Airborne geophysics : a novel approach to assist hydrogeological investigations at groundwater dependent wetlands

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Abstract: This paper provides an assessment of existing airborne baseline geophysical data in relation to the hydrogeological characterisation of protected groundwater dependant terrestrial ecosystems (wetlands) found on Anglesey, Wales. The attenuation of the radiometric data identifies the main areas of water saturation in the very near surface. The radiometric data have the potential to identify additional areas where similar degrees of saturation exist. The data may therefore be used to help define extensions to existing site boundaries and to provide information in the assessment of new wetland areas. The radiometric data also show regional scale transition from the Carboniferous Limestone in the east, important for water supply to the wetlands, to older more impermeable strata to the west. The conductivity data appear capable of mapping the lateral extent of clay accumulations, concealed below peat cover which can act as a confining layer to the bedrock aquifer. At the regional scale the data reveal the extent of a former Holocene lake system and the hydrogeological control of a Carboniferous limestone/sandstone contact. The data therefore provide a non-invasive spatially-continuous, characterisation of the sites, improving the understanding of their dynamic water balances and, potentially, guiding further ground assessments and invasive investigations.

Wetlands, areas of land whose soil is either permanently or seasonally saturated, are considered the most biologically diverse of all ecosystems. Water supply to wetlands can be complex. Many sites are predominantly fed by surface water; however the following examples are dominated by inflow of groundwater from the underlying aquifers. This has implications for the type of habitat that the wetland supports, for understanding the groundwater catchment and ultimately managing the water quantity and quality that supplies the wetland. In many countries wetlands are protected by International (e.g. Ramsar) and local (e.g. SSSI, Sites of Special Scientific Interest) conventions and are the subject of Biodiversity Action Plans. The Water Framework Directive (WFD) also requires these sites to be in good condition. Knowledge of the hydrogeology of wetlands provides a key element in understanding the dynamic water balances that underpin successful restoration, management and future conservation.

A number of protected Ramsar wetland sites (alkaline and calcareous fens) are found in NE Anglesey (Ynys Môn), Wales and they include Europe's largest wetland conservation project. The sites are dependent upon groundwater derived from the Carboniferous Limestone aquifer, and give rise to a specific biodiversity related to the waters calcareous quality. A recent (2009) high resolution, fixed wing airborne geophysical survey across Anglesey has provided a baseline set of magnetic, radiometric and electromagnetic measurements using a flight-line spacing of 200 m (Beamish and Schofield, 2010). The potential of these data to assist with developing the existing local scale and wider hydrogeological conceptual knowledge of wetland sites, and to help target site investigations are being assessed. The two main geophysical data sets considered here are radiometric (gamma ray spectroscopy) and electromagnetic (EM) measurements. The two data sets provide distinct but complementary information relating to the properties of the soils and near-surface lithologies associated with the wetland areas.

The study uses the attenuation (low emission behaviour) of the radiometric data together with the highest frequency EM data to investigate the geophysical responses associated with four Ramsar sites together with additional SSSIs across a large 12x12 km study area across NE Anglesey. In order to control our geophysical interpretations, existing regional scale information on the distributions of post glacial (Holocene) sediments is assembled alongside that of the bedrock geology. The interpretations also benefit from recent detailed hydrogeological and stratigraphical assessments, e.g. SWS (2010), undertaken as part of ongoing wetland conservation projects.

The airborne survey

Regional airborne geophysical surveys in mainland Britain have been previously described by Beamish & Young (2009) and Beamish & White (2012) and on Anglesey by Beamish & White (2010) and Beamish & Schofield (2010). The survey of Anglesey was flown using N-S lines at 200 m separations and at a nominal elevation of 56 m. The Anglesey survey area, shown in Figure 1, is a polygon covering 1198 km^2. The survey was carried out between the 12'th and 18'th June 2009. According to monthly rainfall data on Anglesey both May and June 2009 were unexceptional in terms of rainfall. May provided 61.7 mm compared with a decade May-average of 61.05 mm. June provided 55.0 mm compared with a decade average of 54.85 mm. The context of groundwater dependent wetlands should also be noted.

The data delivered include magnetic, radiometric (gamma ray) and active electromagnetic (electrical conductivity) measurements. Here we use the results obtained from the radiometric and conductivity measurements to assess the geophysical responses within the 12 x 12 km rectangular area of NE Anglesey shown in Figure 1. Along line sampling of the radiometric data is ~60 m (1 Hz sampling) and about 15 m (4 Hz sampling) for the conductivity data. In contrast to ground geophysical measurements, the airborne data constitute large volume assessments of the subsurface.

The ground area or footprint from which most of the contribution of radioactivity to each 1 Hz measurement was assessed by Pitkin and Duval (1980) and the modelling methods used in the calculation are discussed by Billings and Hovgaard (1999). For a stationary measurement, at a height of 60 m, 90% of the airborne response will be provided across a circle of radius 160 to 180 m (Kock and Samuelsson, 2011). In practice, for a moving measurement, the footprint will be elliptical and the 90% contribution area would cover about 109,000 m^2 (Billings and Hovgaard, 1999). Within that ellipse, the greatest contribution will come from directly beneath the aircraft and will fall off rapidly with lateral distance from the flight line.

The volume (i.e. both laterally and vertically) of the subsurface involved in each electromagnetic (EM) measurement is quite complex since it depends on frequency, altitude and the conductivity of the subsurface. Beamish (2004) describes the volumetric footprints (skin-depths) of the airborne system considered here. Each measurement may typically be associated across a principal area of sensitivity of less than 100 x 100 m over the ground surface. Apparent conductivity estimates are obtained by simple modelling of the EM field components at each of 4 measured frequencies (0.9 to 25 kHz). The frequency characteristics of these data, in terms of depth of penetration and field-of-view, have been recently described by Beamish & White (2012). The highest frequency (25 kHz) provides the shallowest depth of investigation and these data are used here to examine the near-surface responses of wetland areas.

The 256-channel gamma spectrometry covers the energy range from 0.3-3 MeV. A standard set of corrections are applied to the data including removing aircraft, cosmic and radon background; application of stripping corrections derived from calibration data and application of height attenuation corrections. These are based on protocols described in IAEA (2003). The fully corrected count rate data are used to estimate the concentrations in the ground of each of the three radioelements, potassium (K), uranium (U) and thorium (Th). Total count information is obtained across the full energy spectrum which, being a spectral summation, offers enhanced signal/noise when examining low amplitude behaviour.

The attenuation of radiometric data, in relation to soils and bedrock across the survey area is primarily studied here. The attenuation of radiometric signal due to water or soil moisture is well-established (Carroll, 1981, 1987). According to existing and more recent work on radiometric attenuation in UK soils (Beamish, 2013), attenuation levels are largely governed by the near-surface water content of the soil profile with density and porosity acting as secondary variables. This is particularly the case for low density, high porosity organic-rich soils, such as peat.

The depth sensitivities of the radiometric and conductivity data used here are quite distinct. In the majority of non-organic soils, 90% of the radiometric signal is obtained from the upper 40 to 50 cm of the soil profile. In peat the 90% signal threshold may vary between 60 cm (when wet) and several meters (when dry). A more detailed analysis, involving density and porosity, is given by Beamish (2013). Generally for soils exceeding ~0.5 m in thickness, soil thickness does not play a significant role in the degree of radiometric attenuation due to the near-surface water content. By way of contrast the high frequency conductivity data are largely insensitive to the properties of the at- and near surface material. As is noted later, the data studied here amalgamate the conductivity distribution from surface to depths of ~ 8m (typically).

Study area

The Anglesey Fens (Special Area of Conservation or SAC) represent one of the most important wetland areas in Europe. In Anglesey they comprise of Cors Erddreiniog (main study area), Cors Goch, Cors y Farl and Cors Bodeilio SACs, there are also other SSSI wetlands located within the study area such as Gwenfro and Rhos y Gad (Fig. 3a). The wetlands are all, to varying degrees, dependent upon the quality and quantity of groundwater input, to maintain their hydrological functioning and support the specialist plant assemblages. Calcareous and alkaline fens are key features of these wetlands which depend upon groundwater input, mainly from the Carboniferous Limestone which dominates the study area. It is due to this reliance on groundwater that they are referred to as ‘Groundwater Dependent Terrestrial Ecosystems’ (GWDTE).

The European Water Framework Directive (WFD) requires member states to ensure that designated sites (SACs) are in favourable condition by 2015. Where groundwater input (often quality) is identified as causing unfavourable status the competent authorities must undertake investigations and put into effect actions to reduce the causes of unfavourable status. To date many WFD investigations have relied on traditional ecohydrogeological techniques to characterise wetland sites. This is the first known attempt in Wales and the UK to characterise wetlands with the use of airborne geophysical techniques.

A large scale hydrogeological conceptual model (Fig. 2) shows the location of the Anglesey Fens SAC and other SSSI wetlands in the study area. The Carboniferous Limestone forms an asymmetrical syncline and is fault bounded to the south by the Berw Fault. The Lligwy Sandstone which forms the base of the Carboniferous sequence is associated with springs and diffuse groundwater discharge to the east of Cors Erdderiniog, this contact is discussed below. Groundwater flow from the Carboniferous aquifer discharges to the wetlands diffusely and via springs within the sites and on the margins of the sites. The groundwater brings carbonate rich waters essential to support the calcareous and alkaline fens for which they are designated as SACs.

The 12 x 12 km study area (Fig. 1) is shown as a 3D perspective view using an accurate DTM and an orthographic arial photograph in Figure 3a. The locations of 4 Ramsar sites (Cors Erddreiniog, Cors Goch, Cors y Farl and Cors Bodelio) and additional SSSIs (largely unlabelled apart from the conjoined Gwenfro and Rhos y Gad sites, GR) are identified with polygons across the landscape. An inner rectangle (6 x 5 km) identifies a further area of more detailed study at the 2 northern sites, Cors Erddreiniog and Cors Goch. The area is mainly rural with the largest conurbation being the town of Llangefni identified in Figure 3a.

Soils and superficials

The main soil units across the area are summarised in Table 1 and are shown in Figure 3b. The soil mapping used is taken from a 1:50k scale database (NSRI, 2008). The main soil unit on Anglesey and across the study area is the East Keswick unit which is described as a medium loamy drift with silaceous stones (Table 1). The soils are described as loamy and sandy and are freely draining. Of particular relevance to the geophysical radiometric data are two areas of humified peat, which are associated with Cors Erddreiniog and Cors Bodelio. The largest area of standing water is the Cefni Reservoir (CR) formed by dam construction during the 1940’s.

Table 1. *Main soil associations and descriptions across the study area.*

Soil Association	Description
East Keswick	Medium loamy drift with silaceous stones
Forest	Reddish medium silty drift with silaceous stones
Flint	Reddish medium loamy over clayey drift with silaceous stones
Peat (Adventurer)	Humified peat

Both geological mapping and stratigraphical site investigations at the wetland sites (e.g. SWS, 2010) indicate a pervasive boulder clay unit overlying bedrock across the majority of the survey area. This unit is believed to have been deposited during the last glaciation event (Devensian). The boulder clay has been described as diamicton (a poorly sorted gravel in a fine grained matrix) by Wheeler et al. (2009) and as glacial till in WMC (2008). In the BGS 1:50k mapping (BGS, DIGIMAP, v6.20, 2010) of the superficial deposits, alluvial deposits are recorded across all four of the Ramsar sites and in many of the topographic lows across the area. Tidal flat deposits are associated with the coastal environs of Red Wharf Bay (Fig. 3a).

Bedrock

The solid bedrock across the area (Fig. 3c and Table 2) provides a further framework for understanding the nature of the groundwater dependent wetlands of this study. A significant proportion of bedrock in the NW and SE of the area is Neoproterozoic including the schists of the Monian Supergroup and rocks of the Mona Complex (Gwana Group rocks of Pre-Cambrian age). The Mona Complex is overlain by Ordovician rocks defined by the Ogwen Group. These sequences are unconformably overlain by the Devonian Lower Old Red Sandstone deposits (LORS). The LORS is then unconformably overlain by the central Carboniferous Limestone unit (CL). Towards the north west, the Carboniferous unit includes a basal sandstone unit (the Lligwy Sandstone) shown in grey and bounded by solid lines in Figure 3c. Three further Carboniferous sandstone areas are also similarly identified. One of these areas coincides with the Cors Goch Ramsar site.

Table 2. *Bedrock lexicon codes and rock descriptions across the study area.*

Lexicon code	Lexicon description	Rock Description	Period
CL	Carboniferous Limestone	Limestone and basal Lligwy Sandstone	Carboniferous
LORS	Lower Old Red Sandstone	Sandstone and (Subequal/subordinate) argillaceous rocks, interbedded	Devonian
OGW	Ogwen Group	Argillaceous Rocks, undifferentiated	Ordovician
N	Monian Supergroup	Schist	Neoproterozoic
NGW	Gwana Group	Schist	Neoproterozoic
NK	Skerries Group	Tuff	Neoproterozoic
NMG	Mona Gneiss	Gneiss	Neoproterozoic
UIIN	Unnamed igneous Intrusion	--	Unknown

Much of the detailed understanding of the hydrogeology of the area has been derived from a series of studies carried out at the Cors Erddreiniog wetland site that forms Europe's largest conservation project. Since this information provides a degree of control in relation to the interpretation of the geophysical information, a 6 x 5 km (inner rectangle, Fig. 3) was chosen as a detailed study area. This initial study area includes the Cors Erddreiniog and Cors Goch wetland sites.

Cors Erddreiniog

Cors Erddreiniog is a complex wetland and is designated as an SSSI. It is the principal site within this study however a number of wetlands including Cors Goch, Cors y Farl and Cors Bodeilio which together with Cors Erddeiniog form part of the Anglesey Fens Special Area of Conservation (SAC) and the Anglesey and Llyn Fens Ramsar site.

Cors Erddreiniog is a wetland of international importance and has three key Annex 1 Habitats;

- 3140 Hard oligo-mesotrophic waters with benthic vegetation of *Chara spp.*
- 7210 Calcareous fens with *Cladium mariscus* and species of the *Caricion davallianae*
- 7230 Alkaline fens

A small island portion exists to the south east of the main site (Fig. 3a). Little information is available on this island portion, although the wetland conditions, as per the main site, are thought to be due to groundwater derived from the Carboniferous Limestone (CL) to the east.

The Cors Goch wetland to the east is a nationally important valley mire developed in a hollow in Carboniferous Limestone. The geology is complex and interstratified with the limestone are beds of a coarse pebbly sandstone as indicated in Figure 3c. The fen is almost divided by a rock promontory into an east and a west basin. The east basin is described as very wet (Gillman and Newson, 1982). The western basin is somewhat drier, but contains similar fen communities, and a small lake (Llyn Cadarn) discussed later.

Gillman and Newson (1982) carried out an extensive stratigraphical investigation at Cors Erddreiniog to improve the understanding of the unconsolidated overburden. The study involved the hand augering of three transect lines. Augering depths range from 1 to 9 m across the site. The historic data have now been incorporated with more recent borehole logs to define detailed stratigraphical cross-sections across the main site (SWS, 2010).

During the Devensian large parts of Anglesey were variably covered in diamicton clay, often moulded into drumlins (Hart, 1995; Phillips et al., 2010). Gillman & Newson (1982) report a boulder clay unit overlying bedrock 'throughout most of the site', but its lithology is not described in any detail. According to Rigare (2010) it is considered likely that boulder clay was intercepted along the eastern boundary of the site as the clay contained some coarse-grained material.

At the start of the Holocene (~10 ka BP) lakes formed locally in glacially-scoured depressions (basins), leading to the deposition of lacustrine clay. Gillman & Newson (1982) suggest that the lake Llyn yr Wyth Eidion (LE, Fig. 4) is a remnant of a larger calcareous lake extending into the study area. They also differentiate between two lacustrine deposits. At the base of the profile, presumably on a foundation of boulder clay, is a layer up to 0.5 m thick of mauve-grey plastic clay containing no macroscopic organic remains. It contains 10 to 25% of calcium carbonate, from early-Holocene surface runoff with a carbonate-rich suspended load. Above this is a thicker (up to 3 m) deposit of steel-grey clay, more or less silty and containing significant quantities of moss remains. This has a much lower carbonate content of around 1 to 5%, and is thought to have been produced when groundwater carrying dissolved carbonate but no suspended material became the dominant water supply. Grey clay/silt (lacustrine) overlies the bedrock deposits to the west of the site. Marl is then encountered beneath the site as a white to grey silt, with frequent shell fragments. Littoral and other marl deposition mechanisms are discussed by SWS (2010). The topmost deposit of peat is derived from fen vegetation and can be up to 5 m thick in places.

The thicknesses of the individual units as defined in the control transects are highly variable due to a number of bedrock ridges and troughs that cross the site. The upper peat and lower clay units present the main thicknesses above bedrock (located from 0 to 8 m below surface) with a typical peat thickness of ~ 2m and similar for the deeper clay above bedrock. A thicker unit of marl is observed in the vicinity of Llyn yr Wyth Eidion which is reported to be up to 7m deep (Wheeler et al., 2009).

Results

6 x 5 km area

Radiometric data

The geophysical data across the inner 6 x 5 km survey area were gridded using a natural neighbour algorithm and a cell size of 50 m. A standard method of presenting the radiometric data uses a ternary plot (a 3-way RGB colour stretch) that summaries the K, Th and U radioelement contributions. Figure 4a shows the ternary image across the area with the Ramsar and SSSI sites and Carboniferous sandstone/limestone boundaries discussed previously. The colour zones tending to white denote a relative high in all 3 radioelements and the zones tending to black denote low emissions in all 3 radioelements. The main bedrock controlled transition occurs at the western edge of the Carboniferous unit which is clearly associated with enhanced U. To the west of this unit, a mixed K-Th (approximately yellow) response is observed. Slight movements to areas of K or Th enrichment are observed but these are towards the resolution limits of the data. The largest of the black attenuation zones shows a strong association with the peat areas associated with Cors Erddreiniog and its small island section in the SE. Attenuation zones are also associated with the non-peat Cors Goch wetland area (both east and west basins) and with the adjacent SSSI site. The attenuation zone extends NE beyond the defined limits of the Cors Goch site indicating similar ground conditions exist outside the designated site. The white contour shown in Fig 4a is discussed below.

In order to quantify the attenuation information contained in the ternary image, the Total Count (TC) radiometric data can be further used to identify the low emission zones. Figure 4b shows contours of the lowest value TC data (< 1000 cps) using a 5 range contour interval. The lowest interval (0 to 200 cps) is only observed as a closed contour in the vicinity of Llyn yr Wyth Eidion. The lake is sufficiently small that the airborne footprint will sample both the water body and surrounding soils. Despite this limitation, the data provide a form of control on the degree of attenuation and implied soil water saturations across the area. Using a low value threshold of 1000 cps, as in Figure 4b, provides an assessment of water saturation levels within Cors

Erdderiniog and Cors Goch. The simple threshold mapping procedure can be extended to higher values (such as TC=1400 cps shown in Fig. 4a) to identify further areas of localised attenuation.

The low count behaviour of the radiometric data has been ascribed to increasing levels of attenuation in areas of higher soil water content. It is observed that the main area of standing water within the test area (Llyn yr Wyth Eidion) is associated with the lowest observed radiometric response. Ideally the airborne data should be calibrated against continuous ground-based measures of water content. Such measurements are typically invasive and would, in practice, be difficult to assimilate at the spatial scale and field-of-view of the airborne measurements. Such calibrations remain a longer-term goal of our studies. Using the information in Figure 3b, we note that the main areas of secondary areas of attenuation (e.g. TC < 400 counts) may be connected to the drainage patterns across the site.

Drainage conditions at the site and a broader conceptual hydrogeological understanding of the site are discussed in SWS (2010). Internal drainage directions at the site are described as tortuous since the entire site is dissected by a complex series of drains constructed in the nineteenth and twentieth century. Surface water enters the site at the south east margin via an un-named stream. Flow from the stream has been diverted northwards into the site, by means of an artificial drain, towards the lake (see Fig. 5) and this may then be associated with the southerly directed lip of low values extending from the minimum observed across the lake. Drainage from the lake flows to the west (typically WNW, see Fig. 5) where it joins the southerly flowing main SW drain to form the headwaters of the Afon Cefni which feeds the Cefni reservoir to the SW (Fig. 2). The main area of secondary attenuation observed (Fig. 4b) appears consistent with the broad WNW drainage across the central area of the site.

It is also worth noting the mapped area of peat associated with the Cors Erddreiniog site (Fig. 3b). The radiometric ternary response and the low value TC contours show a high degree of correspondence with this area of mapped peat. The high water retention of peat is well established with measured soil moistures routinely exceeding 85% (e.g. Lewis et al., 2011). In contrast a lower, but still significant, attenuation response is observed across the Cors Goch wetland which is mapped as having a mineral soil cover (East Keswick) above Carboniferous sandstone (Fig. 3b). The radiometric attenuation results, by implication, indicate that the soils across the wetland area have a high humic/organic content.

Conductivity data

The apparent conductivity values at the highest frequency (25 kHz) are shown as a continuous colour image in Figure 4c. The data display sensitivity to both near surface influences and bedrock materials. The lowest conductivities (e.g. < 1 mS/m) are largely associated with the older Neoproterozoic rocks in the west. A zone of elevated conductivities (> 8 mS/m) is associated with, but not confined to, the NNE trend of the basal Carboniferous Lligwy sandstone. Additional localised anomalies exceed 20 mS/m with the highest value (~35 mS/m) centered on Llyn yr Wyth Eidion. A second, less conductive anomaly is associated with Llyn Cadarn in the western basin of Cors Goch (both lakes are arrowed in Fig. 4d). A simple thresholding of these data (to values exceeding 12.5 mS/m) allows the most conductive zones to be identified as shown in Fig. 4d. There is an apparent association with both elevated conductivities and localised high conductivities (closed contour bull's-eyes) with the N-S trending Carboniferous sandstone/limestone contact.

The 4 frequency EM baseline survey data have a limited vertical resolution of near-surface materials in the upper ~8 m. These are, however, of direct interest to site investigations of groundwater dependent wetlands. An assessment into their spatial and frequency characteristics was carried out using the conductive anomaly associated with Llyn yr Wyth Eidion. The precise, along-line, profile of measurements crossing close to the centre of the lake is shown in Figure 5. The 1250 m length profile has been rotated from a N-S to an E-W orientation for convenience. The 4 frequency apparent conductivity data are shown above the profile location. It is evident that the 2 highest frequencies (25 and 12 kHz) display a peaked response centred on the lake with the highest frequency showing the largest response. The two lower frequency responses show only a very marginal response (i.e. possibly at 3 kHz). The type behaviour observed is indicative of a thin, near surface conductive zone.

The highest frequency data is incapable of resolving any 'thin-bed' characteristics in the upper 8 m. The observed response essentially responds to the vertically integrated conductance of the near-surface materials. In order to permit an interpretation of the behaviour observed, forward modelling of a concealed conductive unit (e.g. representing a clay unit) was carried out. The upper surface of the conductive unit was placed at a fixed depth of 5 m in background material (above and below the unit) having a conductivity of 5 mS/m. The thickness of the conductive unit was then allowed to increase from zero (not present) to 10 m. The conductivity of the unit was also studied and here we compare the results for a unit with conductivities of 25 and 50 mS/m. The sensitivity of apparent conductivity to clay thickness calculated at 25 and 3 kHz is shown in Figure 6. In simple terms, if a concealed zone of 3 m thick clay were to exist across the survey area it would not be detectable from background (no clay), except (marginally) at 25 kHz. The results indicate that a relatively conducting (~50 mS/m) material is required to generate a 25 kHz response exceeding 30 mS/m as is observed across the lake. Although the analysis is highly simplified, it does indicate that the 25 kHz data is capable of responding to and detecting increasing thicknesses of near surface conductive unit(s). When the conductivity of the material is spatially uniform the amplitude of apparent conductivity would relate, in a quasi-linear fashion, to thickness (e.g. Fig. 6).

12 x 12 km area

Given the control provided by the detailed studies across Cors Erddreiniog and Cors Goch within the inner test area, the analysis developed above was applied to the main 12 x 12 km area centred on the Carboniferous formation. This area, summarised in Figure 3, contains two further Ramsar sites (Cors y Farl and Cors Bodelio) and further control is provided by a large water body (the Cefni reservoir) and the physical boundary contrast provided by the coastal zone bounding the area in the NE.

Radiometric data

The low value TC contours, extending to a maximum of 1400 cps are shown in Figure 7a. The heavy black contours display the limits of the Carboniferous formation. The data set has been cut to a low tide coastal model and the data across Red Wharf Bay in the east will have been influenced by tidal conditions. The attenuation conditions previously observed at the two northern Ramsar sites are found to be repeated at the two southern sites (Cors y Farl and Cors Bodelio). Additionally two low value (TC in the range 800 to 1400 cps) areas are observed within the confines of two central SSSI wetland sites (labelled GR). In the north of the area, two further low amplitude zones are observed. The western most zone is associated with an SSSI site and is located within a topographic low (Fig. 2a) following the trend of the Carboniferous sandstone. An attenuation zone to east is associated with an elevated hillside. A series of attenuation zones are observed in the SE on the schists of the Monian Supergroup (Fig. 3c) and occur in association with water courses and marsh features. Finally the control provided by the Cefni reservoir (CR) generates a well defined set of low values with minimum values of around zero counts in the western area. According to Beamish (2012) a 1 m water column will attenuate gamma-ray flux by over 99% which reduces to 90% for a 40 cm column. The response characteristics, while subject to the broad field of view of the airborne measurements, appear consistent with the general outline of the water feature with the western and eastern areas separated by an embankment carrying the former Anglesey Central Railway.

Conductivity data

The high value (> 10 mS/m) apparent conductivity contours at the highest frequency are shown in Figure 7c. The data set has been cut to a high tide coastal model to better define zones of saline intrusion which are observed towards the southern margins of Red Wharf Bay. The more conductive of these features extends over 1 km inland and is associated with the course of the Afon Nodwydd.

The conductivity range used in Figure 7b extends the low value behaviour from the previous level of 12.5 mS/m (Fig. 3d) and introduces some small scale, cultural artefacts. As previously the data identify multiple high value centres across the main Cors Erddreiniog site and a single isolated centre associated with the western lake (Llyn Cadarn) of the Cors Goch wetland. The lowest contour interval now extends NNE from the main Cors Erddreiniog site following the contact of the basal Carboniferous Lligwy sandstone. Following a break in continuity, a further large area of enhanced conductivity is again associated with the sandstone in the north. In an analogous manner to the radiometric data, enhanced conductivities are also observed in association with the two southern-most sites (Cors y Farl and Cors Bodelio). The Cors Bodelio wetland occurs along the contact boundary of the Carboniferous limestone and a number of other conductive features also follow the trend of the contact. Using a lower threshold of 8 mS/m indicates the isolated features are almost continuous along the trend. In the NW, various conductive zones are associated with, and confined to, the Ordovician argillaceous formation (OGW) whose boundary in the SE is shown by the dotted line in Figure 7b.

Three localised centres of high conductivity are found in clear association with the assumed resistive water body of the Cefni reservoir (CR). Although the western area is entirely conductive the most conductive zones are observed at the margins of the elongate axis. A more localised, less conductive zone also appears at the northern-most margin.

Discussion

It is well established that the degree of attenuation of gamma-rays for a particular at-surface material (of given porosity and bulk density) is controlled by water content. Løvberg (1984) established expressions for the gamma ray attenuation from source material containing pore water. The expressions are based on the fact that water has 1.11 times as many electrons as most materials including soils (Grasty, 1997). The attenuation sensitivity of at-surface materials (of given porosity and bulk density) to water saturation can be studied using the formulation provided by Beamish (2012). The analysis applies to uniformly radioactive materials. Using 50% porosity materials (e.g. uncompacted soil, weathered bedrock) as a reference, the attenuation behaviour of materials having 4 values of density is shown in Figure 8. The four materials considered have densities of 0.1 gm/cm^3 (e.g. peat), 1.1 gm/cm^3 (e.g. a low density mineral soil), 1.6 gm/cm^3 (e.g. a higher density mineral soil) and 2.7 gm/cm^3 (e.g. a limestone). It is clear that a light organic-rich soil such as peat has very high gamma-ray sensitivity to water content particularly in the range from 0 to ~ 50% saturation. In order to fully control an interpretation of the airborne data we would require knowledge of the at-surface materials and properties across the study areas. We note that, apart from existing soil mapping, this information does not exist at an appropriate scale.

The attenuation behaviour of the ternary and Total Count information across two of the defined wetland areas was presented in detail in Figure 4a,b. It is evident that for TC values below 1000 cps (Fig. 4a) the spatial distribution of values is closely associated with the boundaries of the two wetland areas. Two contrasting soil types are mapped across these zones (Fig. 3b), so if this mapping is taken at face value, soil type is not wholly responsible for the attenuation observed. If the 1400 cps TC contour of Figure 4a is considered then only a small number of localised low value zones are identified. One of these zones lies on the sandstone/limestone contact and a second zone is associated with a defined SSSI area. Referring next to the peat area largely associated with the Cors Erddreinog wetland, then the distinct variations extending over a range of 1000 cps (Fig. 4b) could potentially be related to spatial variations in degree of water content in the upper ~50 cm. This is partially implied by the local minimum value (TC = 100 cps) associated with Llyn yr Wyth Eidon. The averaging effect of the field-of-view of the airborne measurement should be allowed for when considering information at the detailed level.

The TC low count information across the larger study area (Fig.7a) lends support to the comments made thus far. Significant low value zones appear in localised areas and are not associated with soil or bedrock type. All four wetland areas are closely associated with low count behaviour. Additional control is provided by the low value behaviour observed across the Cefni reservoir (where a localised zero count response is observed) and the tidal flats of Red Wharf bay. The attenuation responses observed appear to be consistent with an interpretation that identifies degree of water saturation with the attenuation level of the TC radiometric data.

As discussed previously the highest frequency apparent conductivity data is incapable of resolving any 'thin-bed' characteristics in the upper 8 m. The subsurface lithologies observed across the Cors Erddreiniog wetland site indicate that one, or more, generally thin conductive units exist beneath peat cover. The modelling undertaken suggests the highest frequency data will respond to the accumulated thickness of a thin, concealed conductive unit in the near-surface. The data cannot resolve or identify thin-layer lithologies that may contribute to the response and it is therefore referred to simply as a conductive (e.g. 50 mS/m) clay.

The high value conductivity information across the two northern-most wetland areas was presented in detail in Figure 4d. A series of localised high value zones (e.g. > 20 mS/m) are observed towards the eastern margins of the site along the sandstone/limestone contact. The largest of these is associated with Llyn yr Wyth Eidon and a similar, more localised response is observed in association with Llyn Cadarn. The interpretation of these features is that they represent the thickest accumulations of conductive clays associated with existing and former Holocene lakes as postulated by Gillman & Newson (1982). When the data across the wider study area are considered (Fig. 7b) it is clear that elevated conductivities and, by implication, thicker accumulations of conductive material show a strong association with the area of the Carboniferous sandstone/limestone contact. The conductive arcuate zone extending from Cors Erddreiniog is over 6 km in length (Fig. 7b) and coincides with an area of springs and groundwater discharge. The results therefore suggest that groundwater discharge has been the primary mechanism for Holocene lake formation and the subsequent generation of wetland areas.

Conclusion

The study conducted represents the first analysis of near-continuous geophysical measurements across an area containing several internationally important wetlands. Attenuation of the radiometric data is observed at all four of the wetland sites. Theory indicates it is the degree of water content in the near-surface (e.g. < 60 cm) soil profile that controls the degree of attenuation. Within the defined wetland areas, the data have the potential to be interpreted in terms of the different degrees of soil saturation across each site, subject to the averaging effect of the field-of-view of the airborne system. Given the clear association between radiometric attenuation responses and wetland site boundaries, the data have the potential to identify additional areas where similar degrees of saturation exist. The data may therefore be used to help define extensions to existing site boundaries and to provide pathfinder information in the assessment of new wetland areas.

The data respond to soil properties which may be broadly related to soil type. Thus peat areas, by virtue of their low density and high porosity, are highly sensitive to the degree of soil moisture. The attenuation data suggest that some of the soils, not currently mapped as peat, contain a high proportion of low density humic material. The data may therefore assist with soil reclassification.

The highest frequency conductivity data can be used to map increasing thicknesses of conductive material (assumed to be clay) below soil cover. A set of thicker depositional centres is observed across the study area showing a close association with Carboniferous sandstone and limestone contacts and diffuse groundwater discharge. It is suggested that the data reveal both the localisation (greatest thicknesses of lacustrine clays) and spatial extent of a large-scale Holocene lake landscape that has previously been postulated. Diffuse groundwater discharge appears to have controlled initial lake formation and the subsequent development of the large wetland areas. At the site scale, the hydrology at a groundwater dependent wetland is partially governed by water ingress through concealed low permeability basal clays. Since the conductivity data appear capable of identifying site locations with the thickest clays then, by implication, they should also identify those areas with the lowest basal flow rates.

As noted previously, Water Framework Directive wetland investigations have conventionally relied on traditional ecohydrogeological techniques of characterisation. Although limited in fine-scale resolution, the study indicates that airborne data provides continuous information of direct relevance to wetland characterisation. The geophysical data were acquired as part of a general environmental and resource survey across the whole of Anglesey and were not optimised in relation to the vertical and horizontal scales of the wetland zones. Such optimisation could be achieved by smaller-scale helicopter-borne surveys allowing finer-scale discrimination of the near-surface.

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Figure Captions

Figure 1. Location map of the Anglesey airborne geophysical survey area in NW Wales. The main 12 x 12 km study area in NE Anglesey is indicated.

Figure 2. Hydrogeological conceptual model of the eastern Anglesey Carboniferous Limestone, with reference to the Anglesey Fens SAC and additional SSSI wetlands.

Figure 3. Information across the 12 x 12 km large study area with the inner 6 x 5 km study area indicated. (a) Air photo overlaid on a DTM, perspective view looking due north. Four complex polygons in white with infill (labelled) identify 4 Ramsar sites. The remaining polygons are SSSI sites. Two of the SSSI sites, Gwenfro and Rhos y Gad are labelled GR. (b) Main soil units associated with the central Carboniferous bedrock across the area. CR=Cefni Reservoir. Soils Data © Cranfield University (NSRI) and for the Controller of HMSO (2012). (c) Bedrock units with codes identified in Table 2. Areas of Carboniferous sandstone are identified by heavy lines and infill.

Figure 4. Results assembled across the 6 x 5 km inner study area. Red polygons identify the 2 Ramsar wetland sites, Cors Erddreiniog in the west and Cors Goch in the east. Other SSSI sites are identified in purple. Carboniferous sandstone is identified by heavy black lines. Two lakes are identified as LE= Llyn Eidon, LC= Llyn Cadarn. (a) Ternary radiometric image. (b) Contours of lowest value Total Count (TC) radiometric data, extending to a high value limit of 1000 cps. (c) Continuous colour image of apparent conductivity at 25 kHz. (d) Contours of highest value apparent conductivity data at 25 kHz > 12.5 mS/m.

Figure 5. Four frequency apparent conductivity data observed along a single N-S flight line (a 1250 m portion) crossing Llyn Eidon (LE) in the east of the Cors Erddreiniog wetland site. The N-S profile has been rotated to a E-W orientation. The 1:10k map indicates some of the main drainage features (arrowed). AC25 refers to apparent conductivity at a frequency of 25 kHz, and likewise for frequencies of 12, 3 and 0.9 kHz.

Figure 6. Modelled apparent conductivity variations as a function of the thickness of a concealed conductive thin-layer (assumed to be clay) located at a depth of 5 m. The variation is shown at 2 frequencies (25 and 3 kHz) and for 2 conductivities of the clay unit.

Figure 7. Results assembled across the 12 x 12 km outer study area. Red polygons identify the 4 Ramsar wetland sites, Cors Erddreiniog (CE), Cors Goch (CG), Cors y Farl (CF) and Cors Bodelio (CB). Other SSSI sites are identified in purple, with 2 of the SSSI sites, Gwenfro and Rhos y Gad labelled GR. The extent of the Carboniferous limestone unit is identified by heavy black lines

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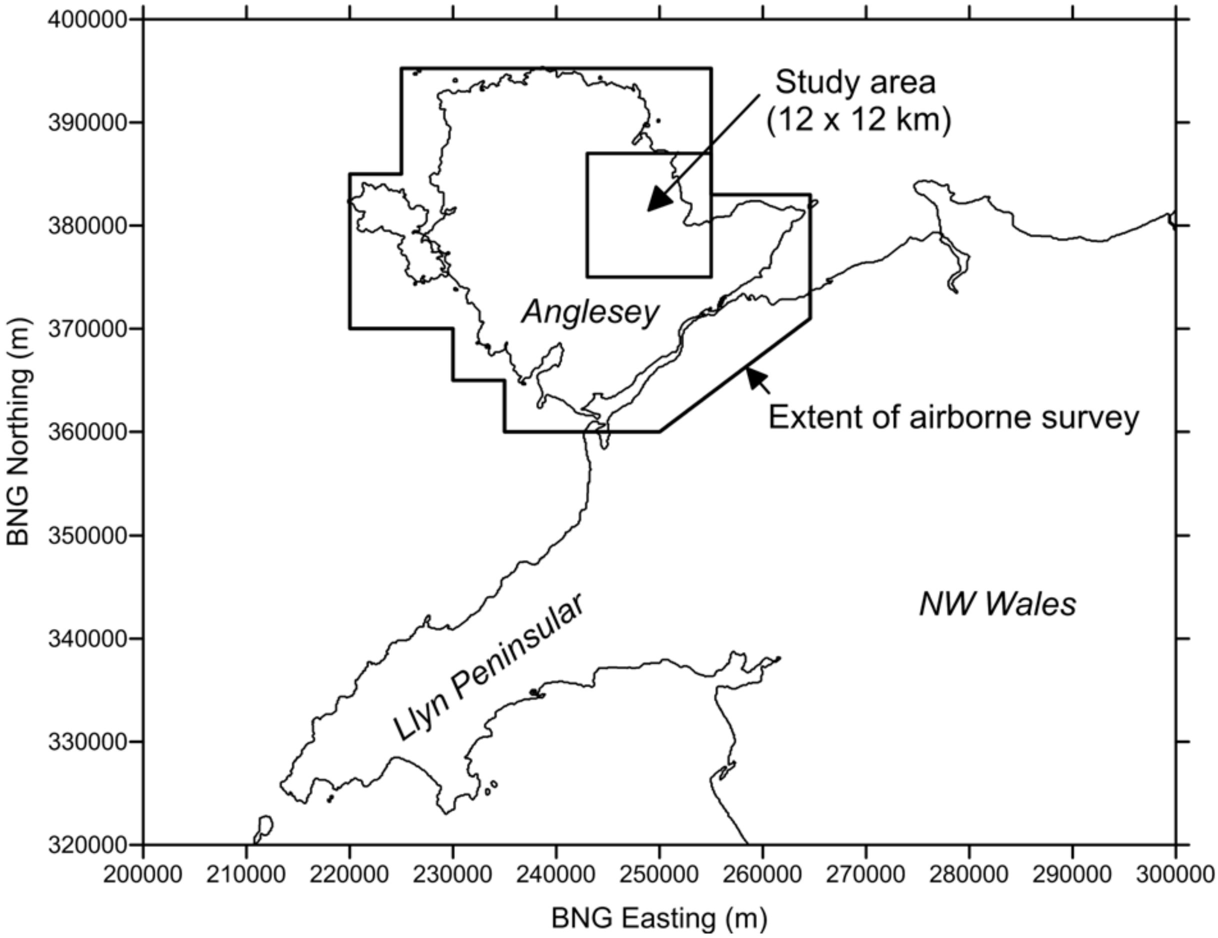
Figure 8. Theoretical radiometric attenuation behaviour of 4 soil/bedrock types with degree of saturation (soil moisture). The 4 soil/rock types all have 50% porosity with bulk densities as discussed in the text.



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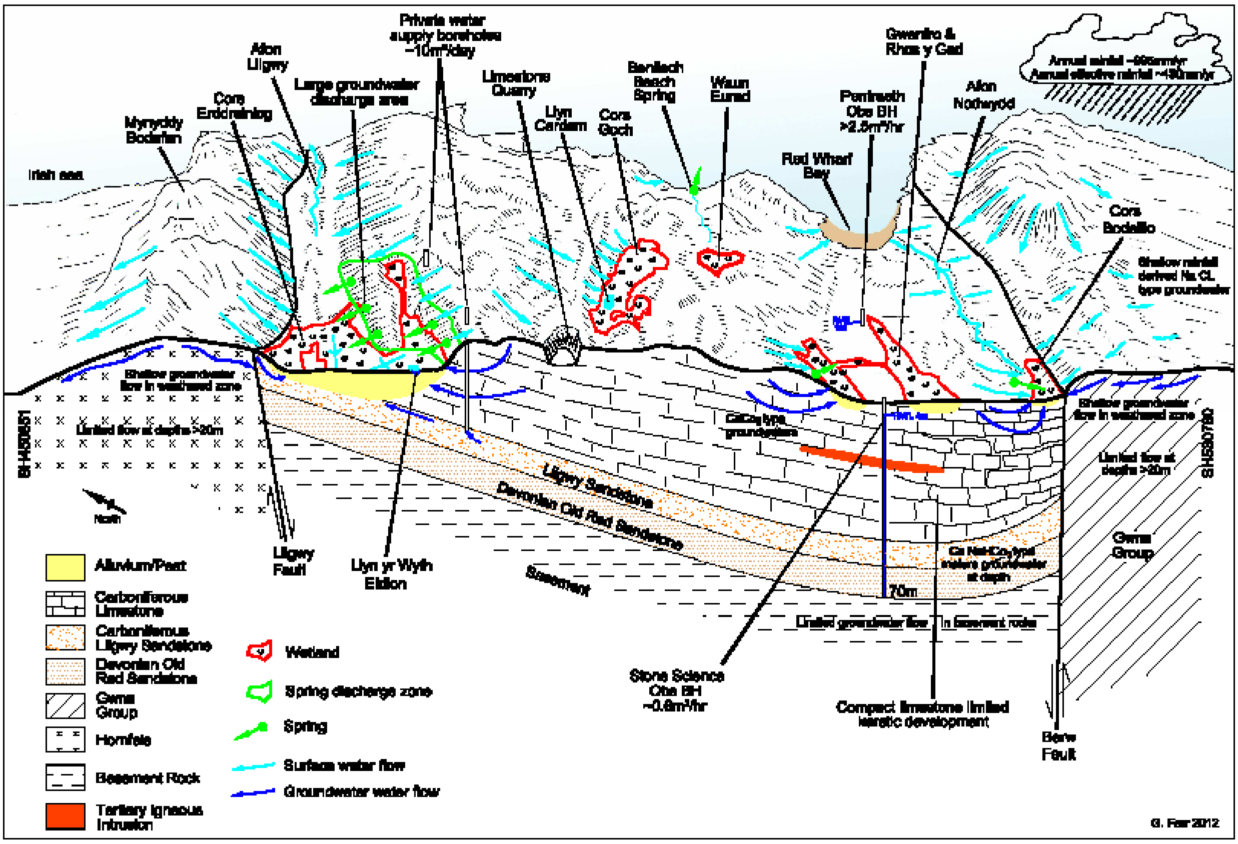

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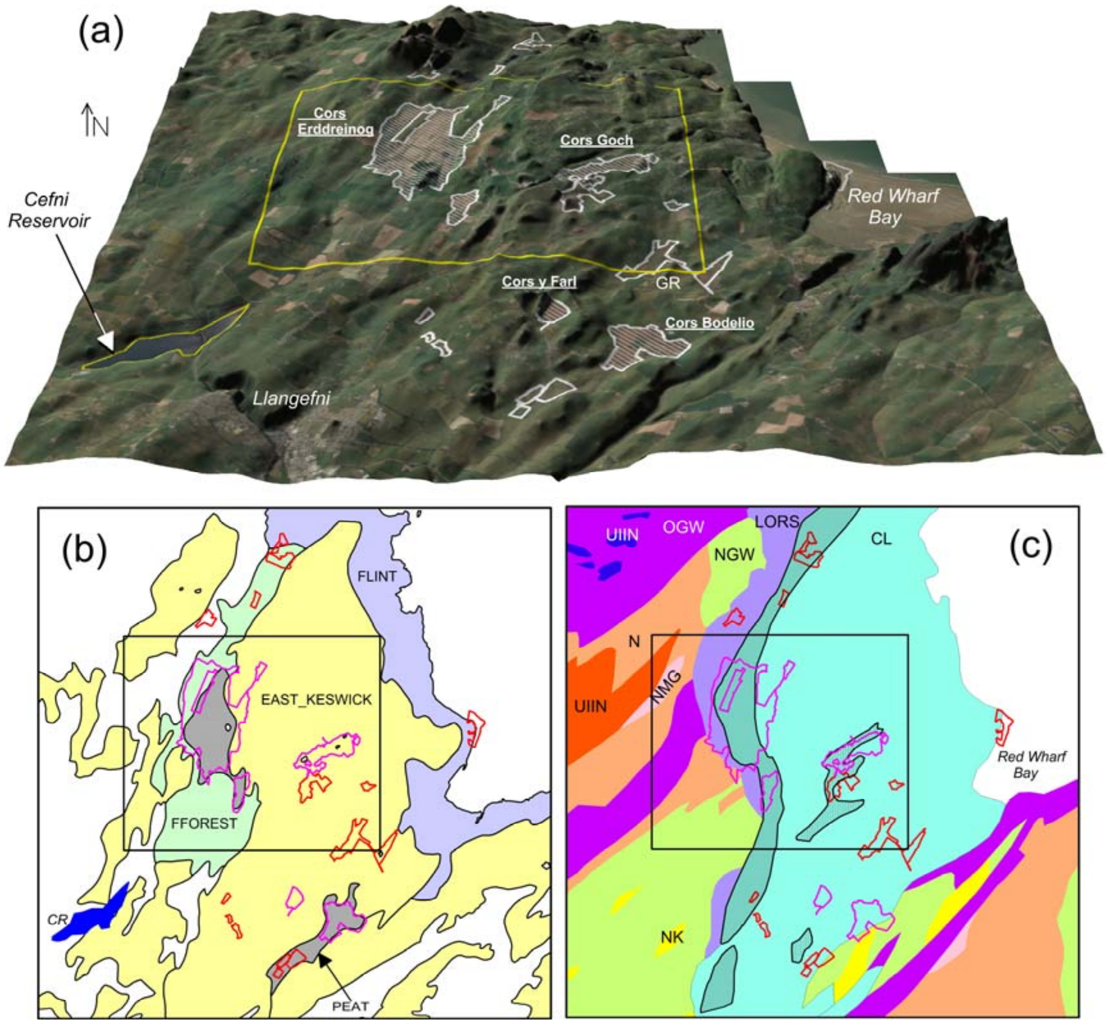

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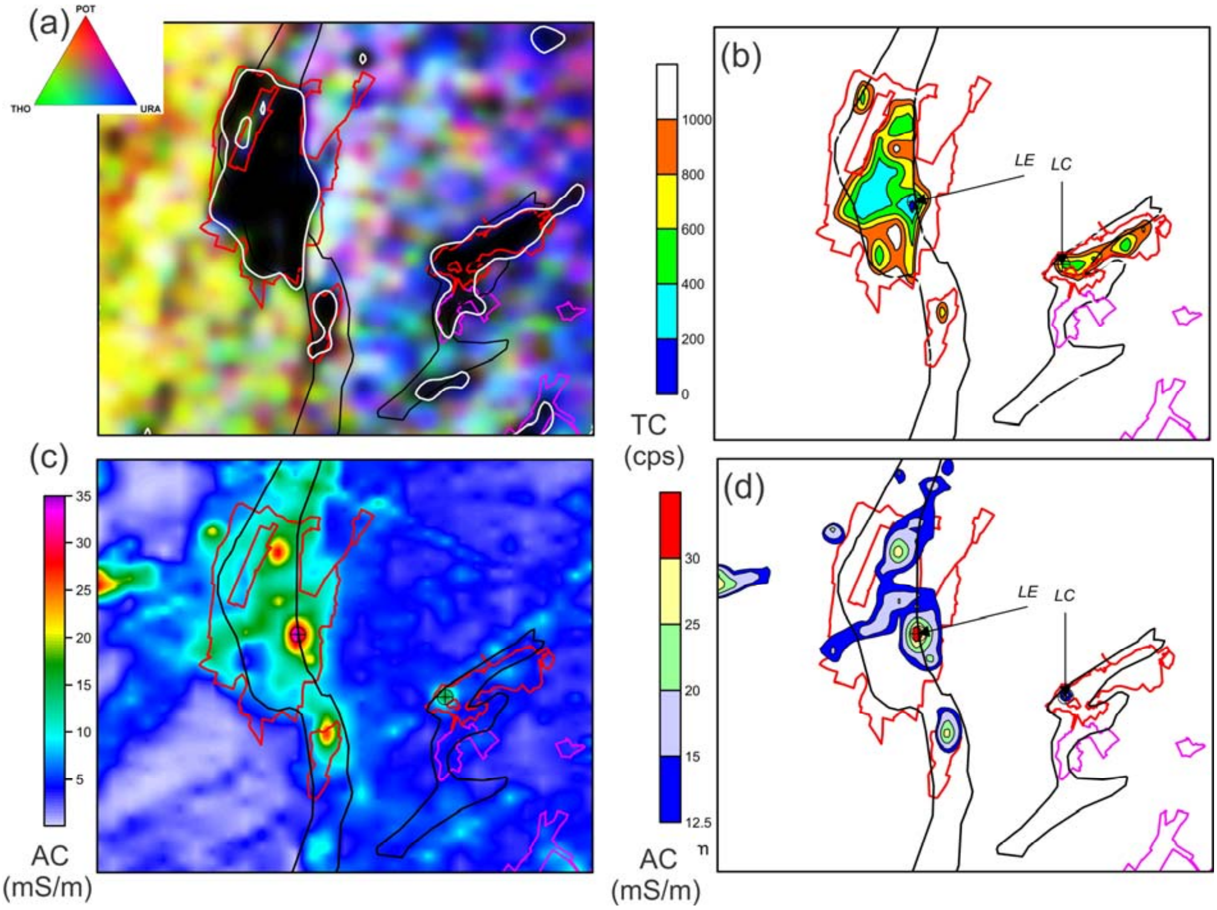

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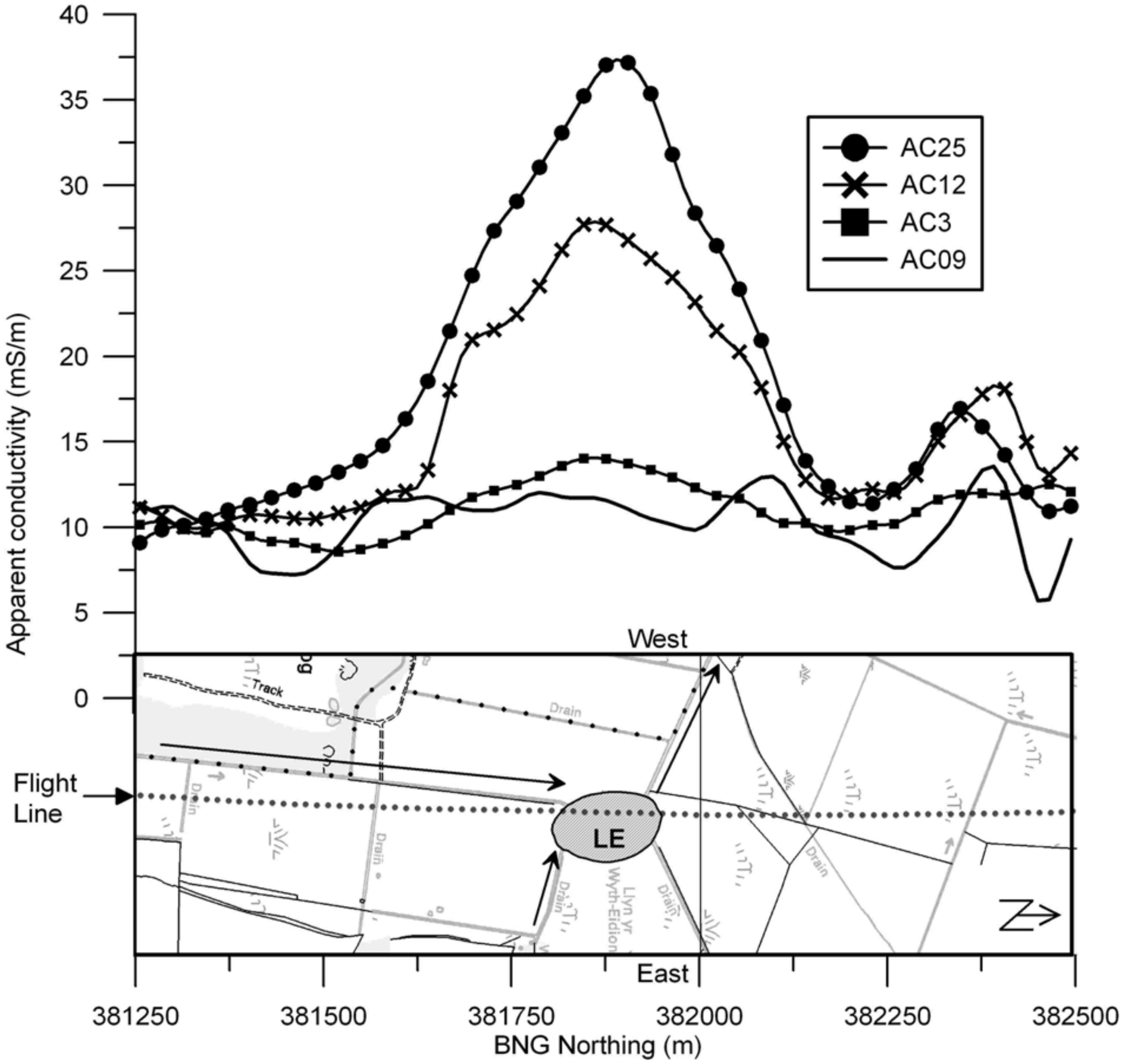

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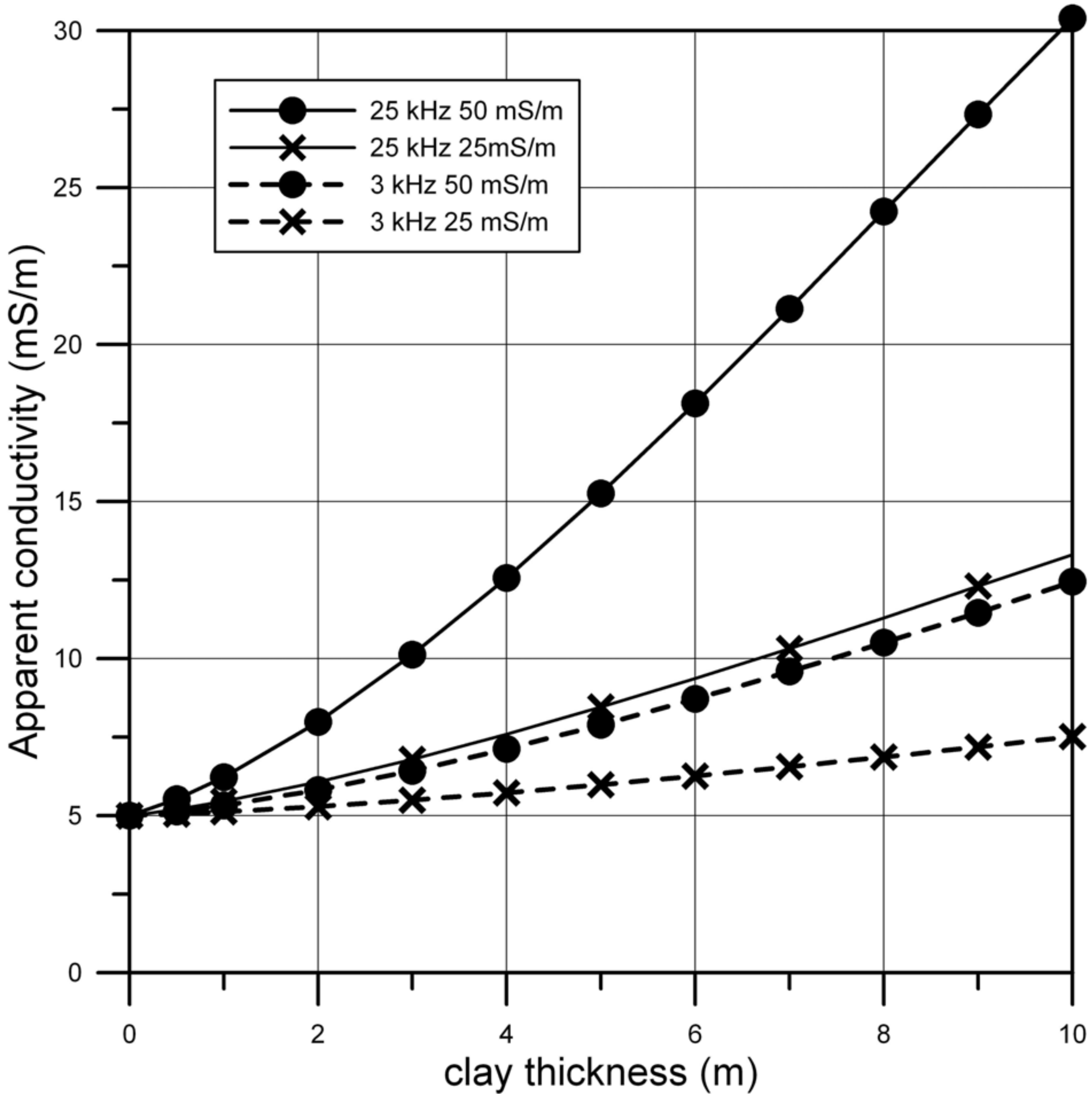

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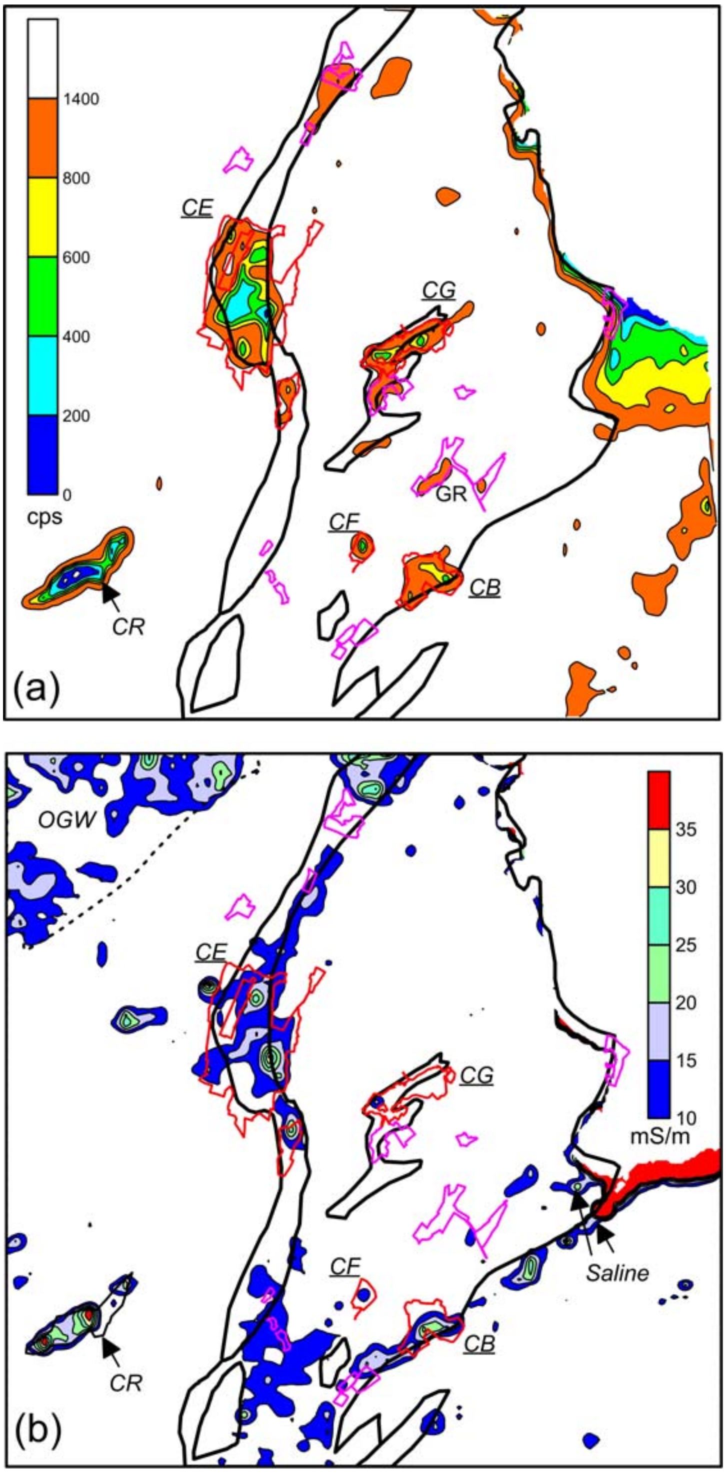

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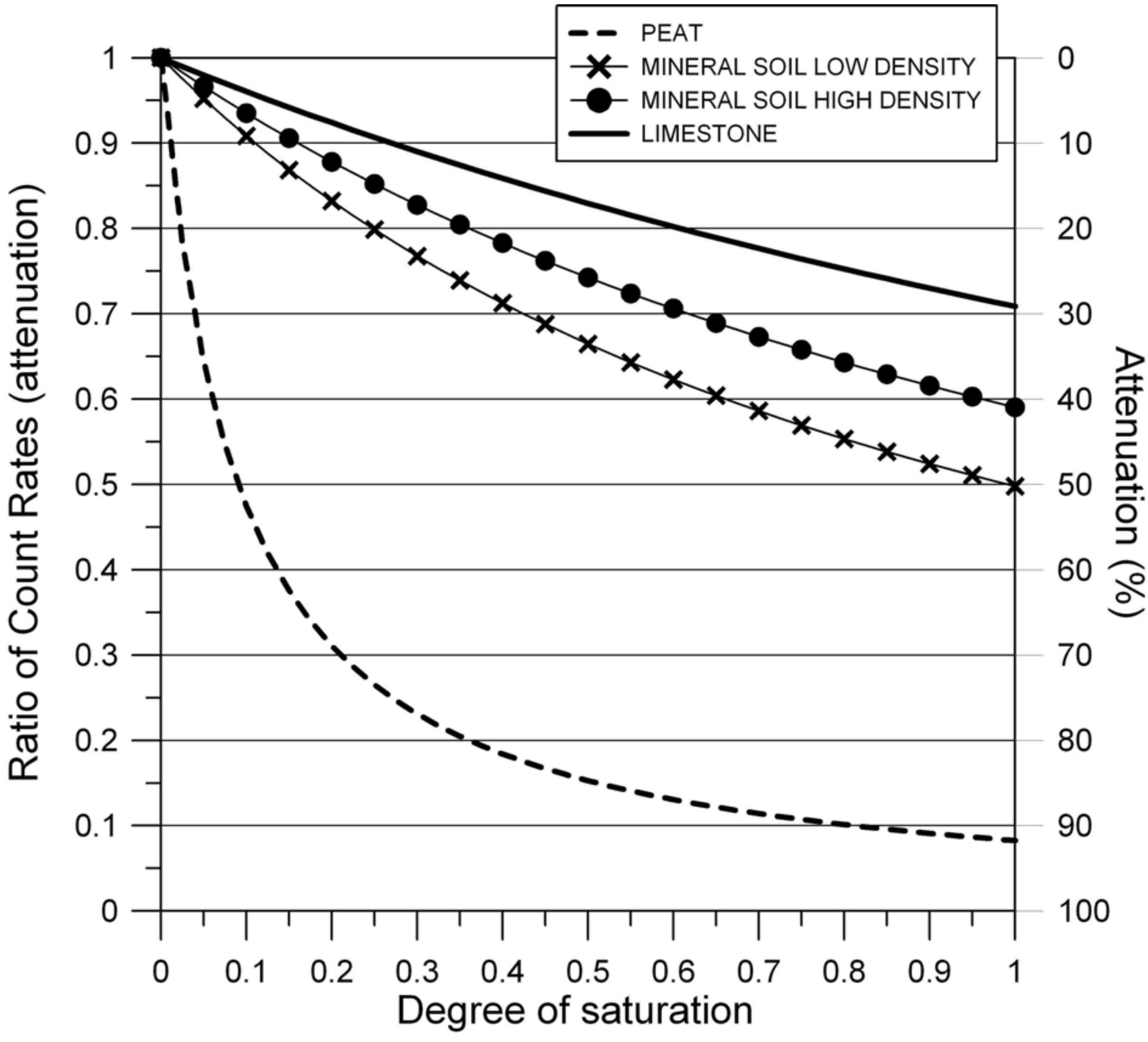

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