SI.

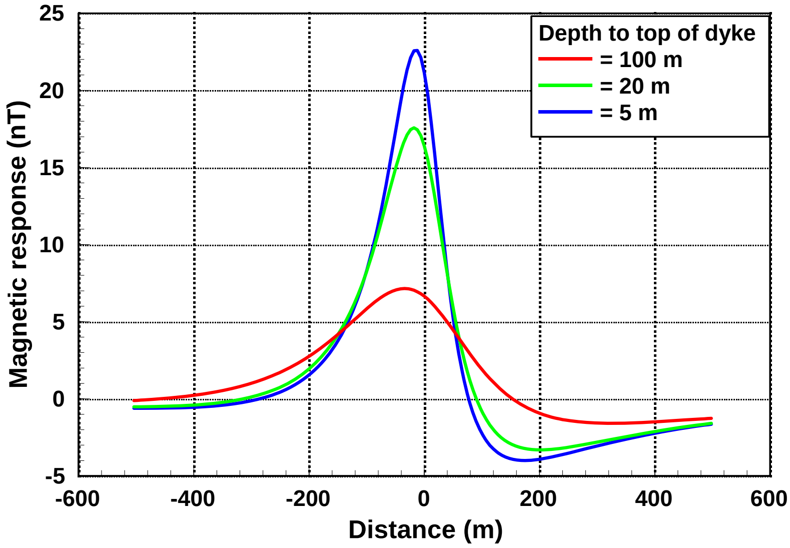


Figure 14a. Modelled magnetic response of a Palaeogene north-west-trending dyke of width 10 m at depths of 100 m, 20 m and 5 m and magnetic susceptibility 0.025 SI.

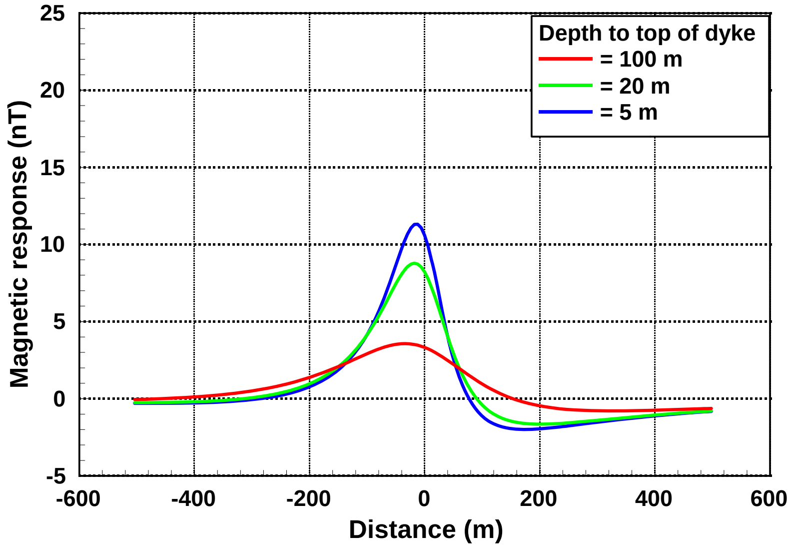


Figure 14b. Modelled magnetic response of a Palaeogene north-west-trending dyke of width 5 m at depths of 100 m, 20 m and 5 m and magnetic susceptibility 0.025 SI.

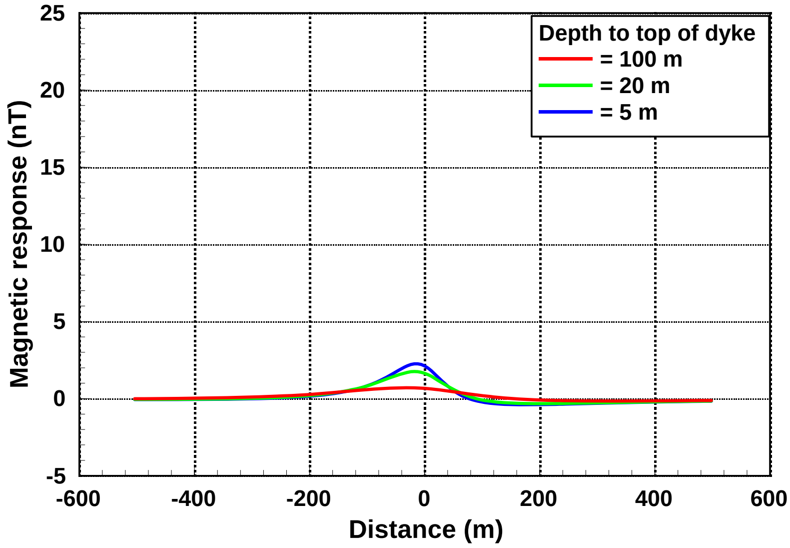


Figure 14c. Modelled magnetic response of a Palaeogene north-west-trending dyke of width 1 m at depths of 100 m, 20 m and 5 m and magnetic susceptibility 0.025 S.I.

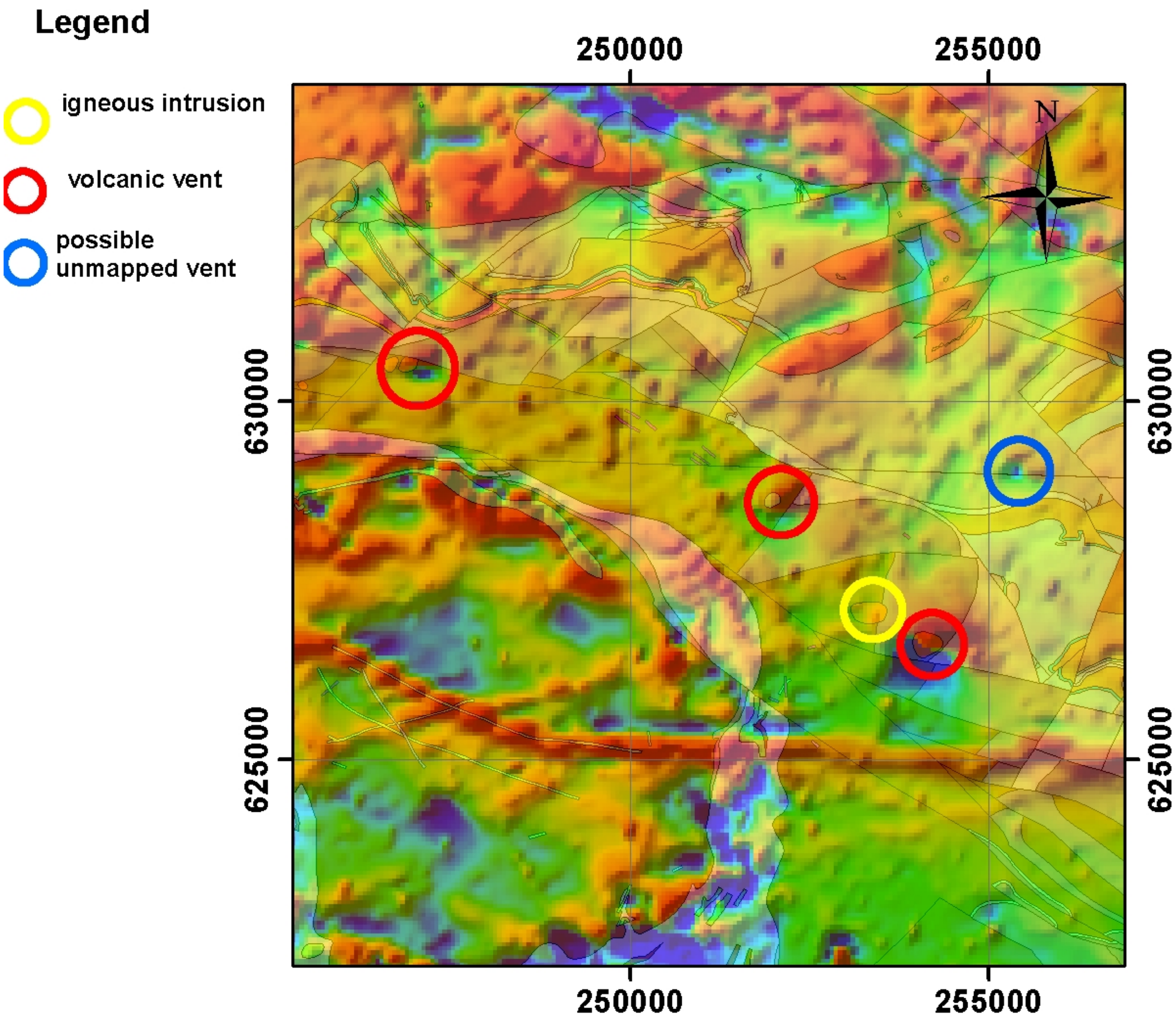


Figure 15. Total field magnetic data from the Ayr survey from around the town of Mauchline overlaid on the 1:50,000 geological map. An igneous intrusion is marked with a yellow circle and red circles show volcanic vents. The blue circle highlights a bipolar magnetic anomaly that may be due to an unmapped volcanic vent.

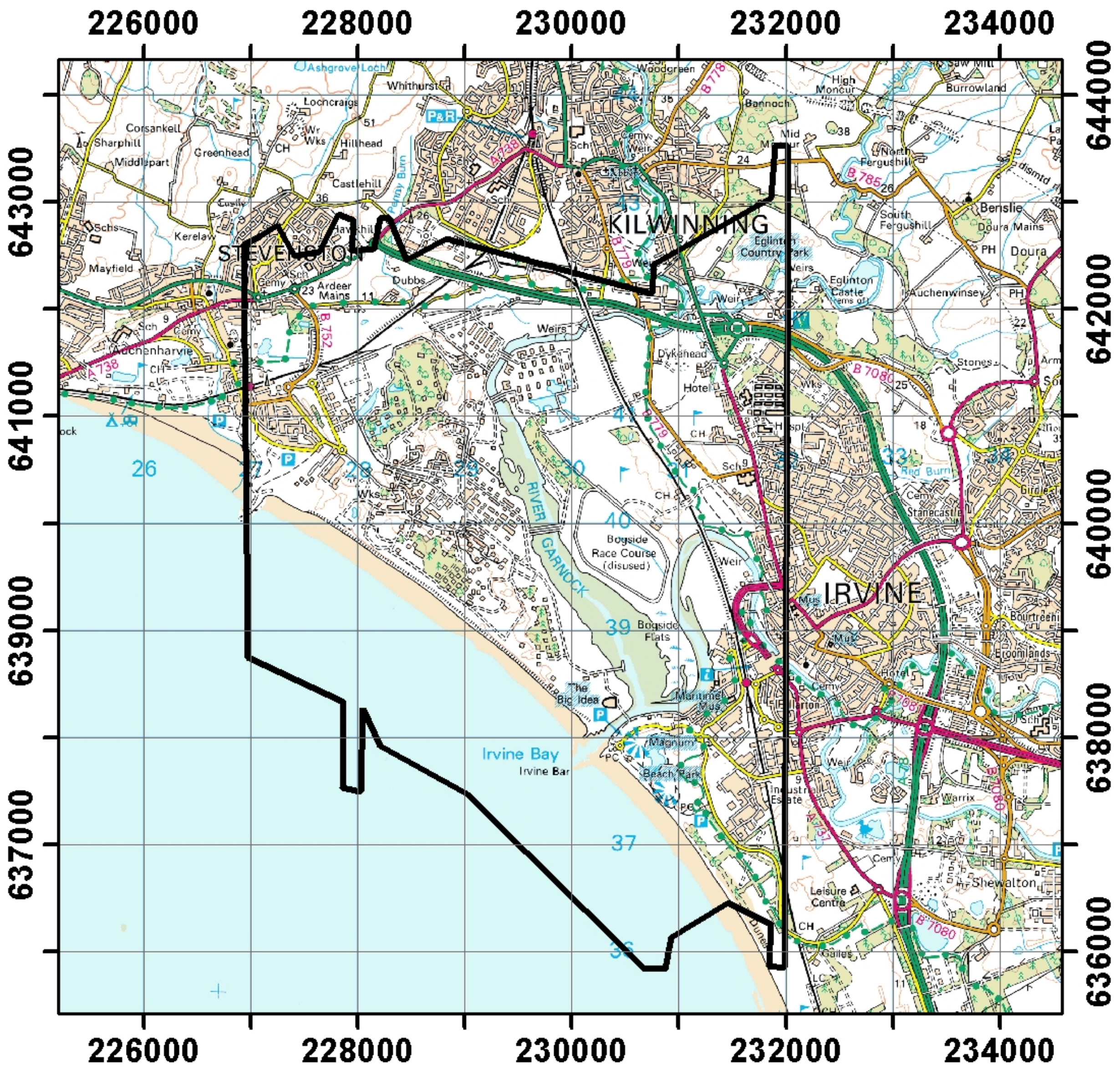


Figure 16a. Extent of the area of the Ardeer infill survey, shown by the polygonal outline. Flight line orientation was south to north and the flight line spacing was 50 m.

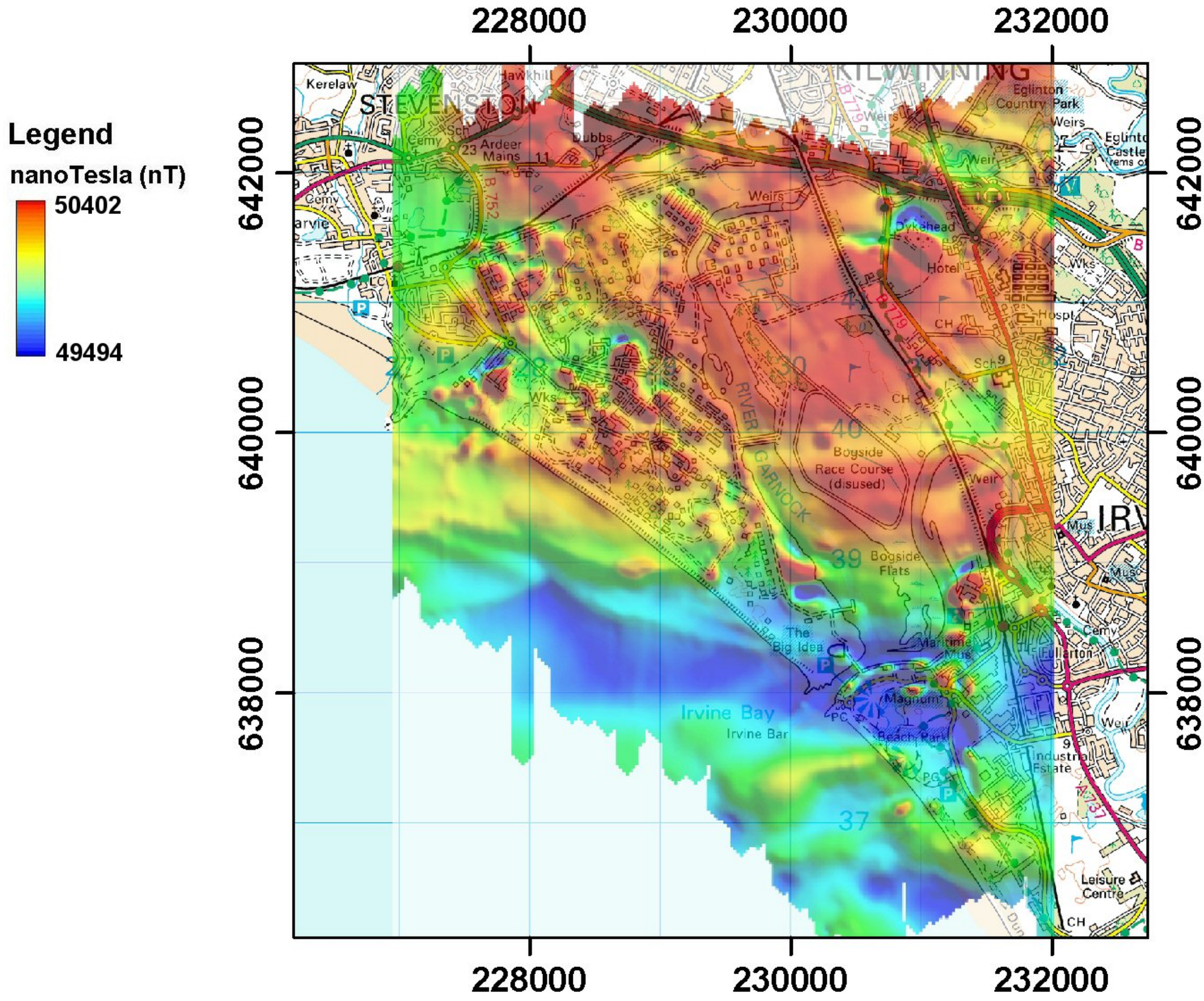


Figure 16b. Total field magnetic data in nannoTeslas (nT) from the Ardeer infill survey overlain on the 1:50,000 Ordnance Survey map. The data range from 49494 to 50402 nT (blue to red colour scale).

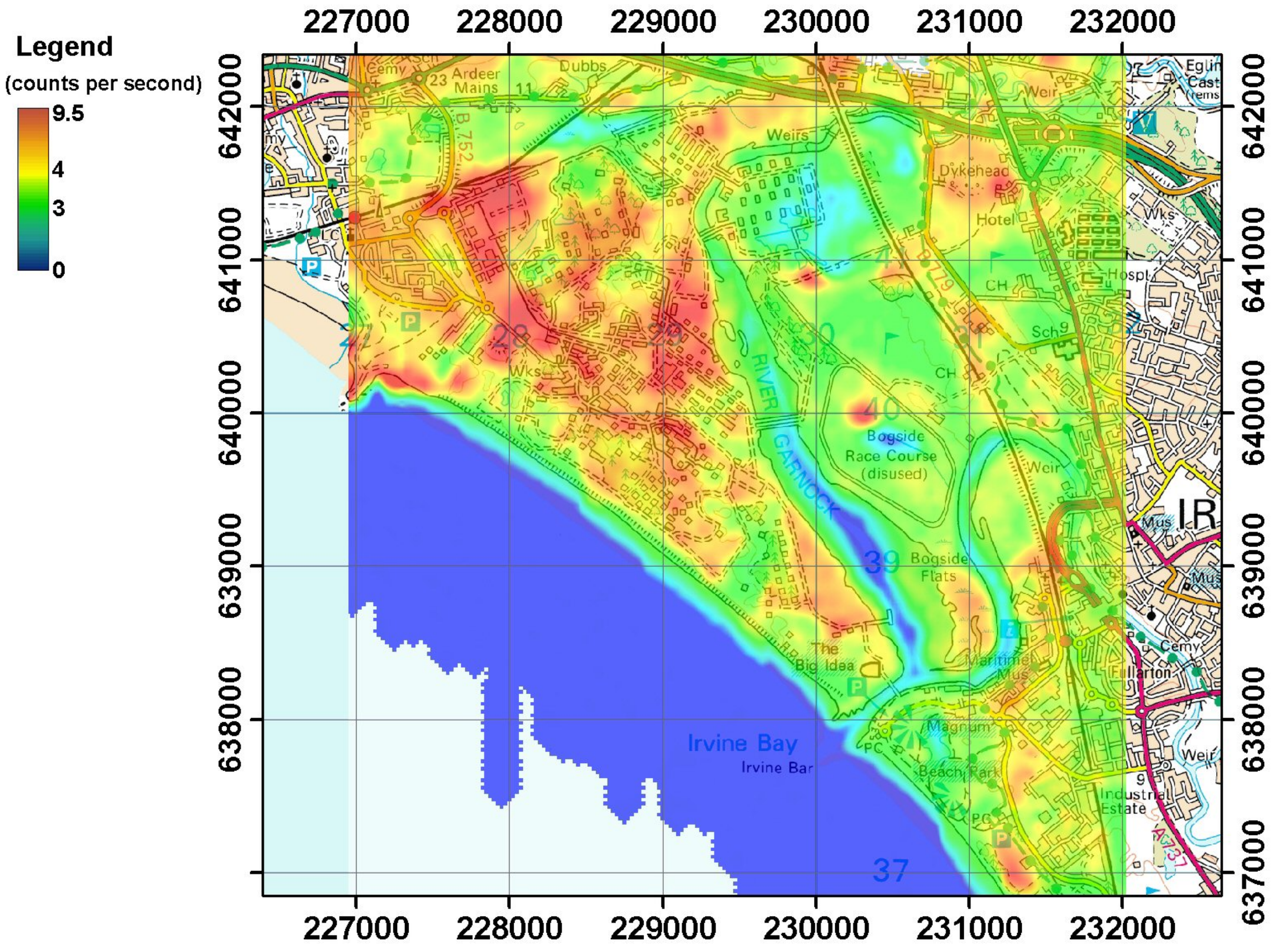


Figure 17a. Total count radiometric data from the Ardeer infill survey. The data range from 0 counts per second (cps) over the sea, shown in blue, to 9.5 cps, shown in red.

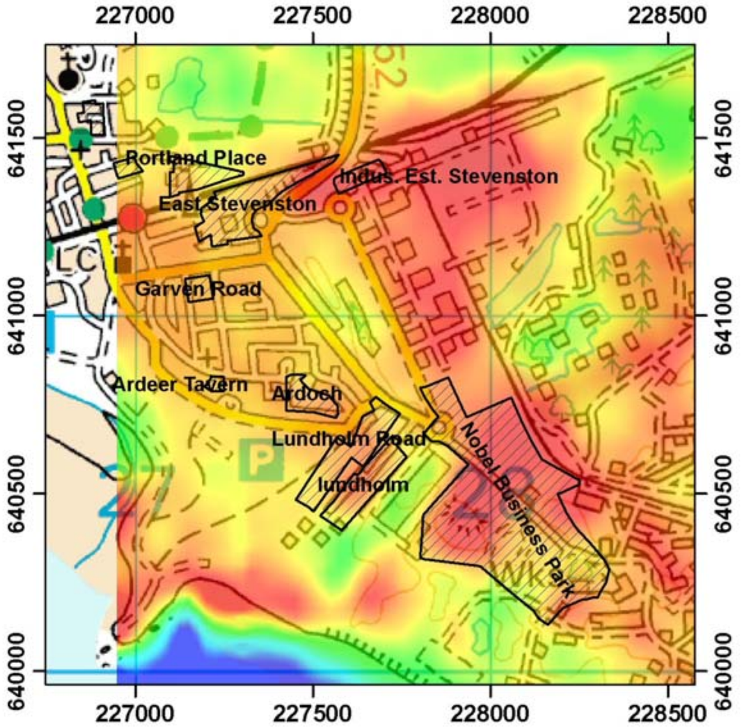


Figure 17b. Total count radiometric data and sites designated as 'Vacant and Derelict Land' in the vicinity of the Nobel Business Park in the west of the Ardeer infill survey. The data range is shown on Figure 17a.

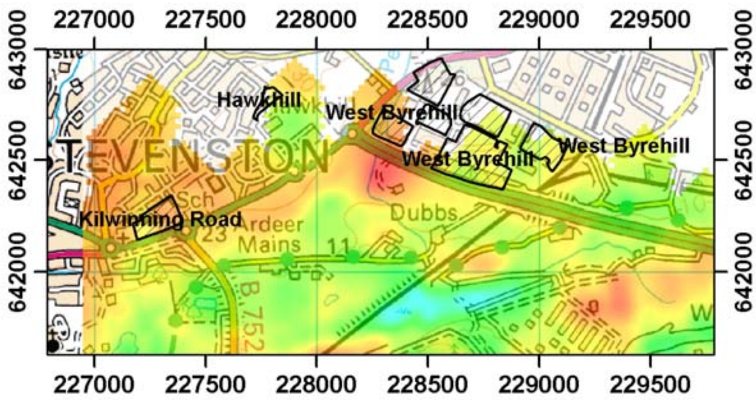


Figure 17c. Total count radiometric data and sites designated as 'Vacant and Derelict Land' in the vicinity of Stevenston in the north-west of the Ardeer infill survey. The data range is shown on Figure 17a.

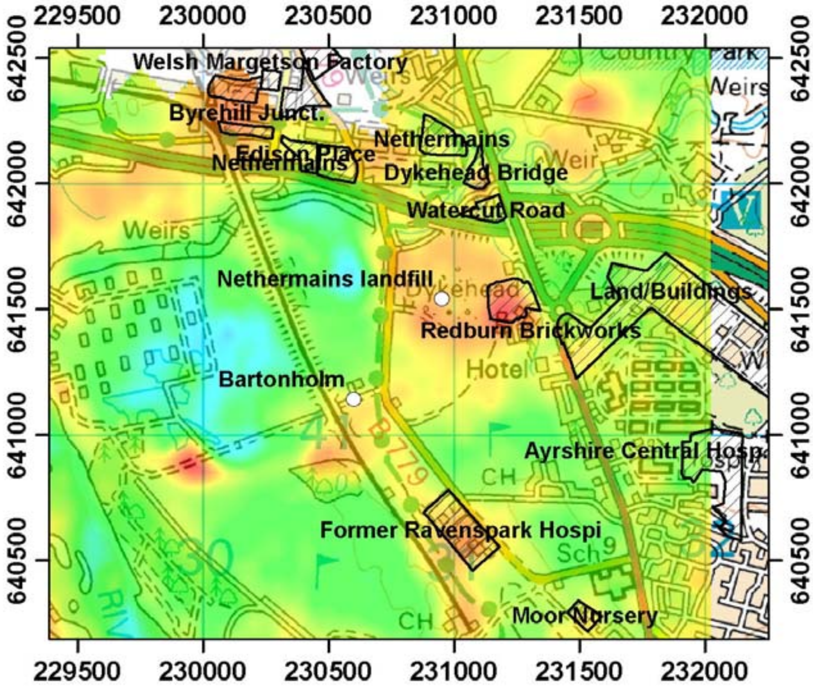


Figure 17d. Total count radiometric data and sites designated as 'Vacant and Derelict Land' in the vicinity of Bartonholm in the north-east of the Ardeer infill survey. The data range is shown on Figure 17a.

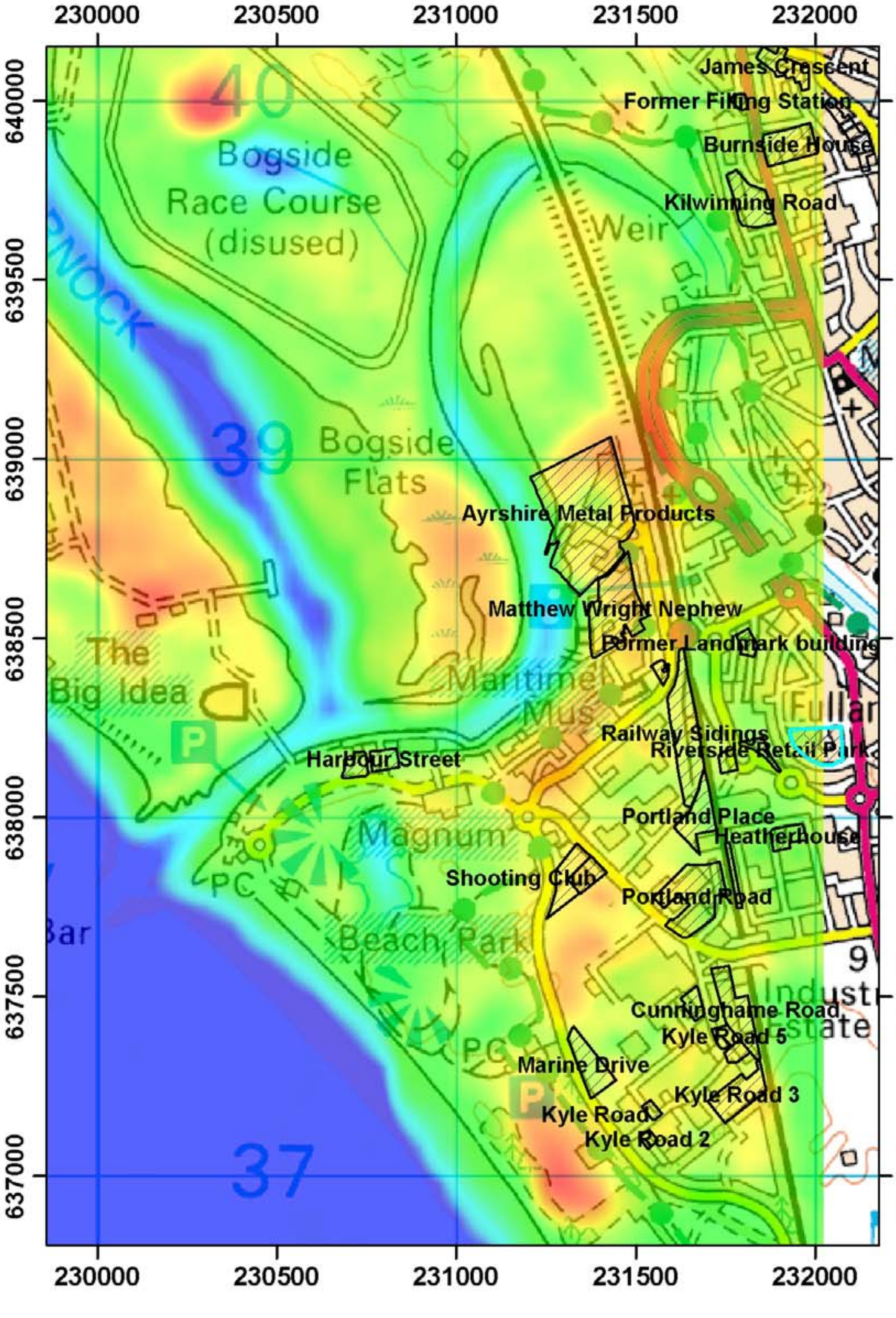


Figure 17e. Total count radiometric data and sites designated as ‘Vacant and Derelict Land’ in the vicinity of west Irvine in the south-east of the Ardeer infill survey. The data range is shown on Figure 17a.

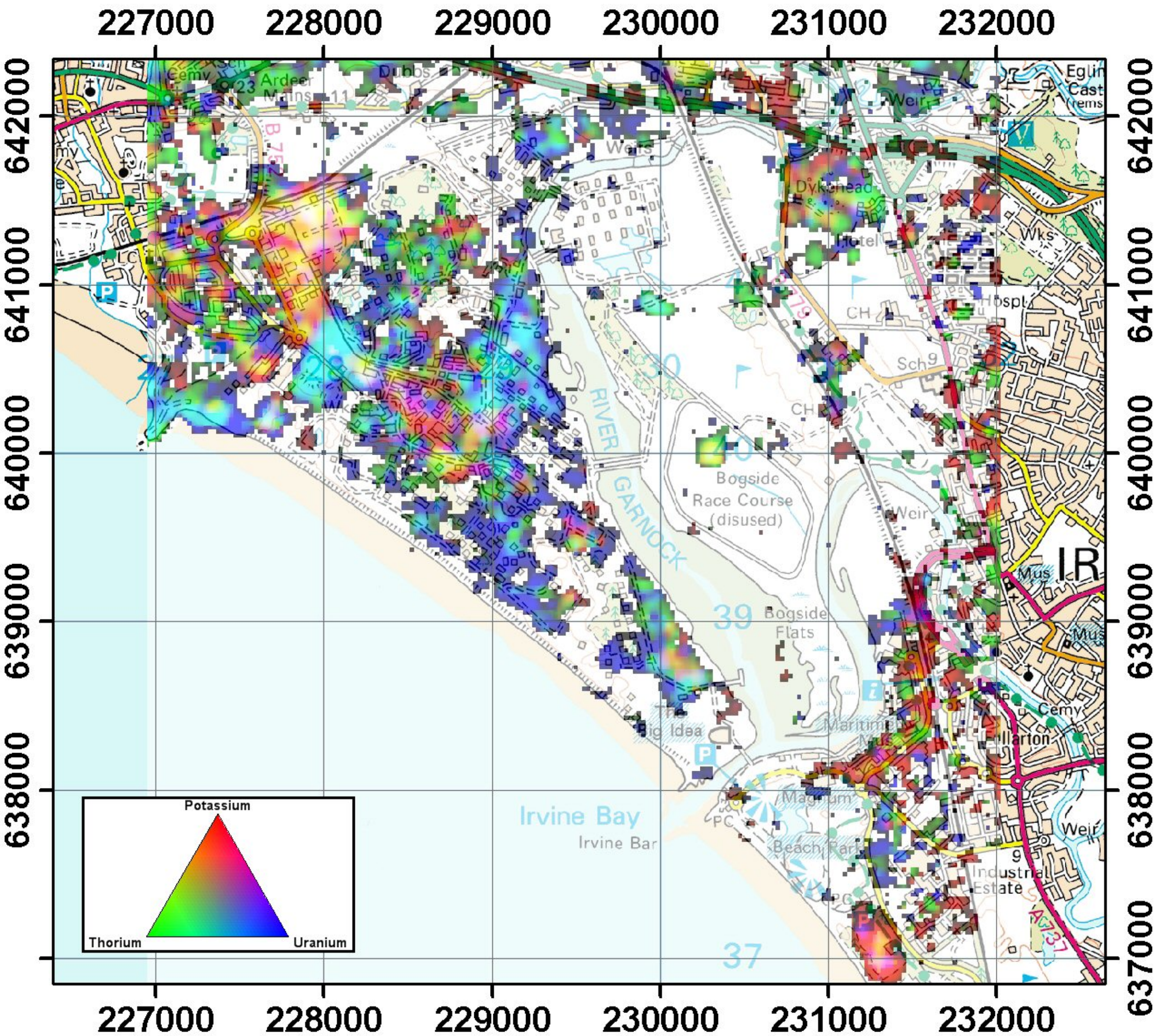


Figure 17f. Ternary image of the radiometric data from the Ardeer infill survey. High potassium is plotted as red, high thorium is plotted green and high uranium is plotted blue. The image has been cropped to only display higher values.

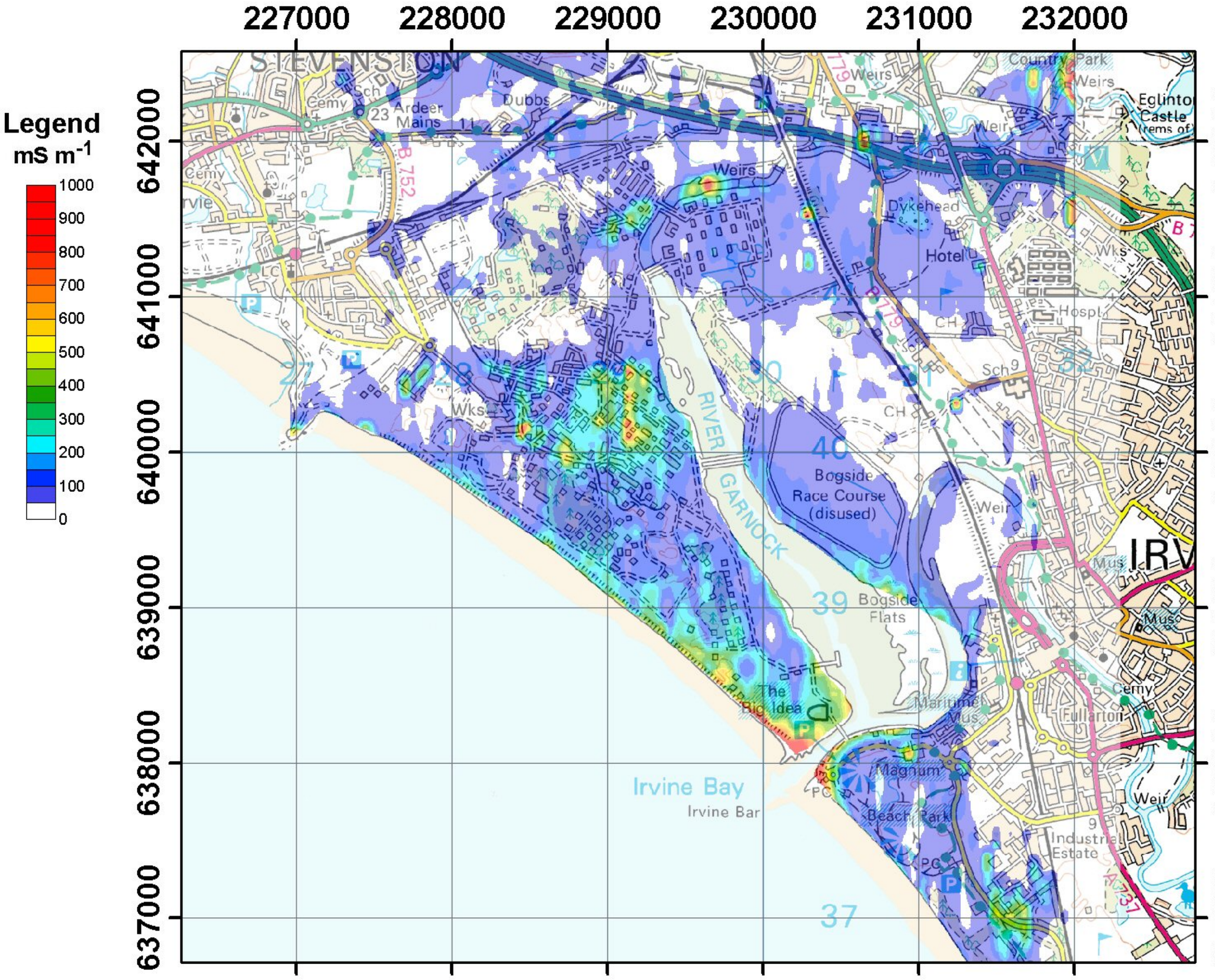


Figure 18a. High frequency EM conductivity data from the Ardeer infill survey, masked to remove low values and very high values that occur over the sea.

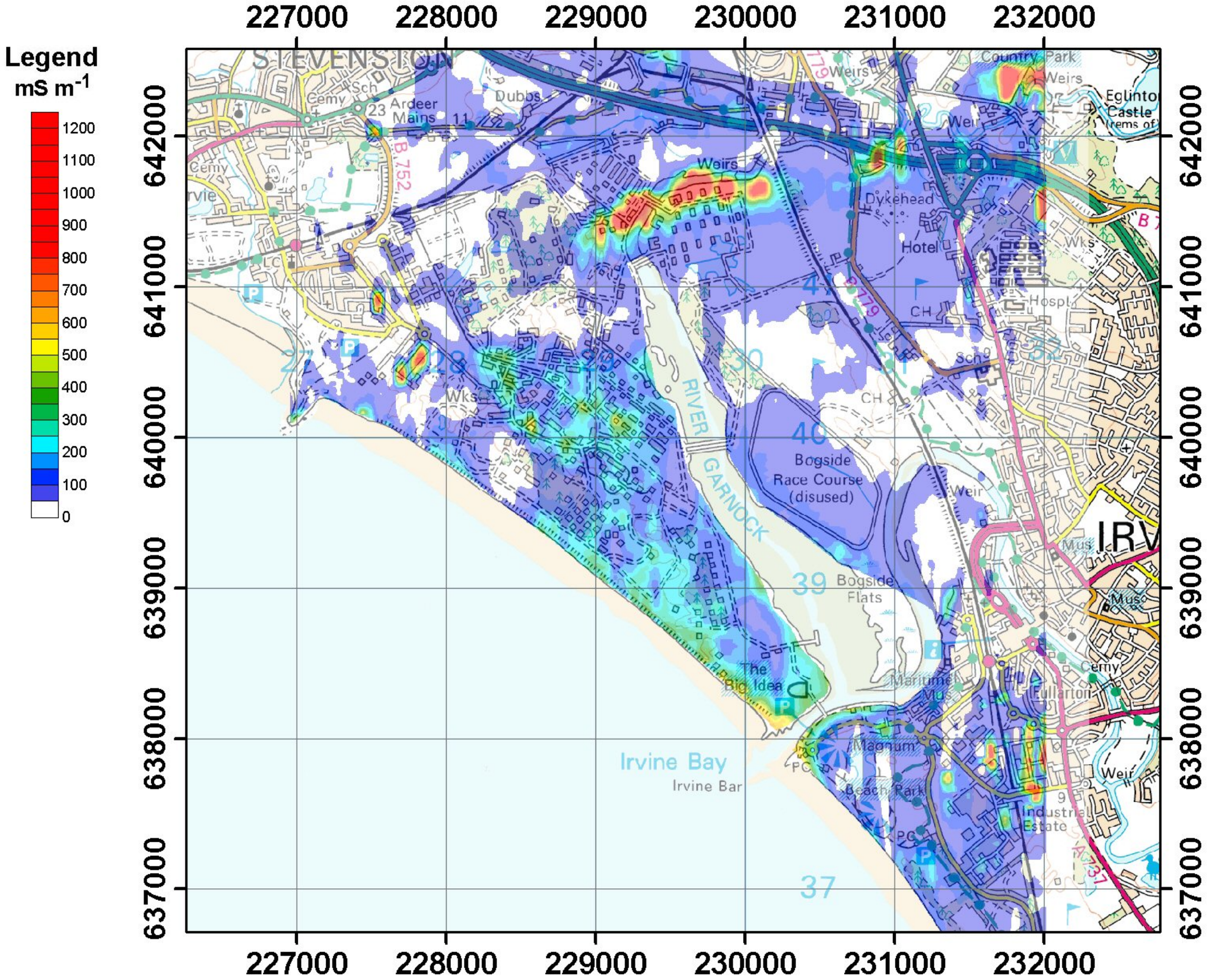


Figure 18b. Low frequency EM conductivity data from the Ardeer infill survey, masked to remove low values and very high values that occur over the sea.

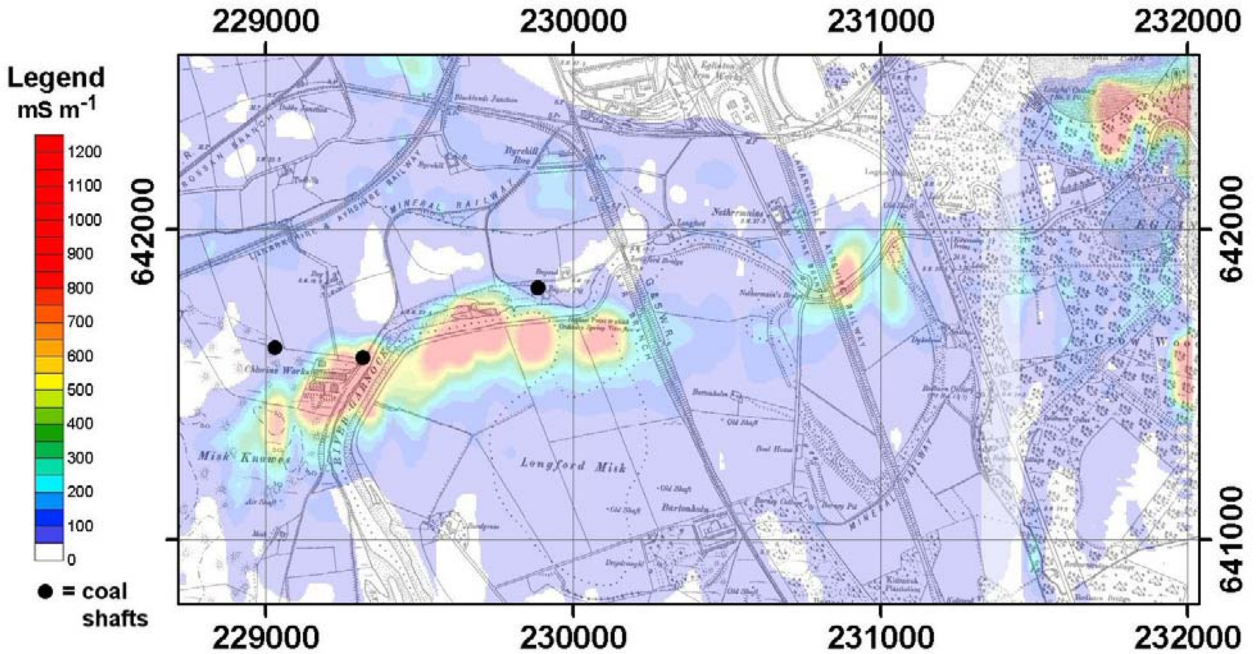


Figure 19a. Low frequency EM conductivity data from the Ardeer infill survey in the vicinity of Longford Misk and Eglington, masked to remove very low values, superimposed on the 1897 Ordnance Survey map. The sites of former coal shafts are shown in the vicinity of Longford chemical works and at Bogend colliery.

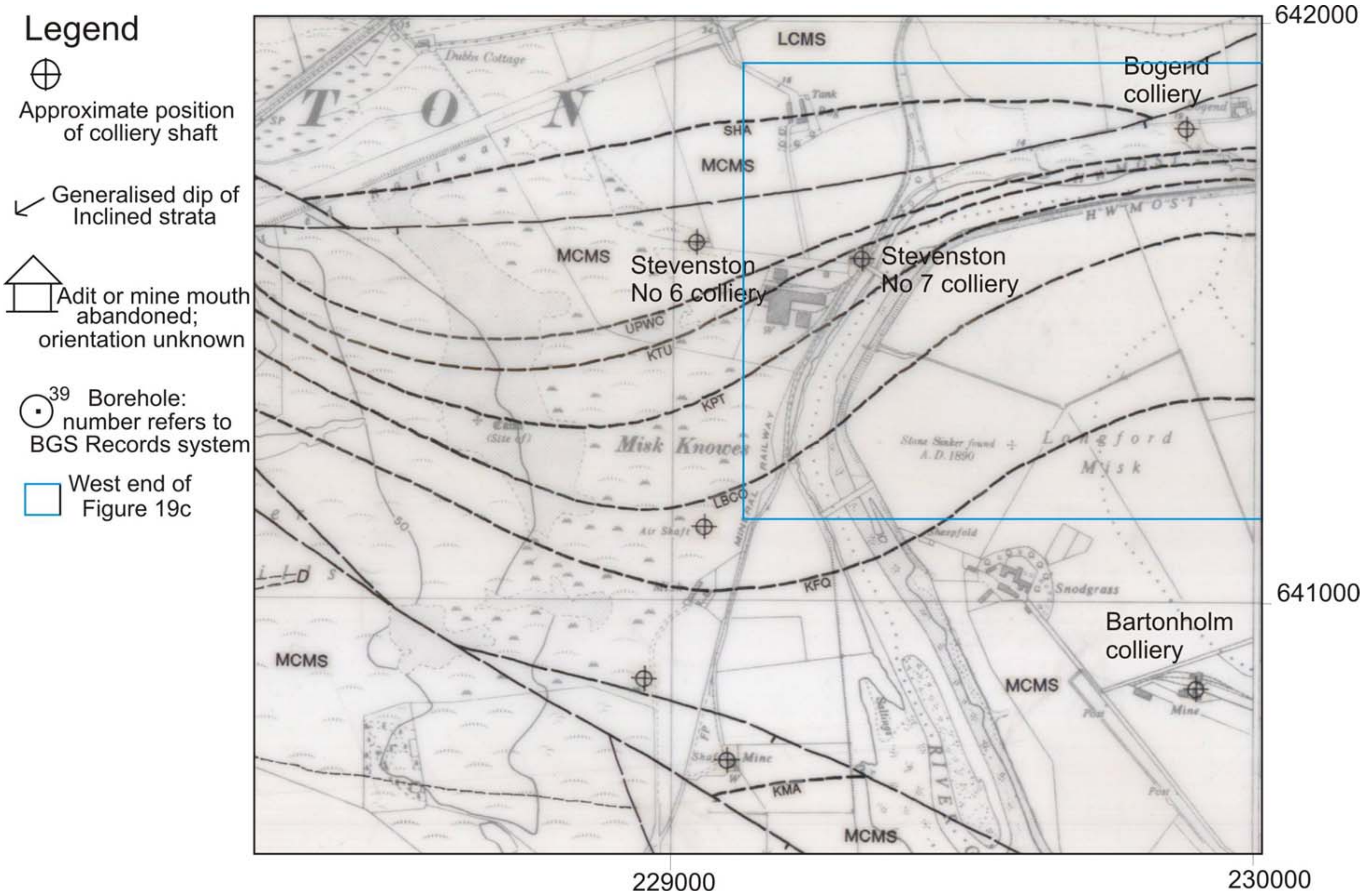


Figure 19b. Bedrock geology map in the vicinity of Longford Misk: D, dolerite; KFQ, Kilmarnock Five Quarters Coal; KIE, Kilwinning Ell Coal; KMA, Kilmarnock Major Coal; KPT, Kilmarnock Parrot Coal; KTU, Kilmarnock Turf Coal; LADC, Ladyha' Coal; LBCO, Linn Bed Coal; LCMS, Lower Coal Measures; MCMS, Middle Coal Measures; PBI, Plann Blackband Ironstone (coal); SHA, Shale Coal; UPWC, Upper Wee Coal; Z_v^B, basaltic pyroclastic vent deposits.

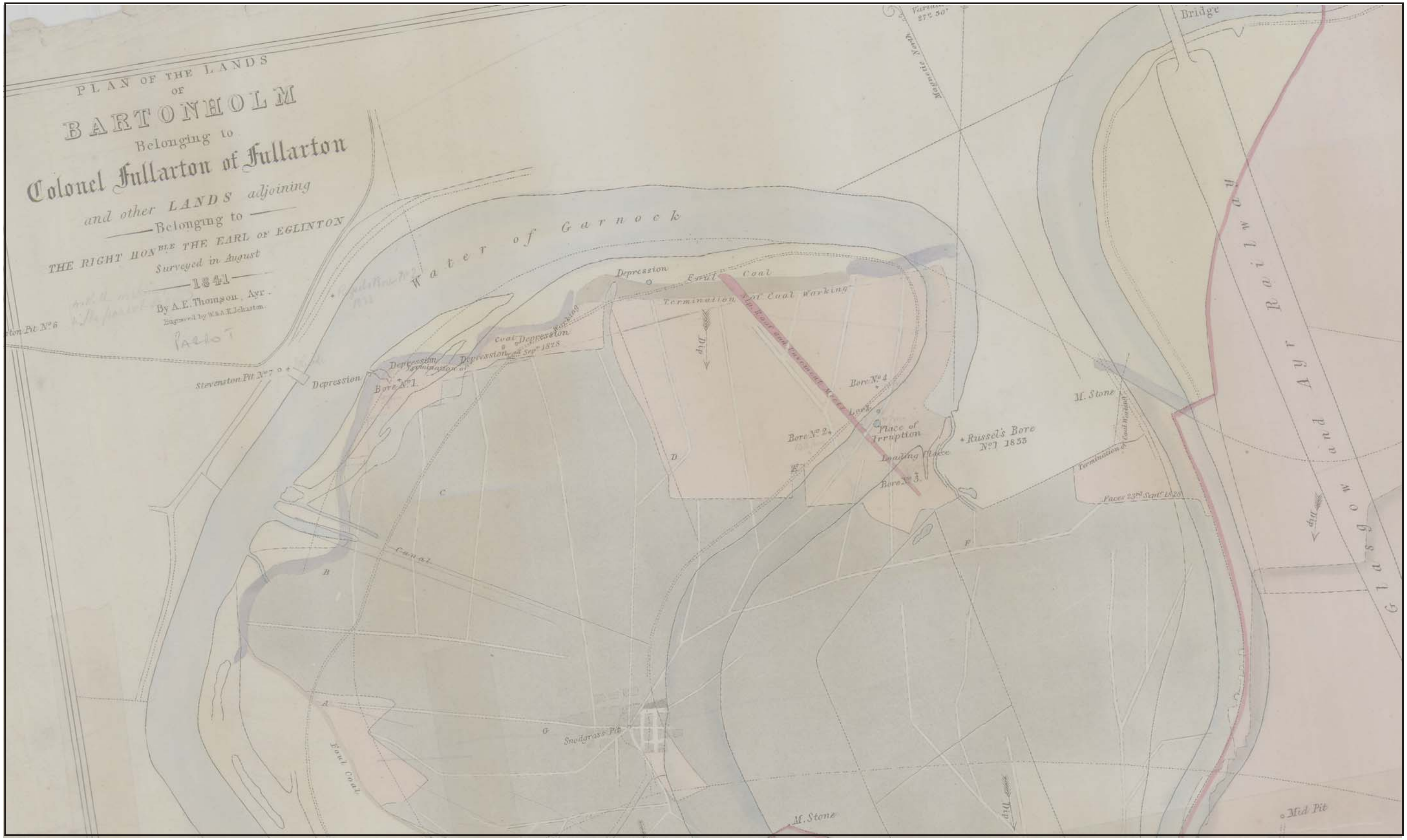


Figure 19c. Excerpt of mine plan for subsurface workings in the Kilmarnock Parrot Coal, in the vicinity of Longford Misk. Note 'Termination of Coal Working' and five 'Depression' hollows mapped on the south bank of the Water of Garnock and also 'Place of Irruption' underlying the former position of the bed of the Water of Garnock indicating the shallow nature of the coal workings. Published with the permission of the Coal Authority.

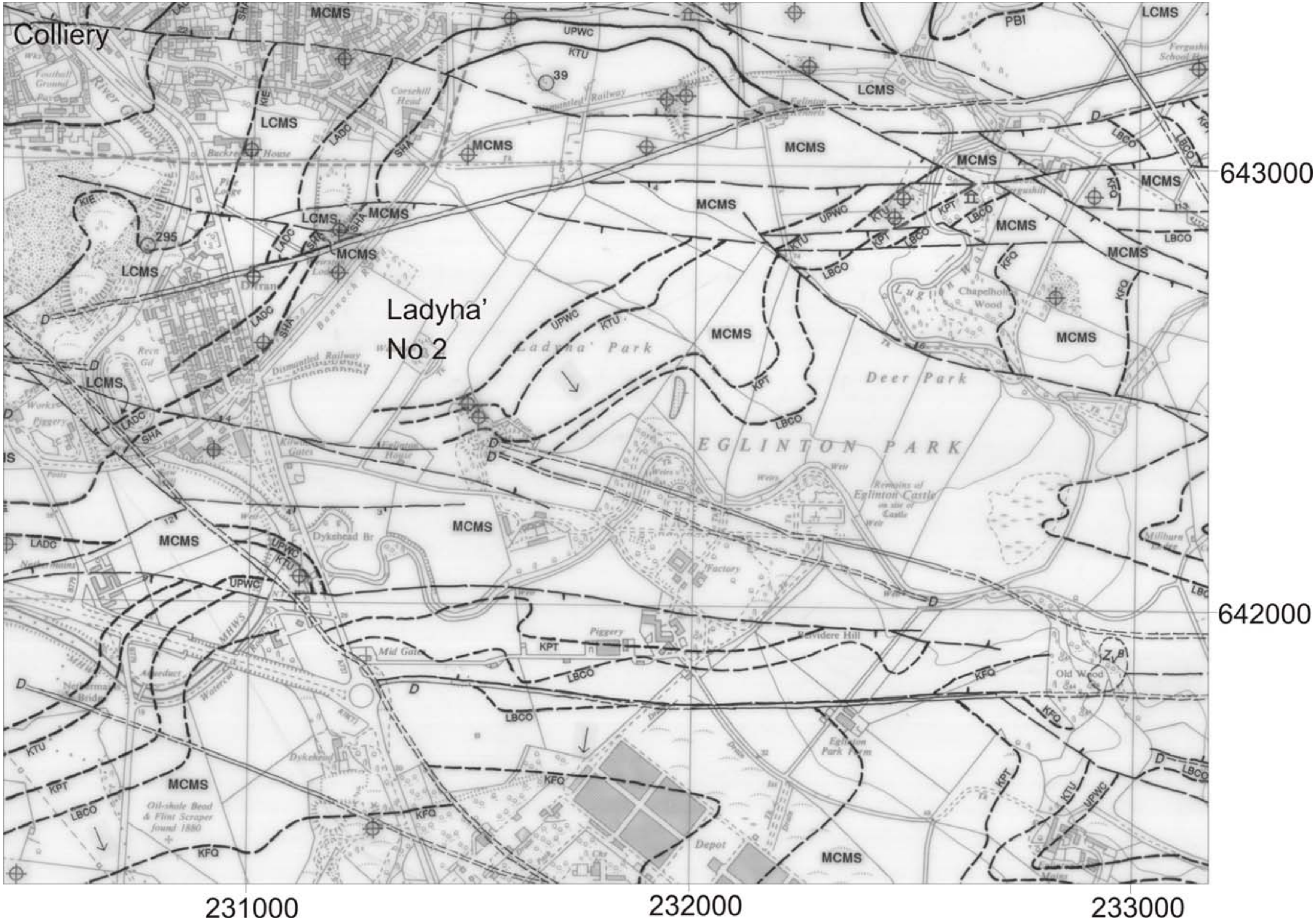


Figure 19d. Bedrock geology map in the vicinity of Eglington Park, Kilwinning. Legend and abbreviations, see Figure 19b.

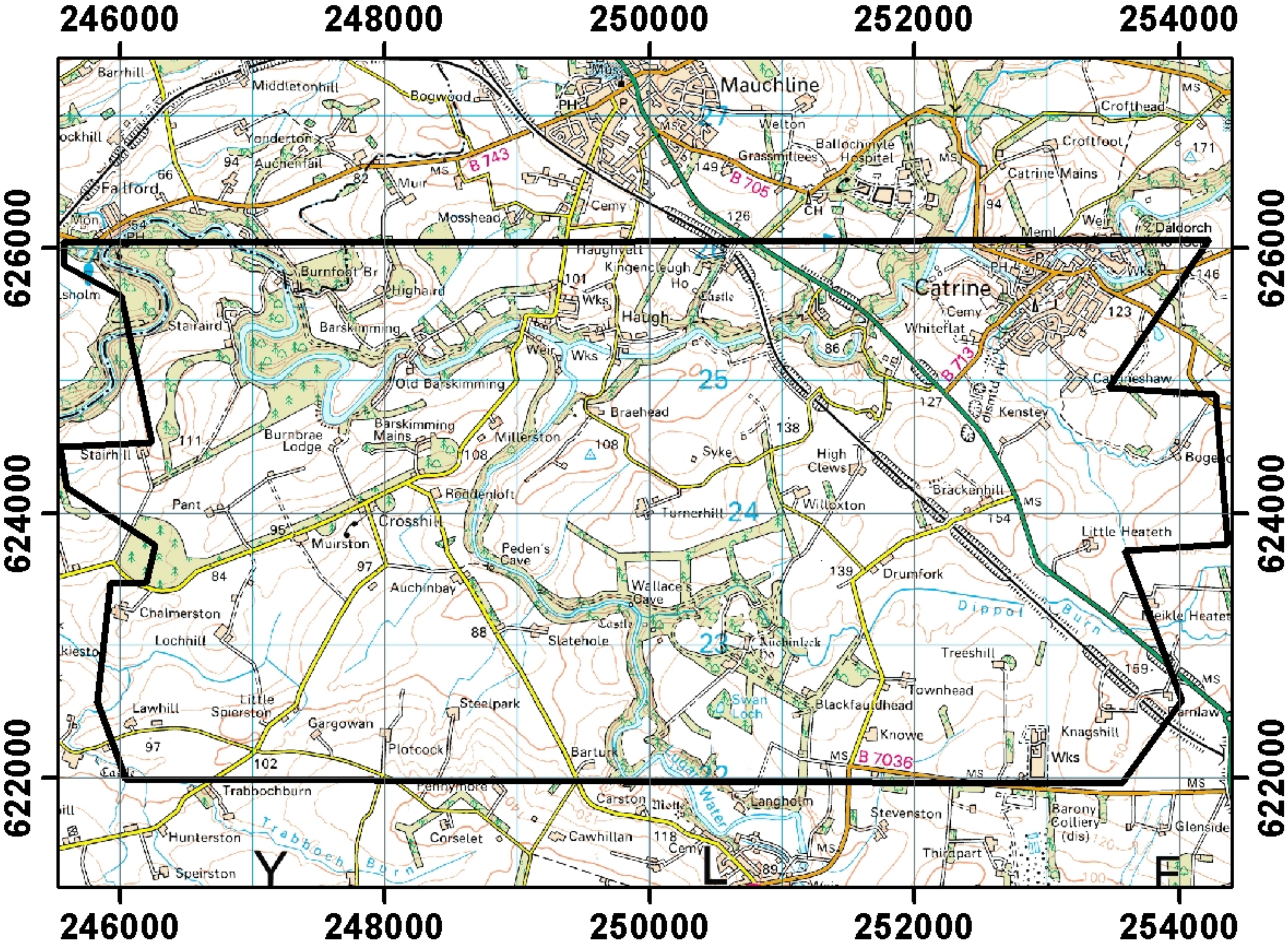


Figure 20. Extent of the area of the Mauchline infill survey, shown by the polygonal outline. Flight line orientation was east to west and the flight line spacing was 50 m.

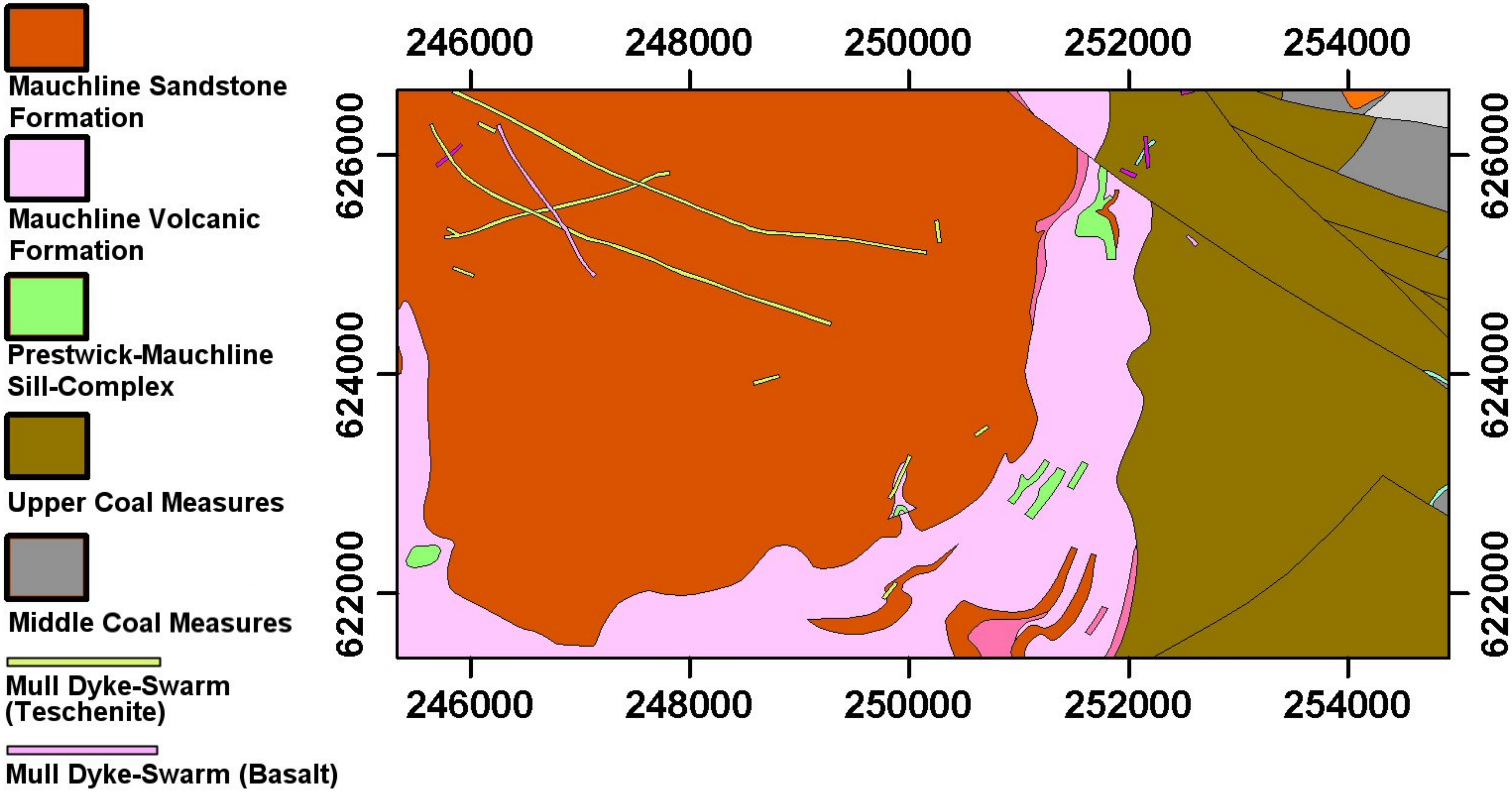


Figure 21a. Bedrock geology for the extent of the Mauchline infill survey area.

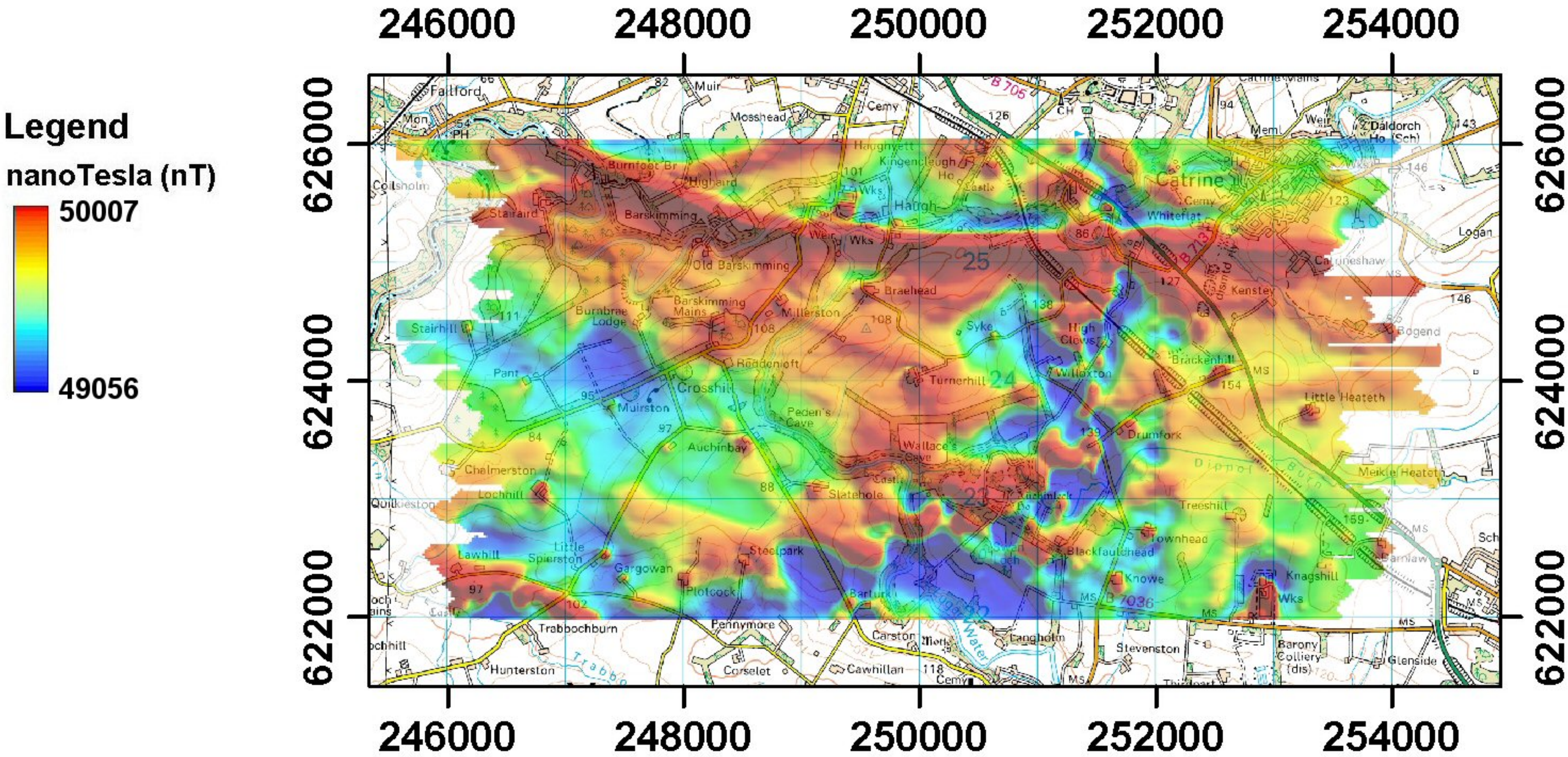


Figure 21b. Total field magnetic data in nannoTeslas (nT) for the Mauchline infill survey. The data range from 49056 to 50007 nT (blue to red colour scale). The magnetic data are overlaid on the 1:50,000 Ordnance Survey map.

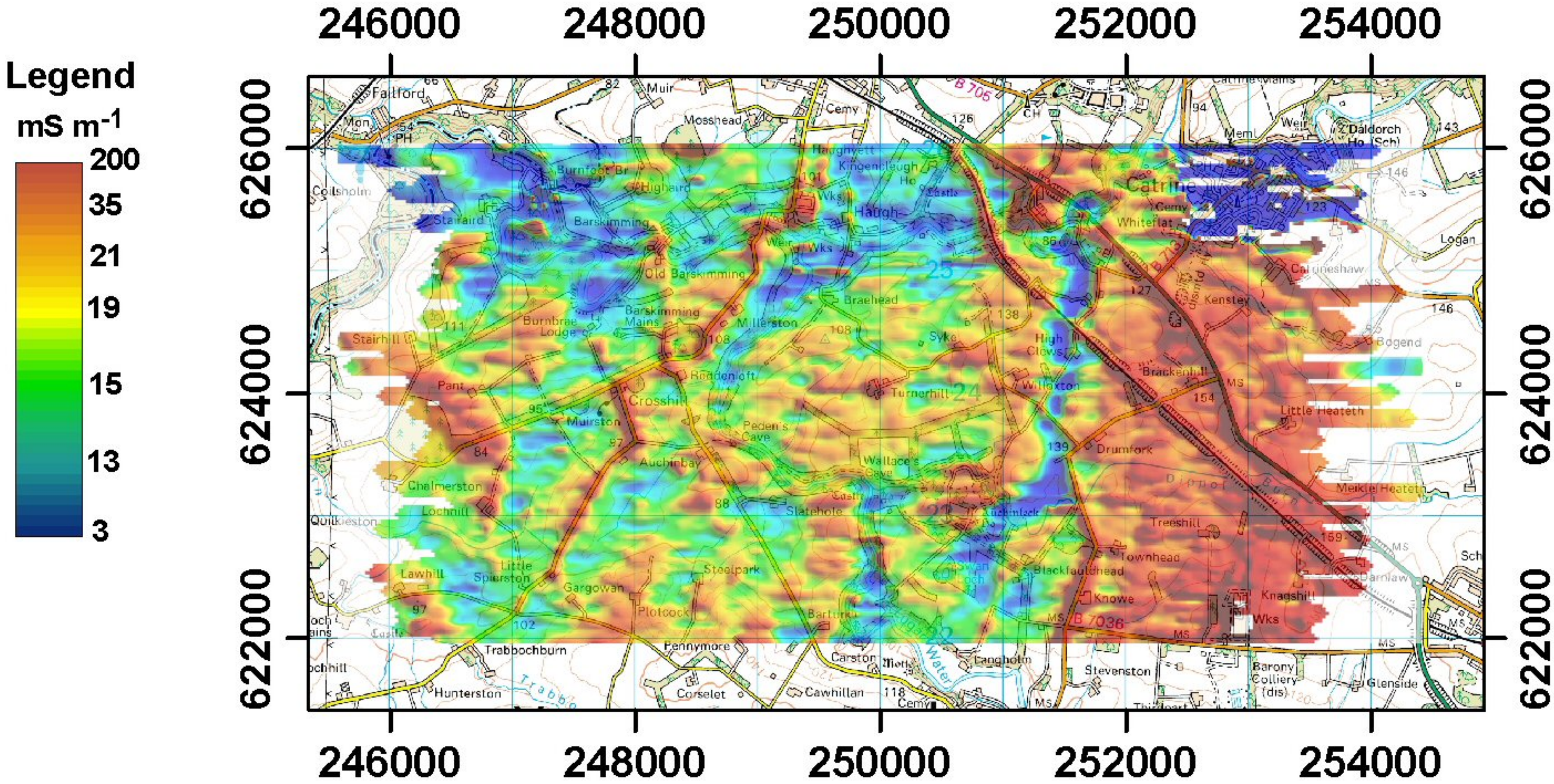


Figure 21c. High frequency EM conductivity data from the Mauchline infill survey. The data range from highs over the cultural features of 50 to 90 mS m^{-1} (shown in red) to 0.1 mS m^{-1} (shown in purple) over the high fly area in the north-eastern corner of the image. The response over the volcanic rocks is 3 to 7 mS m^{-1}.

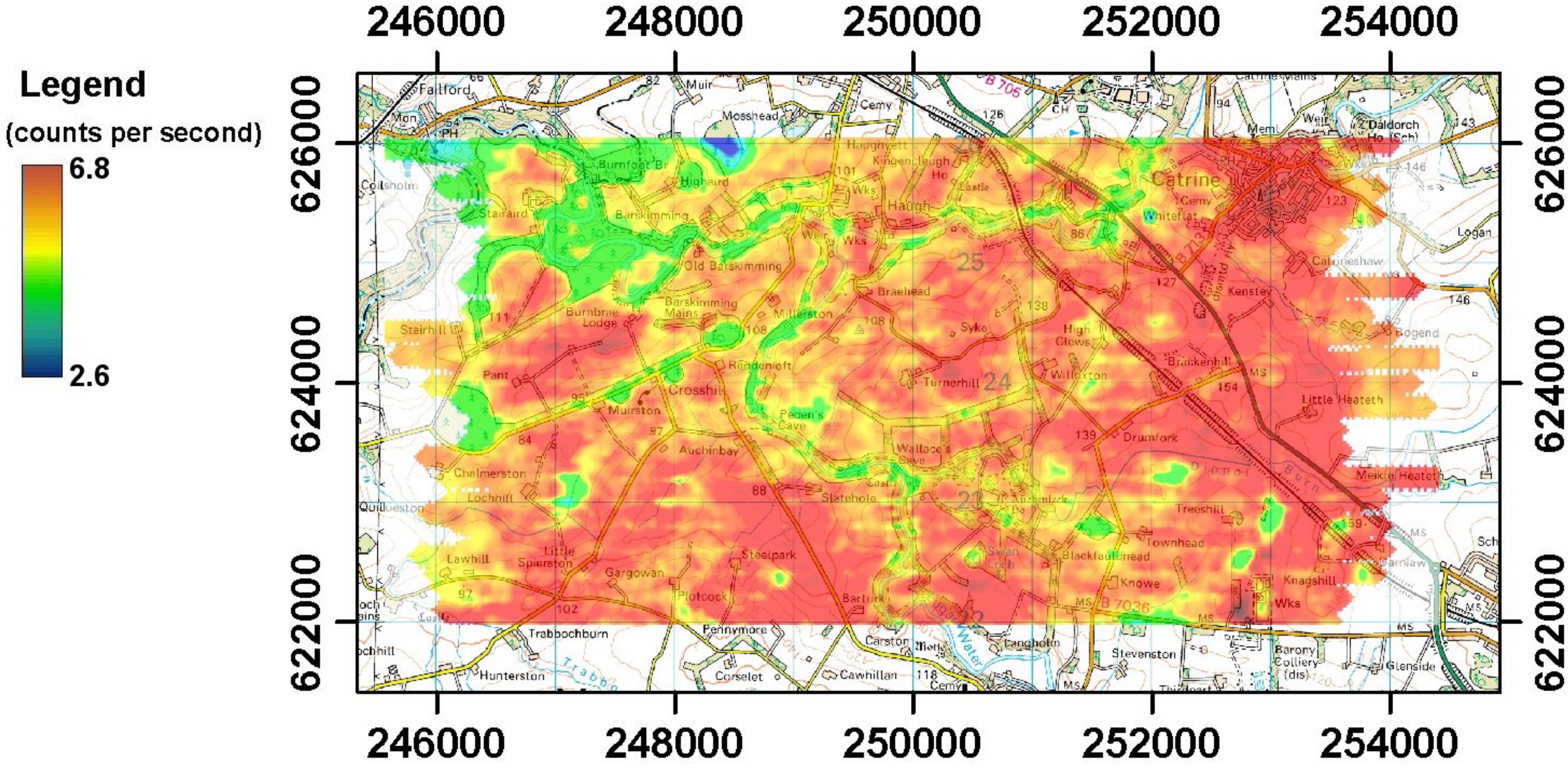


Figure 21d. Total count radiometric data for the Mauchline infill survey. The data range from 2.6 counts per second (cps), shown in blue, to 6.8 cps, shown in red.

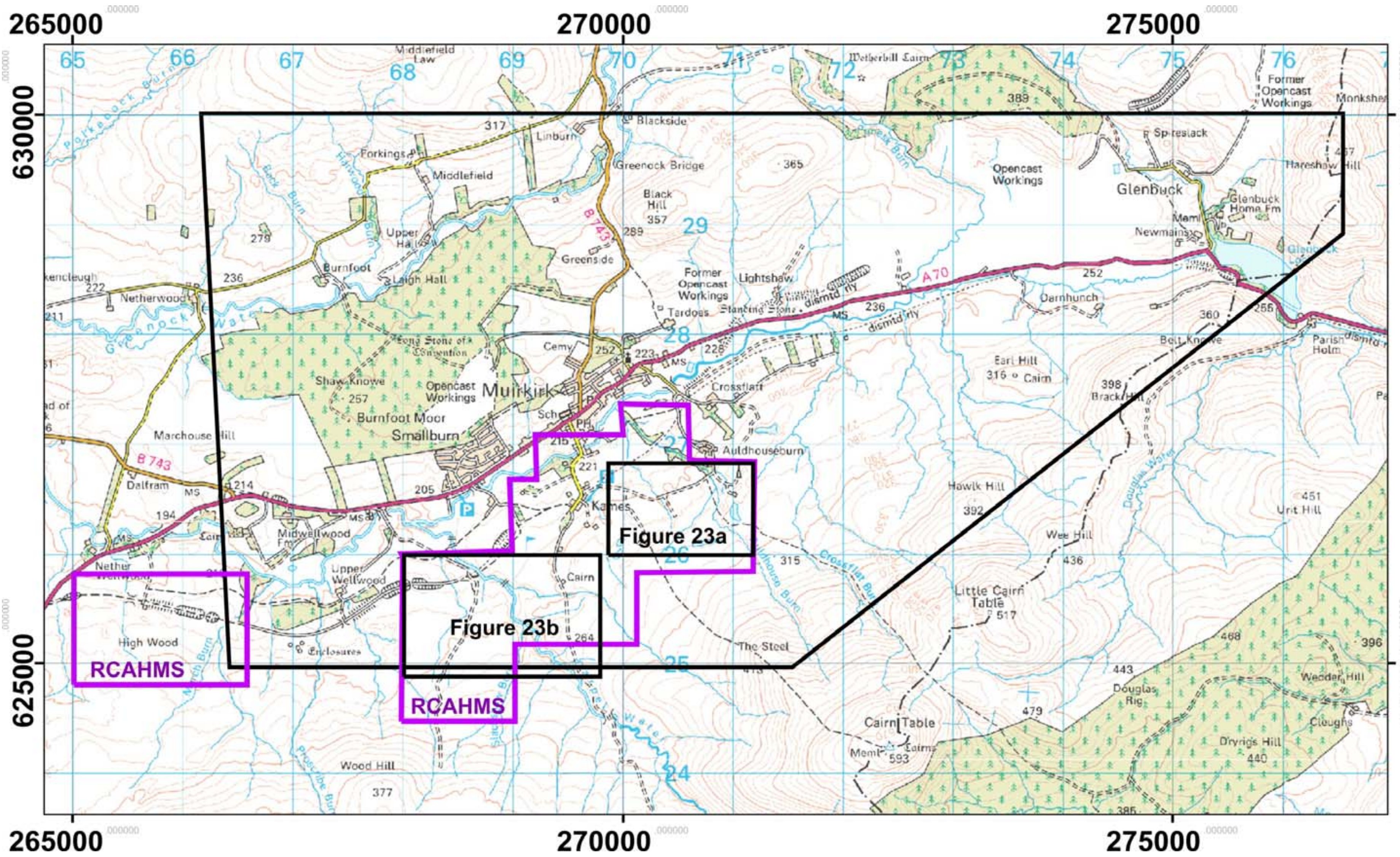


Figure 22a. Extent of the area of the Muirkirk infill survey, shown by the polygonal outline. Flight line orientation was east to west and the flight line spacing was 50 m. The extent of industrial archaeological surveys by the Royal Commission Ancient Historical Monuments, Scotland (RCAHMS) are shown.

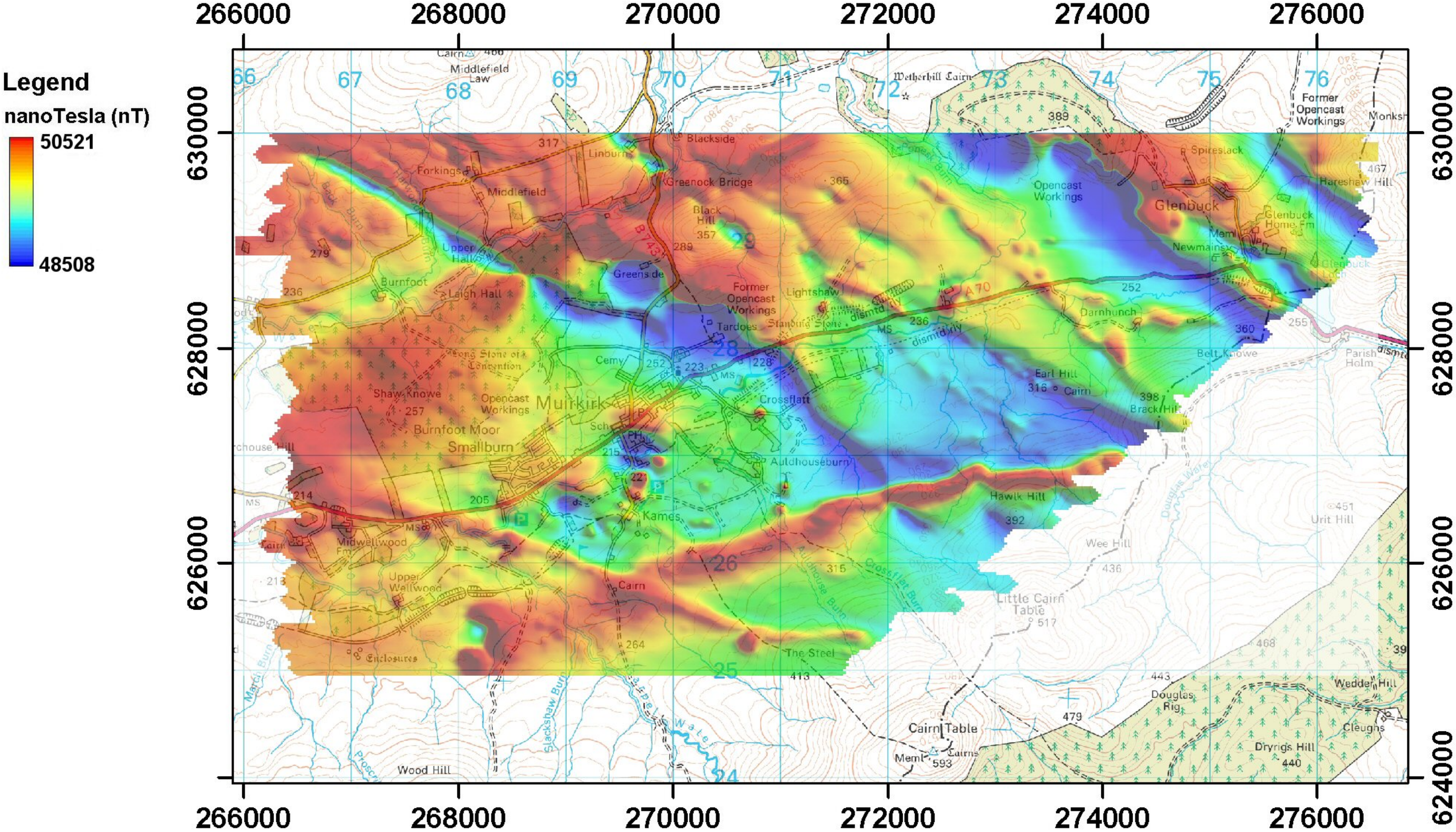


Figure 22b. Total field magnetic data in nannoTeslas (nT) from the Muirkirk infill survey. The data range from 48508 to 50521 nT (blue to red colour scale).

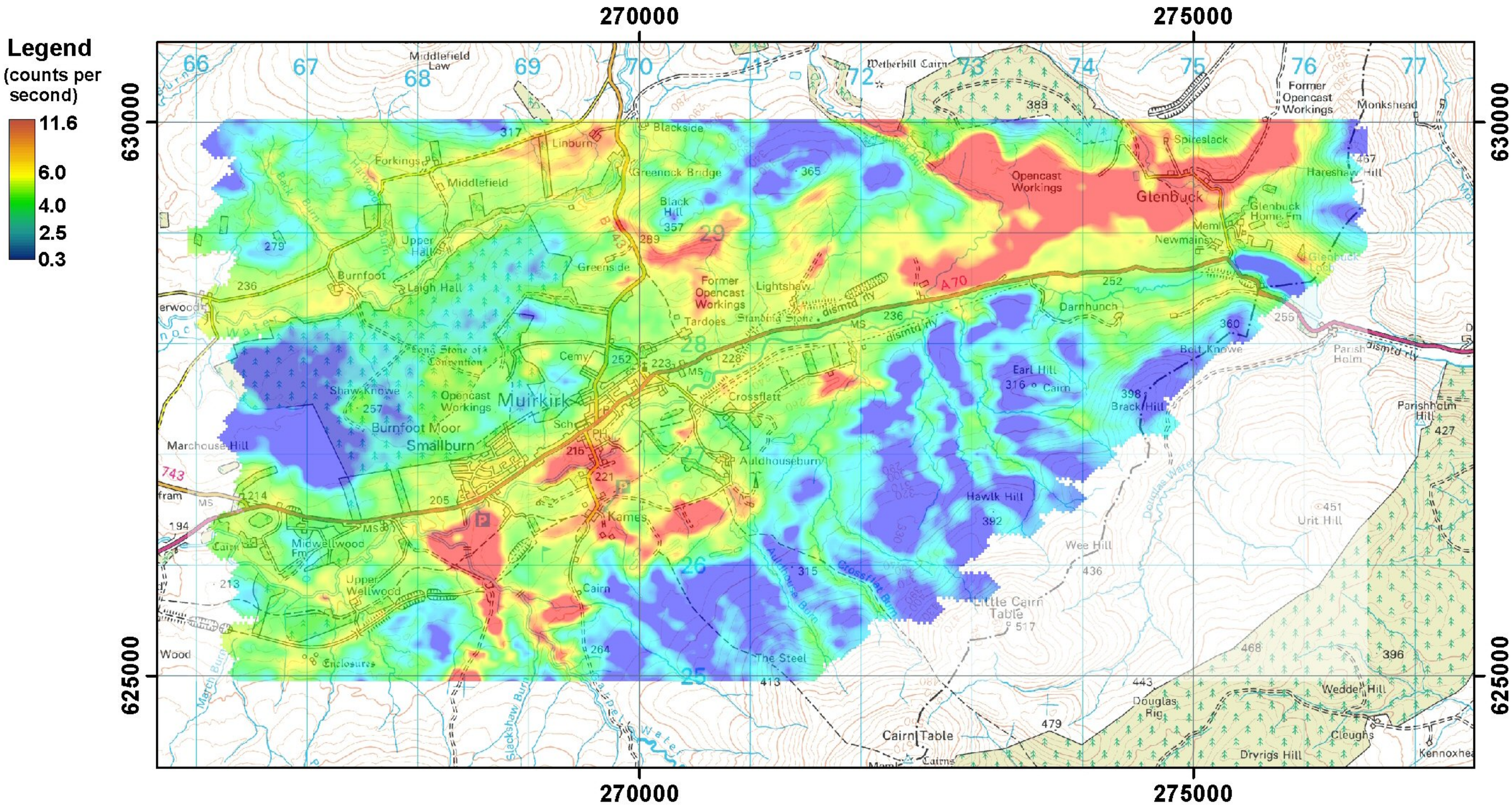


Figure 23a. Total count radiometric data from the Muirkirk infill survey. The data range from 0.3 cps, shown in blue, to 11.6 cps, shown in red.

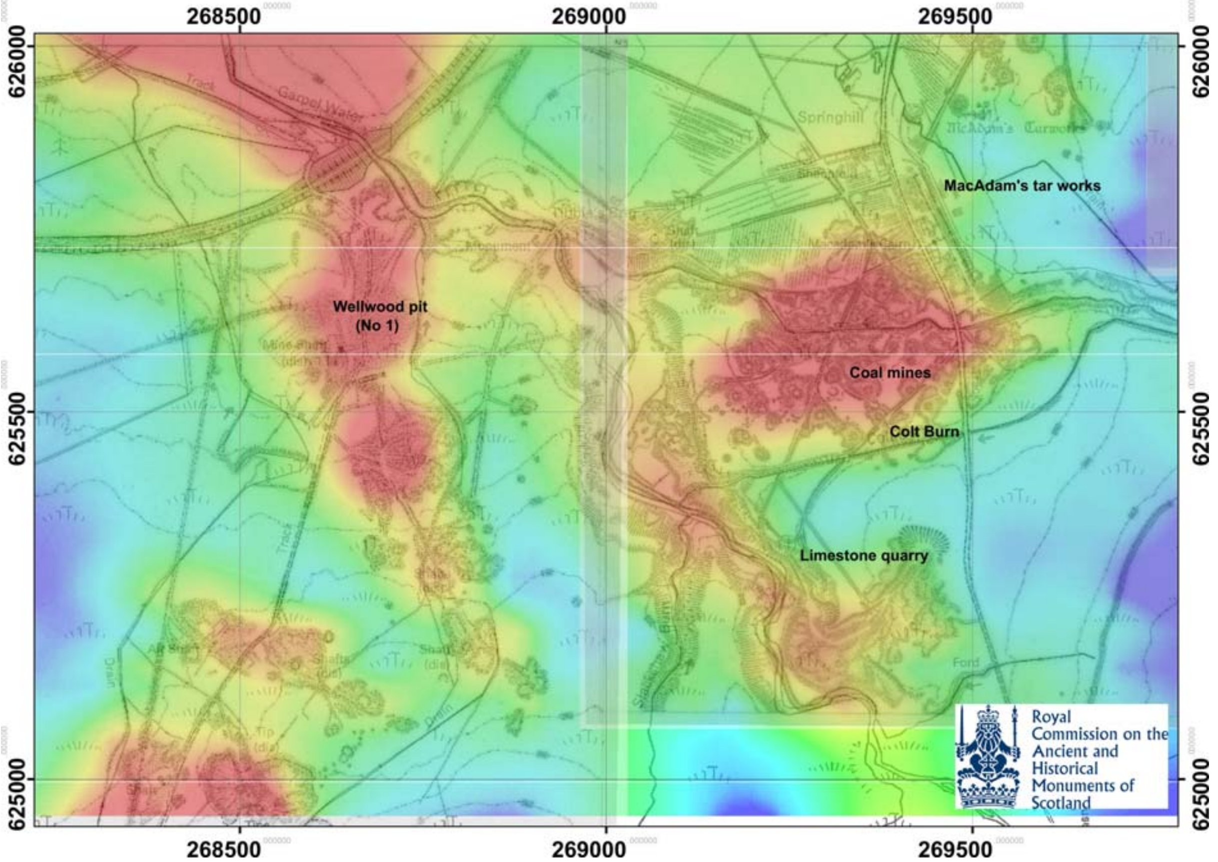


Figure 23b. Archaeological survey and total count radiometric data from the Wellwood area south of Muirkirk. Location of area shown on Figure 22a. Derived from information compiled by and/or copyright of RCAHMS.

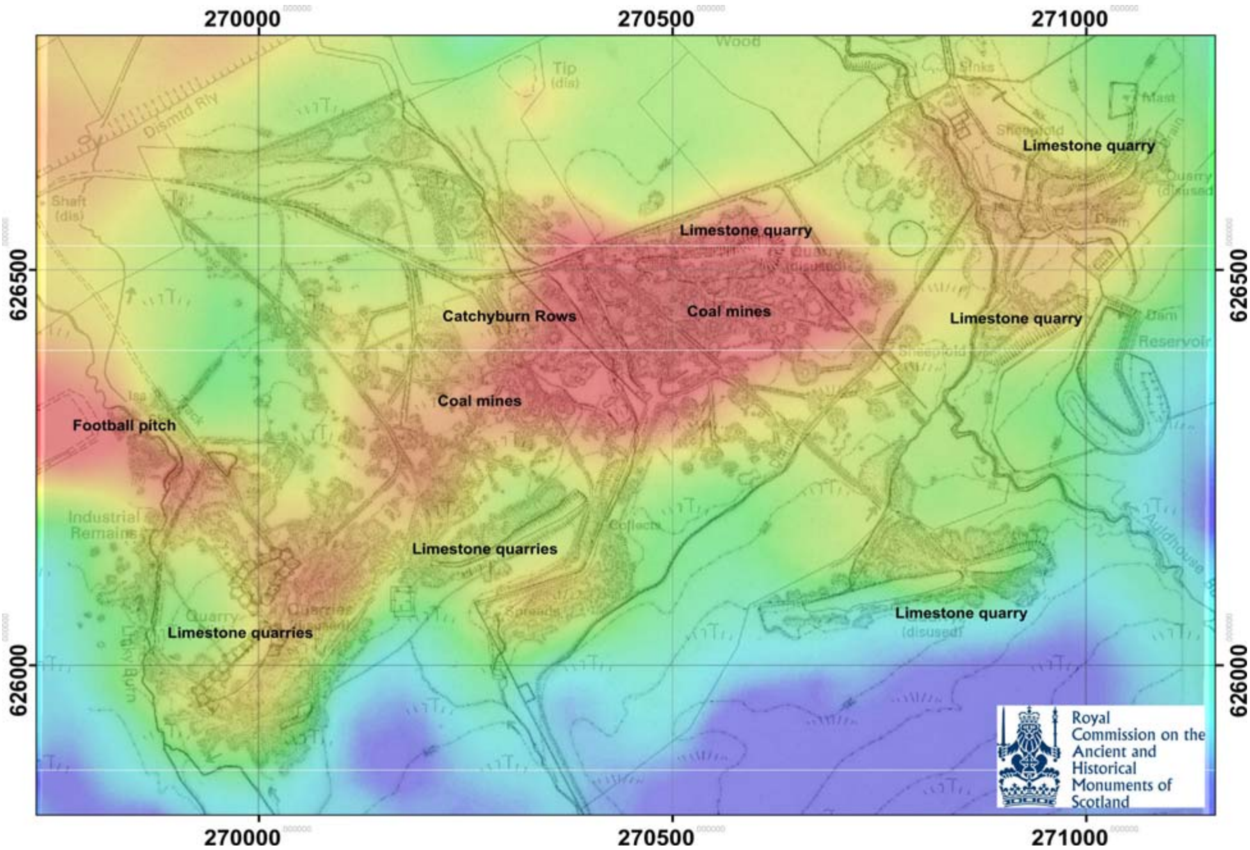


Figure 23c. Archaeological survey and total count radiometric data from the Catchyburn area south-east of Muirkirk. Location of area shown on Figure 22a. Derived from information compiled by and/or copyright of RCAHMS.

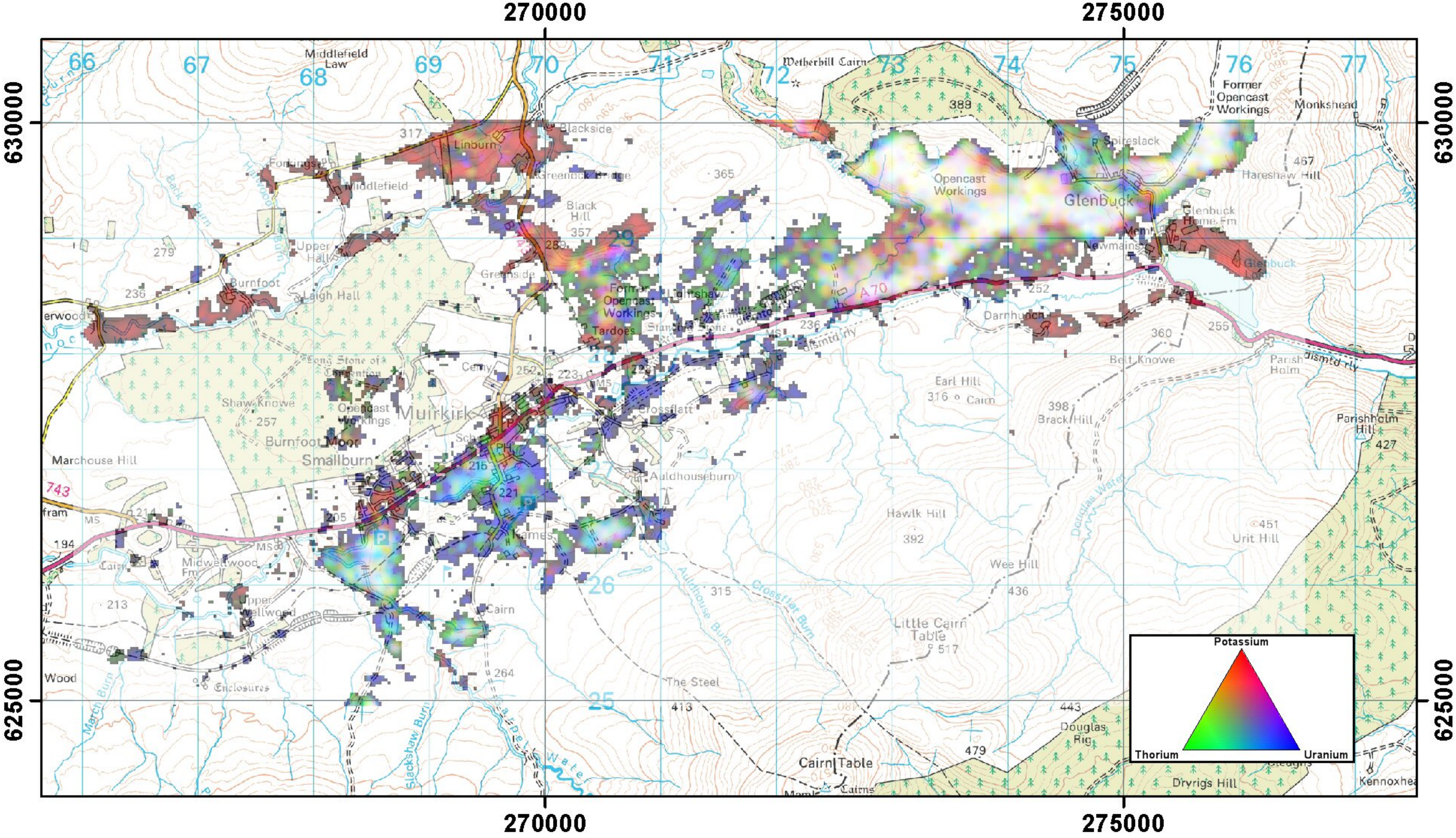


Figure 24. Ternary image of the radiometric data from the Muirkirk infill survey. High potassium is plotted as red , high thorium is plotted as green and high uranium is plotted as blue. The image has been cropped to only display higher values.

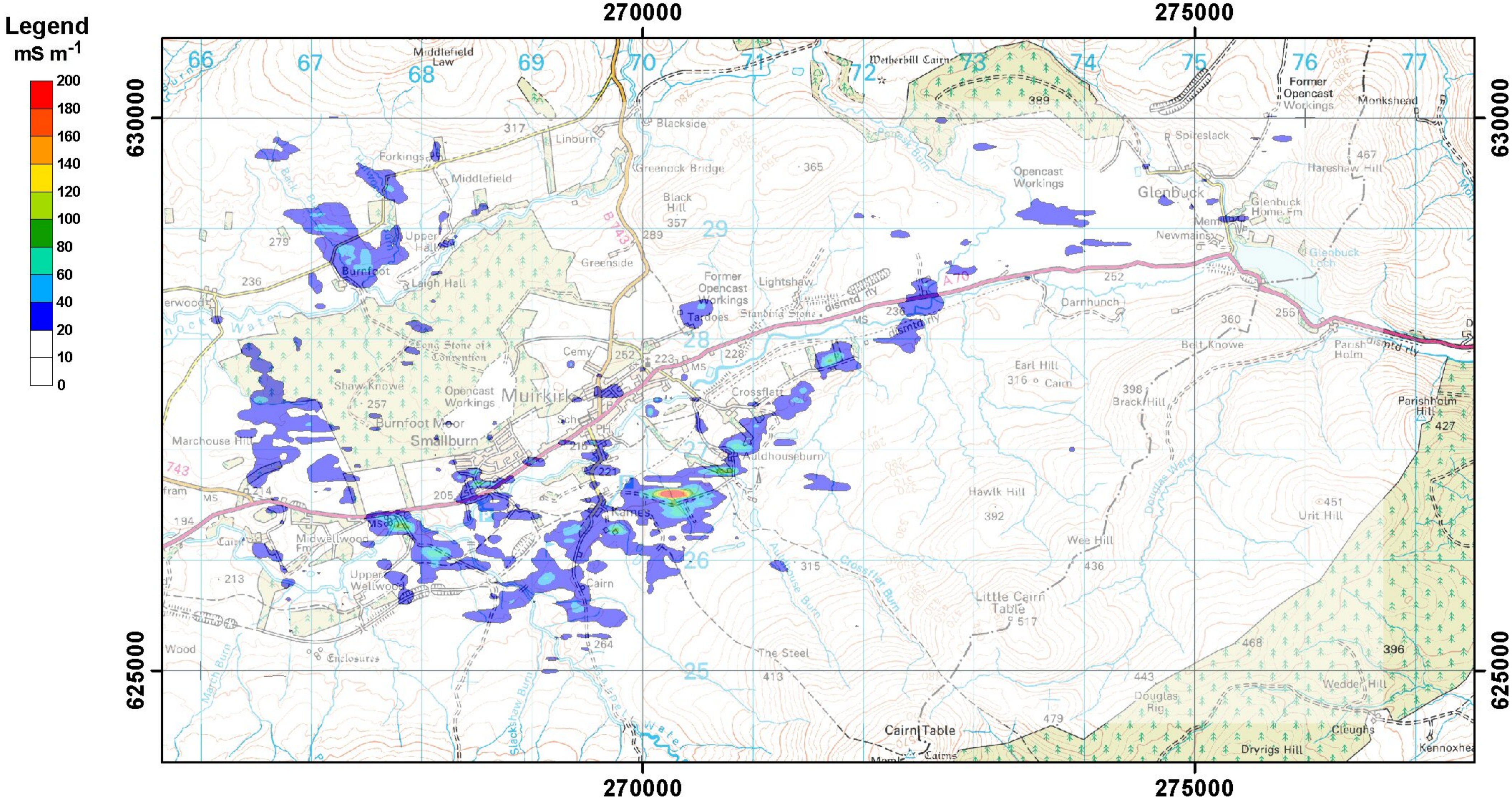


Figure 25. High frequency EM conductivity data from the Muirkirk infill survey, masked to remove low values.

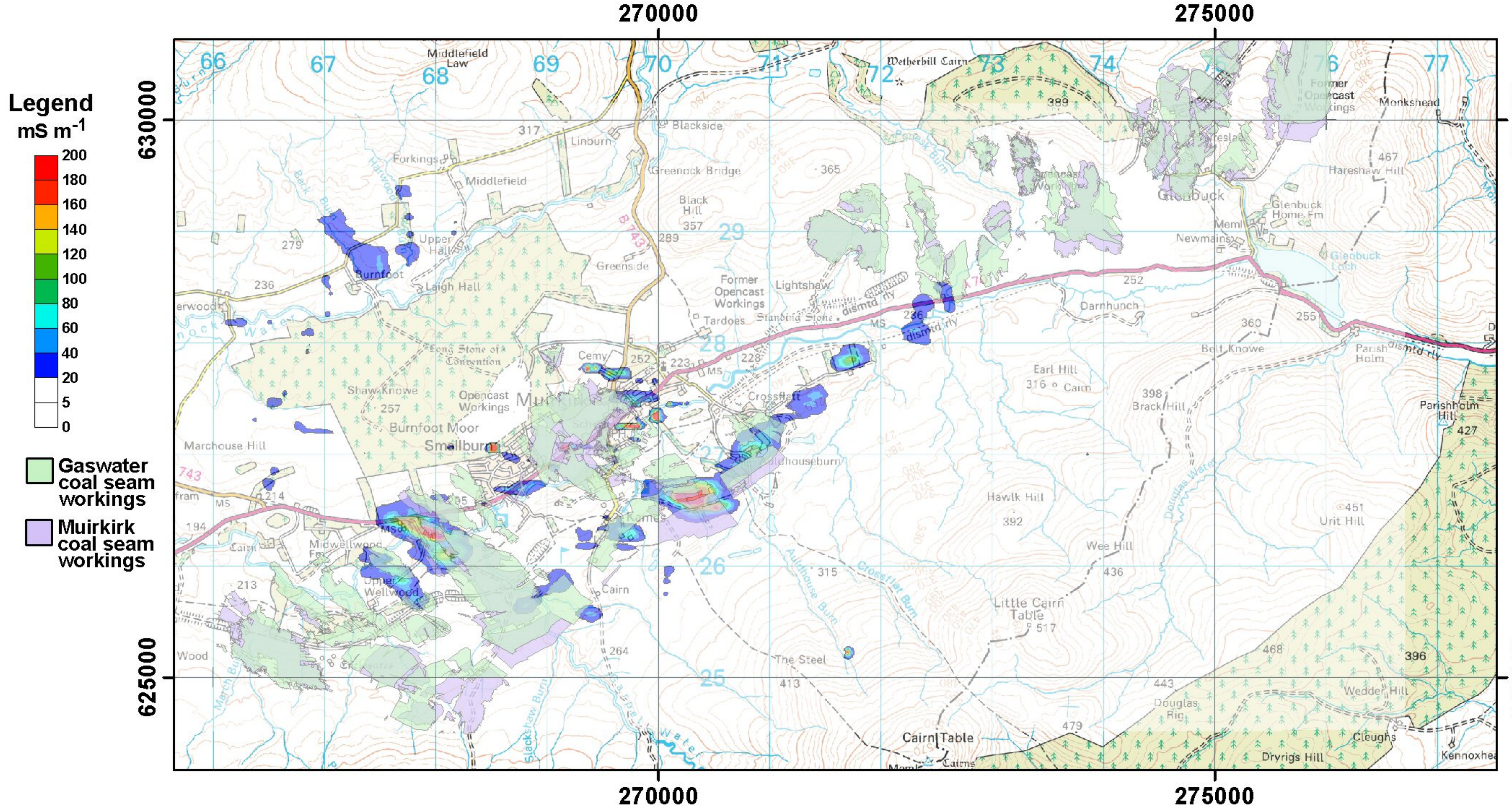


Figure 26. Low frequency EM conductivity data from the Muirkirk infill survey, masked to remove low values. The extent, of known workings in the Gaswater coal seam are shown as light green polygons and the Muirkirk coal seam as purple polygons.

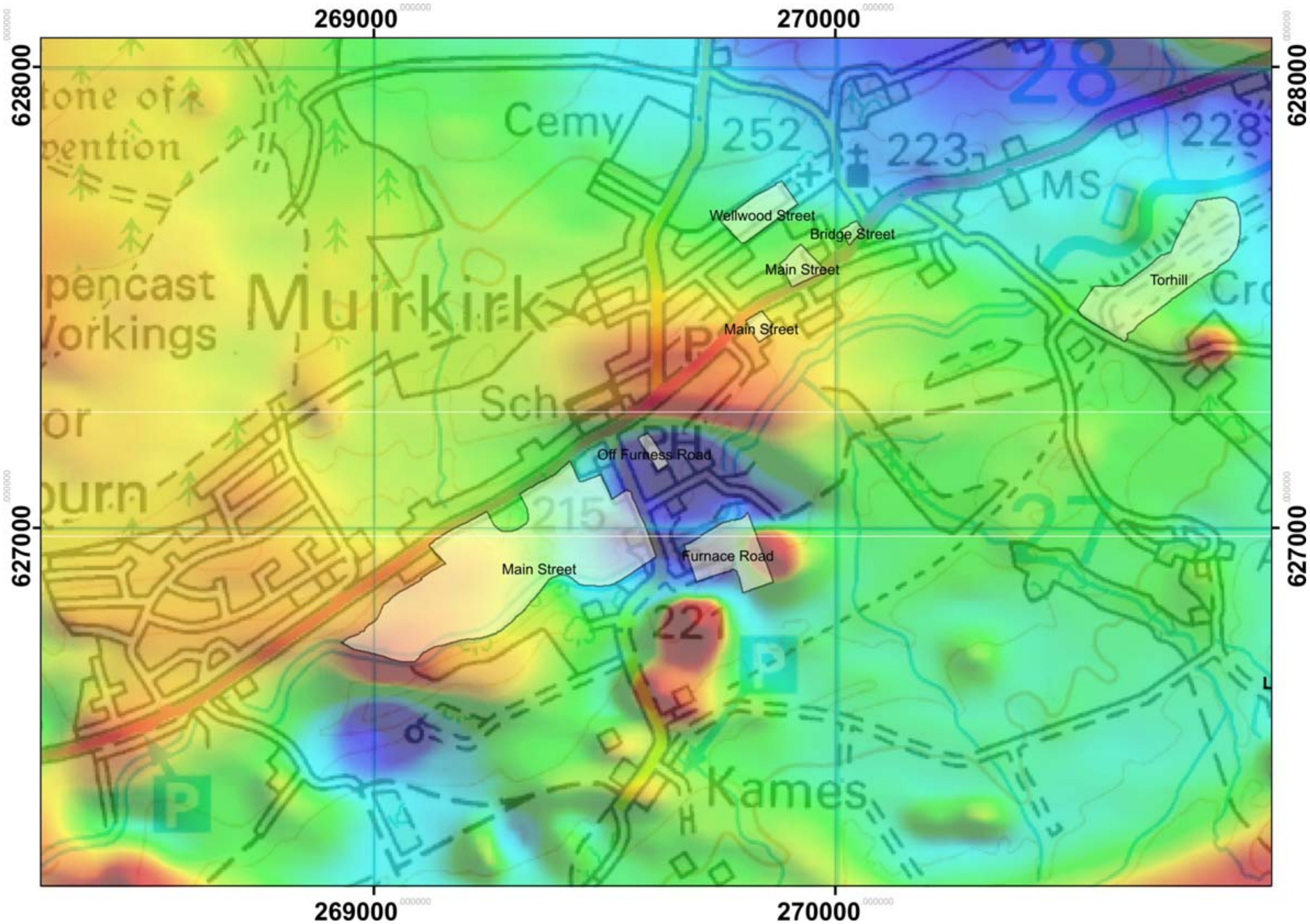


Figure 27. Sites designated as ‘Vacant and Derelict Land’ within the Muirkirk infill survey area overlaid on the magnetic survey data (see Figure 22b for colour scale).