

# **GRADUATE SEMINAR REPORT**

**CRITICAL REVIEW AND CASE STUDY ANALYSIS**

**BY**

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## **ABSTRACT**

Wetlands are a non-renewable resource of high potential for organic archaeological deposits and palaeo-environmental sequences. This resource is at threat from development and climate change. Only a small percentage of the identified wetlands in North West Europe have been studied with regard to their depth, stratigraphic architecture and the heritage assets they contain. In this paper several case studies are combined to show the variation of radar velocity field with different wetland sediment types. Sediment types are classified based on their physical and chemical properties. The results demonstrate how the application of geophysics can be used to identify archaeological features and interpret them within a wetland landscape. The ground penetrating radar (GPR) response and geochemical signatures given by archaeological structures and palaeo-landscape features, presented here improves the quality and reliability of scientific information derived from archaeological prospection in wetland contexts. More accurate values for the dielectric permittivity of different wetland sediments have been calculated, allowing the response of GPR in wetland contexts to be predicted. Geochemical signatures associated with different sediment types and archaeological structures have also been demonstrated. GPR and the geochemical analysis of sediment can be employed across the dryland wetland interface bridging the gap between wetland and dryland archaeology and offers a potential to shape global debates regarding how wetland heritage is managed in the future

# **CHAPTER ONE**

## **INTRODUCTION**

### **1.6 General Statement**

Geophysical methods are an important component of geoarchaeological investigations due to their ability to non-invasively image the subsurface of an archaeological landscape. New developments in multi-sensor and positioning technology have facilitated the use of these methods over large areas, allowing archaeological questions to be addressed on a landscape scale.

Among these methods, the ground penetrating radar (GPR) is one of the most economical and best resolving techniques (). GPR surveys are often carried out by maintaining a fixed distance between the emitting and the receiving antennas (fixed offset or single folding surveys).

More recently, geochemistry has experienced an increase in interest from archaeologists in search of new methods to investigate the internal spatial organization of sites and/or to determine the specific function of features, structures or spaces within sites.

Geochemistry is now also being used in combination with other proxies like geophysics, archaeobotany and micromorphology, providing an in-equivalent insight into microscopic pollution generated by past human activities and thus can explain or confirm the function of features and spaces.

### **1.7 Previous Works**

Ground penetrating radar has been employed to archeological prospecting (Manataki et al., 2015; Conyers, 2013, 2015b). This kind of deployment enables a quick prospecting, usually leading to a successful detection of a variety of archaeological targets, including walls, burials, cavities and

other smaller objects such as pottery (Basile et al., 2000; Da Silva Cesar et al., 2001; Leopold and Völkel, 2004).

The use of geochemical analysis to investigate the organization of archaeological sites was initiated in the 1920s with the pioneering work of Arrhenius (1929), and gained in popularity during the 1970s (Eidt, 1977; Proudfoot, 1976; Provan, 1973; Sjöberg, 1976; Woods, 1977).

## **1.8 Applications of the Method**

### **Applications of GPR**

1. Archaeological studies: GPR is extensively used in archaeology for non-invasive exploration of buried artifacts, structures, and archaeological sites. It can help identify buried remains, ancient structures, and other cultural features without the need for excavation.
2. Environmental and Engineering Studies: GPR is used for environmental site assessments, contaminant plume mapping, and geological investigations related to engineering projects. It helps in assessing the subsurface conditions and potential risks associated with construction and infrastructure development.

### **Applications of Geochemistry**

1. Archaeological Investigations: Geochemistry assists in archaeological investigations by analyzing trace elements and isotopic compositions in artifacts, bones, teeth, and soil samples. This information helps in tracing the origin of artifacts, understanding ancient trade networks, and identifying the provenance of individuals in forensic cases.
2. Environmental Geochemistry: Geochemistry helps evaluate the impact of human activities on the environment and assess environmental risks. By analyzing soil, water, and air samples, geochemists can identify contaminants, study their sources, and assess their potential effects

on ecosystems and human health. This information aids in developing remediation strategies and environmental regulations.

### **1.9 Advantages of the Method**

The advantages of ground penetrating radar (GPR) are listed below;

1. Measurement is relatively easy to make (fast data acquisition).
2. High-resolution tool for non-invasive investigation.
3. It is cost effective.

The advantages of geochemistry are listed below;

1. Geochemistry enables the determination of the geological sources of archaeological artifacts.
2. Geochemical analysis of sediments, soils, and plant remains can help reconstruct past environmental conditions at archaeological sites

### **1.5 Limitations of the Method**

The limitations of GPR are given below;

1. The depth of penetration is reduced if shallow groundwater increases the electric conductivity of the porous media.
2. Depth of penetration is site specific for example penetration in silt, clay and materials having conductivity value above 15-20 semens.

The limitations of Geochemistry are given below;

1. Geochemical analysis in archaeology often requires specialized equipment, laboratory facilities, and trained personnel and thus it requires more expense to carry out.
2. Geochemical analysis typically involves the collection of archeological samples and thus could lead to destructions of precious artifacts during sampling stages.

## **CHAPTER TWO**

### **BASIC PRINCIPLE OF THE METHODS**

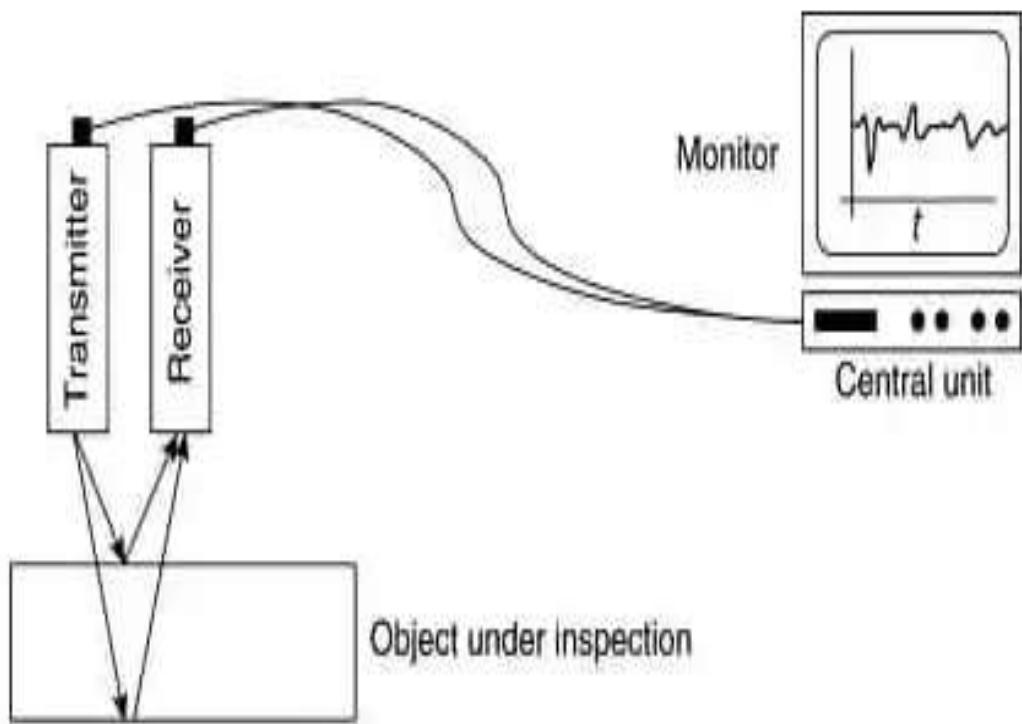
#### **2.1 Basic principle of Ground Penetrating Radar (GPR)**

Ground-penetrating radar (GPR) is a non-destructive technique used for investigating the characteristics of the subsurface. It is a real-time NDT instrument that employs high-frequency radio waves to study the underground sub-surface. This technique provides high-resolution data within a short period. GPR employs high resolution electromagnetic technique to image the subsurface and is designed primarily to investigate the shallow subsurface of the earth, building materials, roads and bridges.

The GPR system consists of a transmitter, antenna, and radargram (control unit). The transmitter emits pulses of electromagnetic radiation into the surface to be surveyed. The difference in permittivity is an indication of the change in sub-surface features (Figure 2.1).

Some of the electromagnetic energy reflects when any change is encountered. The antenna receives these reflected waves, and the corresponding variations are recorded. The information is interpreted and displayed on the radargram. The time taken by the reflected signals to travel back is measured, which is an indication of the depth and location of interruption.

The GPR waves penetrate through different soil debris, water, concrete, and different materials that have different dielectric and conductive properties. These differences are observed in the GPR waves based on which the GPR data is interpreted.



**Figure 2.1: Basic Principle of Ground Penetrating Radar (GPR)**

The data images are finally displayed on the screen, which requires an experienced GPR operator to accurately determine the result.

## **2.2 The Basic Principle of Geochemistry**

The principle of geochemistry revolves around the understanding of the distribution, transformation, and behavior of elements and compounds in Earth systems. It involves the study of the chemical composition, processes, and reactions occurring in rocks, minerals, soils, water bodies, and the atmosphere.

The following are some key principles of geochemistry:

1. **Element Abundance and Distribution:** Geochemistry examines the abundance and distribution of elements in different Earth reservoirs, such as the crust, mantle, oceans, and atmosphere. It investigates the processes that control the variations in element concentrations and their spatial distribution. This helps understand the composition and evolution of Earth's systems.
2. **Chemical Reactions and Equilibrium:** Geochemistry investigates the chemical reactions and equilibria that occur in Earth materials. It explores how elements combine and interact with one another through processes like weathering, metamorphism, and mineral formation. The study of chemical equilibria helps understand the stability and transformation of minerals and compounds under different geological conditions.
3. **Isotopes and Radiometric Dating:** Geochemistry utilizes isotopes, which are variants of elements with different numbers of neutrons, to determine the ages of rocks, minerals, and

fossils through radiometric dating. By measuring the abundance ratios of parent and daughter isotopes in a sample, scientists can calculate the time elapsed since certain geological events, such as rock formation or the extinction of species.

4. **Mass Balance and Conservation Laws:** Geochemistry applies the principles of mass balance and conservation laws to understand the movement and redistribution of elements in Earth systems. It investigates how materials are transported, exchanged, and transformed between different reservoirs, such as the atmosphere, hydrosphere, lithosphere, and biosphere. This helps in tracing element cycles and understanding processes like erosion, deposition, and biogeochemical cycling.

By applying these fundamental principles, geochemists gain insights into Earth's processes, past and present. They contribute to diverse fields such as mineral exploration, environmental studies, climate research, and understanding the origin and evolution of life on our planet.

# **CHAPTER THREE**

## **CASE STUDY**

**Geophysics and geochemistry: an interdisciplinary approach to archaeology in wetland contexts**

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### **3.1 Introduction**

Wetlands are generally rich in cultural heritage due to the unique conditions of preservation (Coles et al., 1973; O'Sullivan, 1998; Van de Noort and O'Sullivan, 2006; Lillie and Ellis, 2007; Menotti, 2012). Decades of archaeological excavations suggest that remains are often fragmentary and deeply buried. This implies that many sites, especially wooden trackways and platforms, and occasionally occupation surfaces and settlements, and industrial debris remain to be discovered. The current management is deemed to be reactionary, attempting to preserve wetland archaeological sites *in situ* once they have already been disturbed (Chapman et al., 2009). This is costly and in many instances the optimal conditions of preservation cannot be attained or sustained (Amendas et al., 2013; Jones, 2013). Due to a less stable environment wetland deposits are less likely to be preserved *in situ* successfully than dryland deposits (Van de Noort et al., 2001, and Matthiesen, 2008; Milner et al., 2011). The ongoing pressure on the archaeological resource from environmental change due to development and, arguably, climate change (see Henman and

Poulter, 2008), as well as afforestation, means that a shift to proactive management strategies is urgently required to aid the rapid discovery and characterization of buried wetland archaeology. This paper presents such an approach using geophysics, geochemical and borehole methods at higher resolution than that previously demonstrated by Utsi (2004), Bates et al. (2007) and Fyfe et al. (2010). By modelling the geochemical and geophysical signature of different targets in a variety of wetland contexts it is possible to address the general skepticism in the academic and commercial archaeological community about the usefulness of geophysics in wetland archaeology. Despite geochemistry having been used as a means of prospecting and characterising anthropogenic sediments in dryland contexts (Persson, 1997 for example), little has been done in wetlands in conjunction with archaeologists to improve understanding of the limitations of individual techniques (Haslam and Tibbett, 2004; Oonk et al., 2009; Eberi et al., 2012).

### **3.2 Problem Statement**

Wetlands are a non-renewable resource with high potential for organic archaeological deposits and palaeo-environmental sequences, but they are under threat from development and climate change. Only a small percentage of identified wetlands in North West Europe have been studied, and there is a need to improve the quality and reliability of scientific information derived from archaeological prospection in wetland contexts.

This paper proposes the use of geophysics and geochemical analysis to identify and interpret archaeological features within wetland landscapes and bridge the gap between wetland and dryland archaeology, with the goal of improving the management of wetland heritage in the future.

### **3.3 Description of the Study Areas**

Five sites associated with wetland archeology in North West Europe were selected for the study.

The description of each of the five sites is given below:

- ❖ **Site 1:** is located at *Castlegar bog, Galway, Ireland* and falls on the *Irish National Grid System ING M82610 39213*.
- ❖ **Site 2:** is located at *Annaghbeg bog, Galway, Ireland* and falls on the *Irish National Grid System ING M81986 37210*.
- ❖ **Site 3:** is located at *Shapwick Heath, Somerset, England* and falls on the *British National Grid NGR ST42204020*.
- ❖ **Site 4:** is located at *Caldicot, Monmouthshire, and Wales* and falls on the *British National Grid NGR ST4870088674*.
- ❖ **Site 5:** is located at *Marsal, Lorraine, France* and falls on the *Longitude and Latitude Coordinate System E 6°36'29" N48°47'22"*.

These sites are shown in figure 3.1

### **3.4 Local Geology of the Study Sites**

The local geology of the study sites are given below:

**Site 1:** which is located at *Castlegar bog, Galway, Ireland* and falls on the *Irish National Grid System ING M82610 39213* has **Limestone Moraine** as the local geologic material.

**Site 2:** which is located at *Annaghbeg bog, Galway, Ireland* and falls on the *Irish National Grid System ING M81986 37210* has **Limestone Moraine** as the local geologic material

**Site 3:** is located at *Shapwick Heath, Somerset, England* and falls on the *British National Grid NGR ST42204020* has **Clays and Sandy Outcrops of Interglacial Burte Beds** as the local geologic material.

**Site 4:** is located at *Caldicot, Monmouthshire, Wales* and falls on the *British National Grid NGR ST4870088674* has **Old Red Sandstones and Carboniferous Beds** as the local geologic material.

**Site 5:** is located at *Marsal, Lorraine, France* and falls on the *Longitude and Latitude Coordinate System E 6°36'29" N48°47'22"* has **Lower Keuper Marl (a Salt-Bearing Formation)**



**Figure 3.1: Map of North West Europe Showing the Location of the Sites Discussed in the Paper**

### **3.5 Location and Accessibility of the Study Sites**

The location and accessibility of the survey sites are shown in the figure 3.2

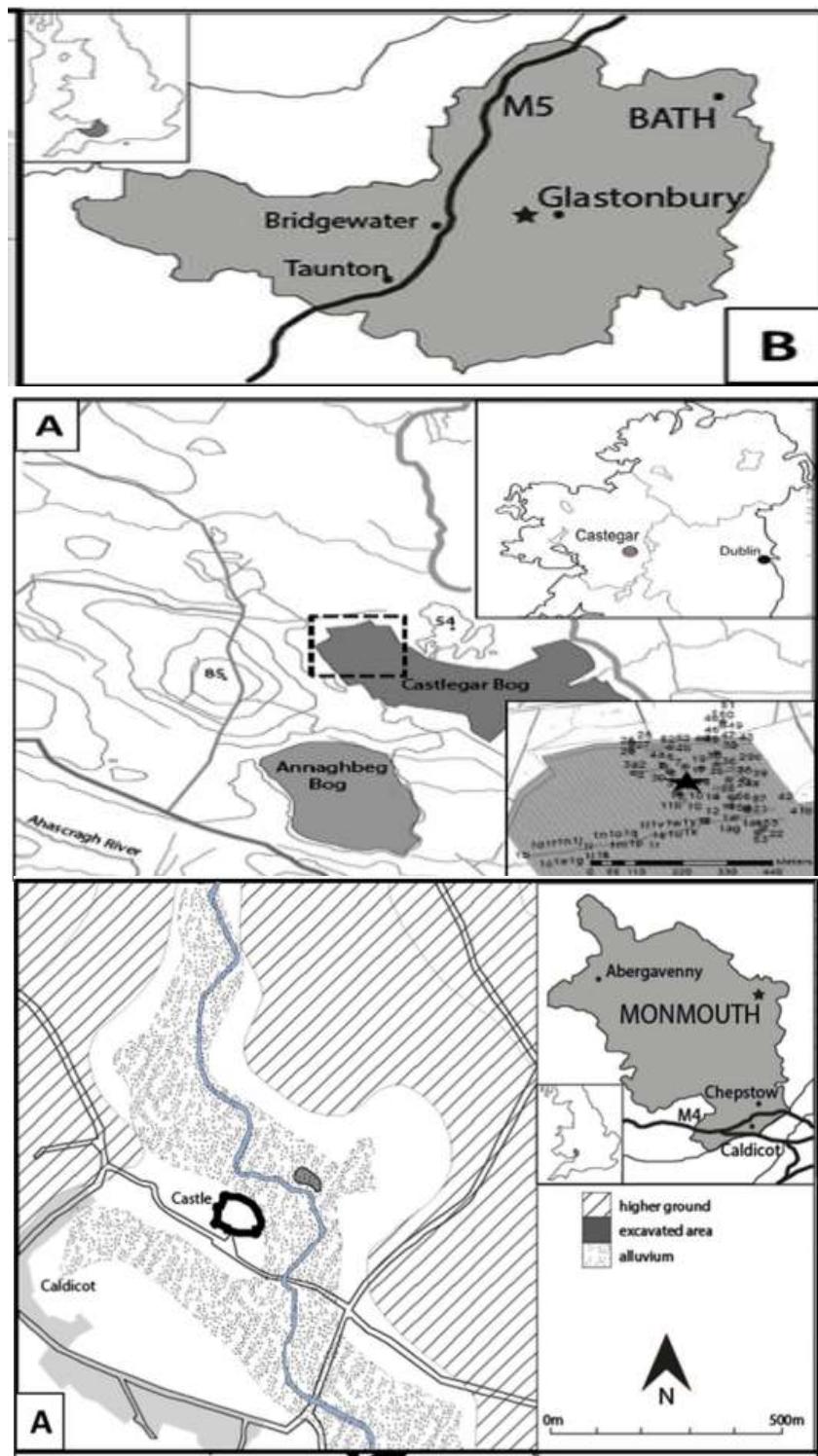
The location of study site at Marsal (2015), is given in Milton (2015).

### **3.6 Aim and Objective of the Study**

The aim of the study is to demonstrate how geophysical techniques can be used to identify archaeological features and interpret them within a wetland landscape, and to improve the quality and reliability of scientific information derived from archaeological prospection in wetland contexts.

The Objectives are to:

1. show the variation of radar velocity field with different wetland sediment types through several case studies;
2. classify sediment types based on their physical and chemical properties;



**Figure 3.2: Location of the Study Sites; B (Shapwick Heath), A top (Annaghbeg and Castle Bogs, Ireland), A down (Caldicot, Wales)**

3. calculate more accurate values for the dielectric permittivity of different wetland sediments, allowing the response of ground penetrating radar (GPR) in wetland contexts to be predicted;
4. demonstrate geochemical signatures associated with different sediment types and archaeological structures;
5. bridge the gap between wetland and dryland archaeology by employing both GPR and the geochemical analysis of sediment across the dryland-wetland interface; and
6. offer a potential to shape global debates regarding how wetland heritage is managed in the future.

### **3.7 Data Acquisition, Processing and Interpretation**

Five sites associated with an archaeological structure or palaeo-landscape were selected for this study (Figure 3.1). Each contain one or more sediment types that are typically found at wetland archaeological sites (Table 3.1).

At Shapwick, Castlegar and Caldicot (**sites 3, 1 and 2 respectively**) the case study **objective** was to **detect evidence of trackways** continuing from areas **previously excavated** and also to improve the **understanding of the local stratigraphy**.

At Annaghbeg bog and Marsal (**sites 2 and 5 respectively**) case study **objective** here focused on **local stratigraphy only** and thus only the velocity profiles are shown.

Slightly different combinations of methods were employed at each site, from long transects covering a large area to grids with data collected at a spacing of 0.125 m for the 400 MHz antennae and 0.25 m for the 200 MHz antennae.

At each site, a grid of ground penetrating radar (GPR) data was collected using the Radan SIR20 software and GSSI hardware, utilizing 200 MHz and 400 MHz common offset antenna set up using the parameters (Table 3.1).

At Annaghbeg and Shapwick (**sites 2 and 3**) long profile were collected across these sites using the 200 MHz antenna. This to identify the most suitable position for the grid. This step was not necessary at the other sites as prior survey or excavation was used to select an appropriate location for the grid. Data for each grid were collected in two directions perpendicular to each other to ensure maximum coverage. An automatic gain control (**AGC**) was applied during collection of the data. **Velocity determination** is an essential part of the research, during data collection an arbitrary value of 10 for the dielectric permittivity was used (Table 3.2) which was corrected in post-acquisition processing. At most sites the two-way travel time to a point reflector was used to calculate this by inserting a metal corer into the ground to a known depth. An additional common mid-point (**CMP**) survey at Shapwick (**site 3**) was carried out due to the wider variety of sediment types encountered. This was completed using Pulse EKKO 1000 GPR console with 225 MHz and 450 MHz antennas provided by the NERC Geophysical Equipment Facility (GEF); Loan 991.

Data collected using the SIR20 system has some processing steps applied on collection including a simplified high pass filter to de-wow the signal. Further processing in Radan 7 included **adjusting the time zero** to the **first positive peak** and a **triangle FIR filter** to remove any **background noise**.

**All the vertical traces** collected from each grid were **combined** to give a **3D block of data** from which **horizontal ‘time-slice’ images** of the area were taken following a **Hilbert transform for magnitude**. **Horizontal stacking** has been applied to longer traces in order to remove noise and allow complete

Table 3.1: Details of each of the study sites

Site	Grid reference	Sediments	Local geology	Associated archeology
Castlegar bog, Galway Ireland	ING M82610 39213	Ombrotropic and fen peat	Limestone moraine	Wooden trackway and platform structures
Annagbeg bog, Galway, Ireland	ING M81986 37210	Ombrotropic and fen peat	Limestone moraine	Undsiturbed paleoenvironmental sequences
Shapwick Heat, Somerset, England	NGR ST42204020	Fen peat	Clays and sandy clays of interglacial buttle beds	The sweet tracks
Caldicot, Wales	Momouthshire, NGR ST4870088674	Alluvial clays and peat beds	Old red sandstones and carboniferous beds	Wooden structures dated to the bronze age
Marsal, Lorraine, France	E6°36'29" N48°47'22"	Alluvial clays and peat beds	Lower keuper marl (a salt bearing formation)	Iron age salt workings

Table 3.2: Data Collection Parameters for both the 200MHZ And 400MHZ Antenna

Parameter	200MHz	400MHz
Samples per scan	512	512
Dielectric constant	10	10
Time zero correction	Auto	Auto
Time window	150	100
Scans per metre (using odometer)	50	50
Transect (trace) spacing	0.5m	0.25m

transects to be displayed.

**Topographic correction** was also applied to longer traces where there is a large change in slope over the area being surveyed.

**The CMP data** collected was imported to **Reflexw (Reflexw, 2012) software** and **basic 2D processing** including **de-wow, time zero correction** and a **gain** were applied. They were then analysed in the **CMP module** using the **semblance analysis** to help **identify weaker signals**.

As geophysical surveys are only a relative means of detection, each of the survey areas has had samples collected for ground validation (**geochemical analysis**).

For collection of the samples, cores were collected from locations of interesting anomalies within the grid and were described using Tröels-Smith (1955) and the Munsell colour chart. Bulk samples were taken using an 8 cm sample interval and analysed for **moisture content, loss on ignition determination, humification and particle size analysis**.

**Moisture content, organic matter content** and **bulk density samples** were determined using the gravimetric technique (Bengtsson and Enell, 1986). **Humification** was measured following the technique outlined for palaeo-studies (Chambers et al., 2011). **Particle size** was analysed using a Beckman Coulter LS230 laser granulometer following random sub-sampling and disaggregation in calgon. **Pore water** was extracted from the sediment in the laboratory following a procedure modified from Dewis and Freitas (1970) and Sharpley et al. (2008), this was found to be the most effective technique after some modification (see Milton, 2015).

### 3.8 Discussion of Results

#### At Shapwick (Site 3)

An anomaly consistent with the location of the projected course of the trackway (Figure 3.3A) is present in a west to east GPR profile north of the interglacial Burtle Bed (Figure 3.3D). At South of the Burtle several point anomalies were located close to the projected course of the trackway. Within the grid, set up in to investigate this area further, a discontinuous high amplitude linear anomaly orientated approximately north-south was identified on the same alignment as the trackway at a depth of 76.8–99.2 ns/1.92–2.56 m (Figures 3.3E and 3.3F, 3.4C and 3.4D).

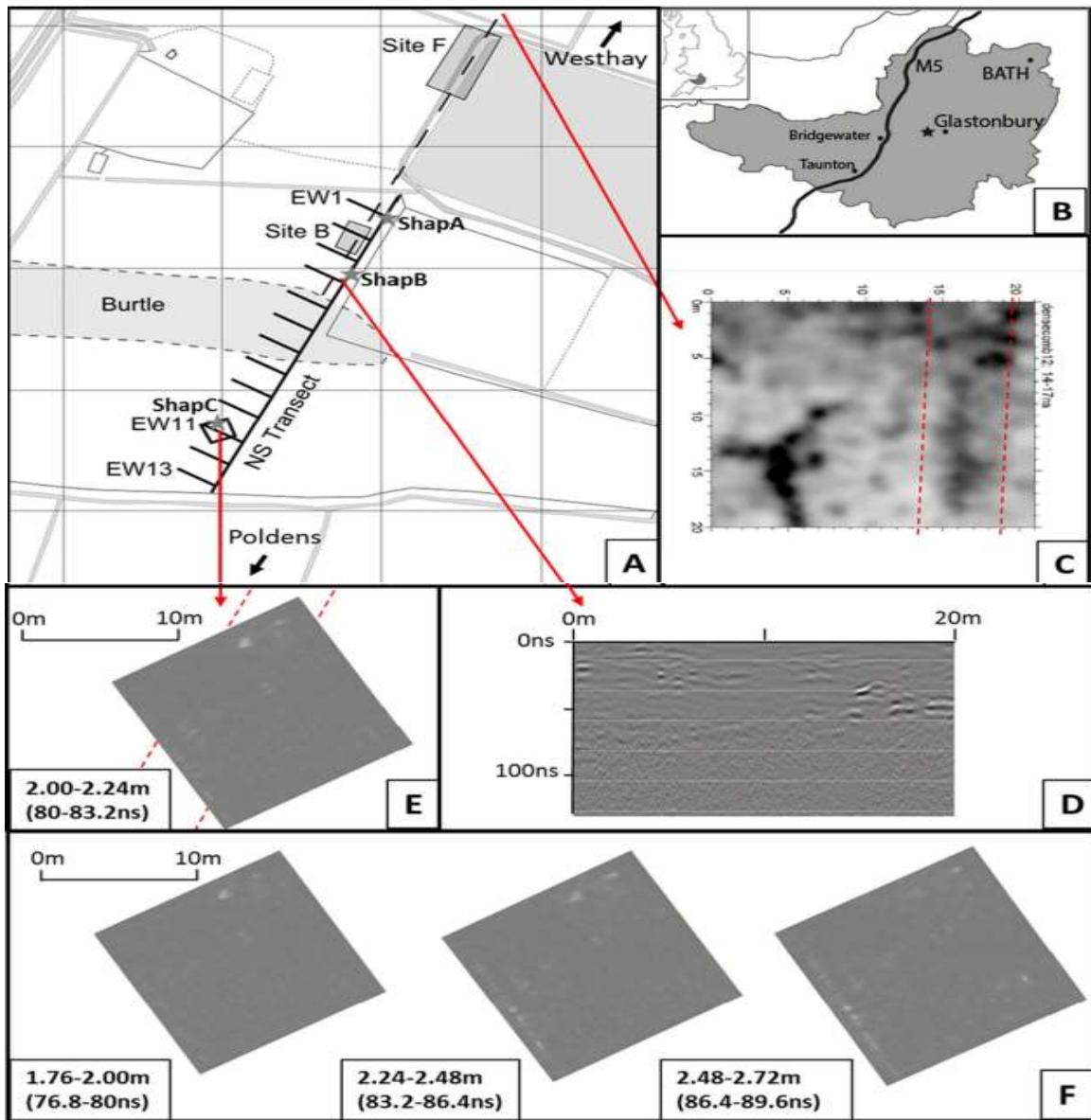
The location of the trackway is well documented as shown (Figure 3.3C).

The depth of the trackway at this location is at the point where there is a clear demarcation of the signal to noise ratio, which can clearly be seen at around 70 ns (Figure 3.3D). It must be remembered that trackway structures are often fragmentary in nature, particularly if poorly preserved, and can be difficult to identify even with excavation. Often many sections need to be excavated and compared in post-excavation to identify alignments of longer structures.

The interglacial Burtle Bed itself is clear in a north to south profile collected along a monitoring transect set up by Jones (2013) (Figure 3.4B). This is the deepest anomaly detected by the 200 MHz antenna at 130 ns (4.36 m).

The sediment was categorised into six broad types; with **geochemical analysis** used to aid interpretation of SHAPC (Figure 3.5E).

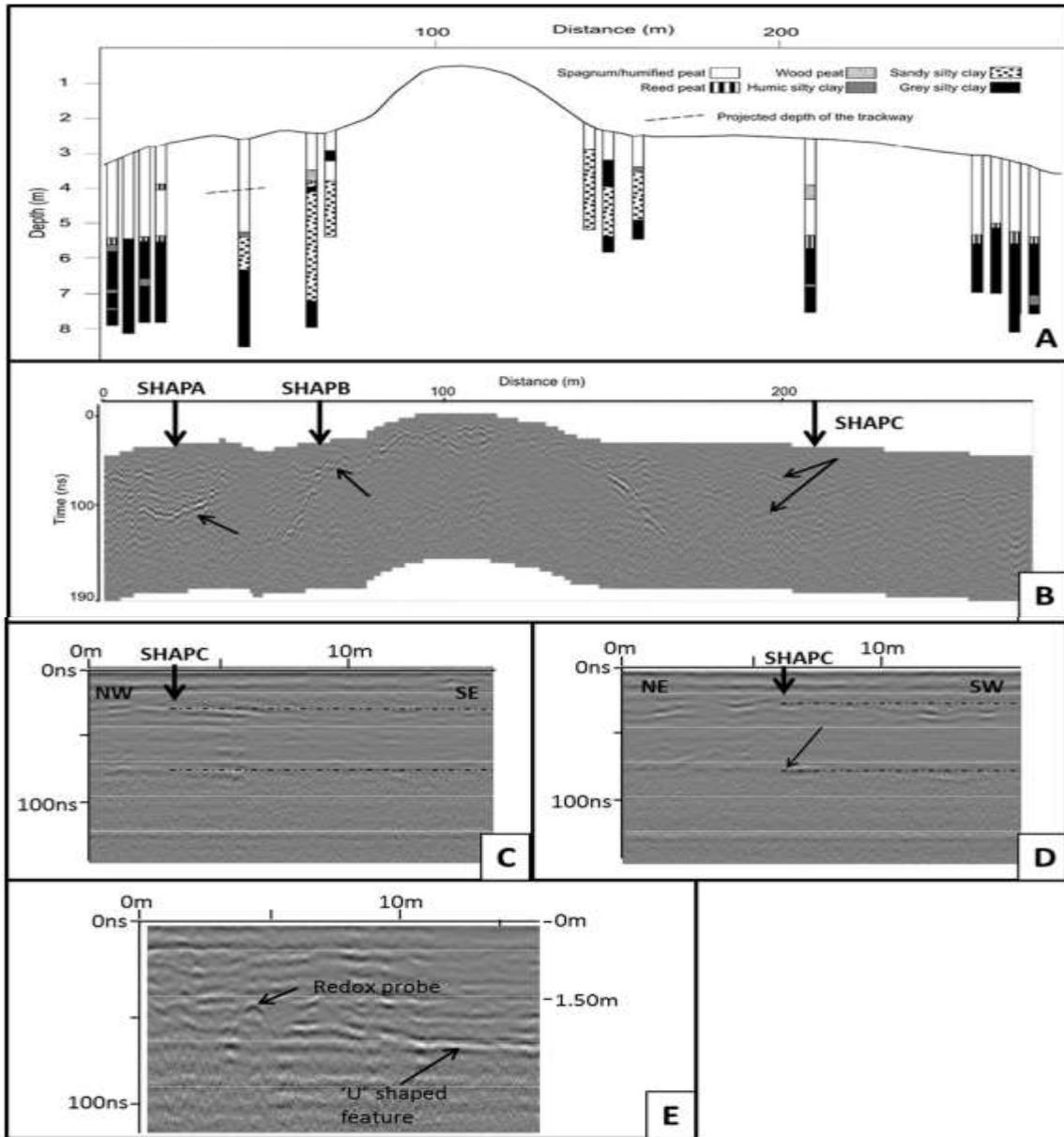
The Burtle Bed is classed as **sandy clay with an EM velocity of 0.07326 m/ns** at SHAPB this is overlain by **colluvium with a velocity of 0.05656 m/ns**.



FIGURES 3.3

**A:** the survey area at Shapwick Heath, showing locations of GPR profiles and grid (solid black lines), locations of cores Shap A, B and C (black stars) and projected course of the trackway (dashed line).

**B:** Shapwick Heath in Somerset. **C:** Timeslice from Armstrong (2010), the black area (of low amplitude) is a tree root and the area between the red dashed line is the trackway. **D:** West-east profile with anomaly interpreted as a cross section of the trackway. **E and F:** Time slice from the grid of data south of the interglacial Burtle Bed, red dashed lines indicate the projected course of the trackway. Black indicates high amplitude and white indicates low amplitude in E and F



FIGURES 3.4

**A:** Survey transect set up by Jones (2013) with stratigraphic units, the location of this transect is the same as the long north-south GPR profile shown in **B**: The north-south GPR profile across the survey area, the interglacial Burtele Bed can clearly be seen in the GPR data as can a 'U' shaped feature adjacent to 'Shap A'. **C and D:** profiles from the grid of data (see Fig. 2A for location), dashed lines indicate depth of stratigraphic features, small arrow indicates location of potential trackway target. **E:** profile used for calculation of dielectric permittivity during initial survey, the archaeological sensitivity of this site meant a redox probe already in the ground had to be used as coring in this area was prohibited.

that seen in the previous survey. South of the Burtle, the peat was considerably wetter at the surface with a slower velocity of 0.04173–0.04244 m/ns (Figure 3.5).

There is also a **layer of wood peat** containing some large pieces of wood at 1.27 m–0.36 m which is characterised by a **spike in conductivity, calcium, magnesium, manganese, sodium and sulphate concentrations**. This sediment has an associated velocity of 0.03960 m/ns. However, the geochemistry reveals raised calcium carbonate content, conductivity and concentration of sodium at 1.96–2.78 m associated with large pieces of wood. The transition of peat to the **underlying clay** is at 3.45 m at this location.

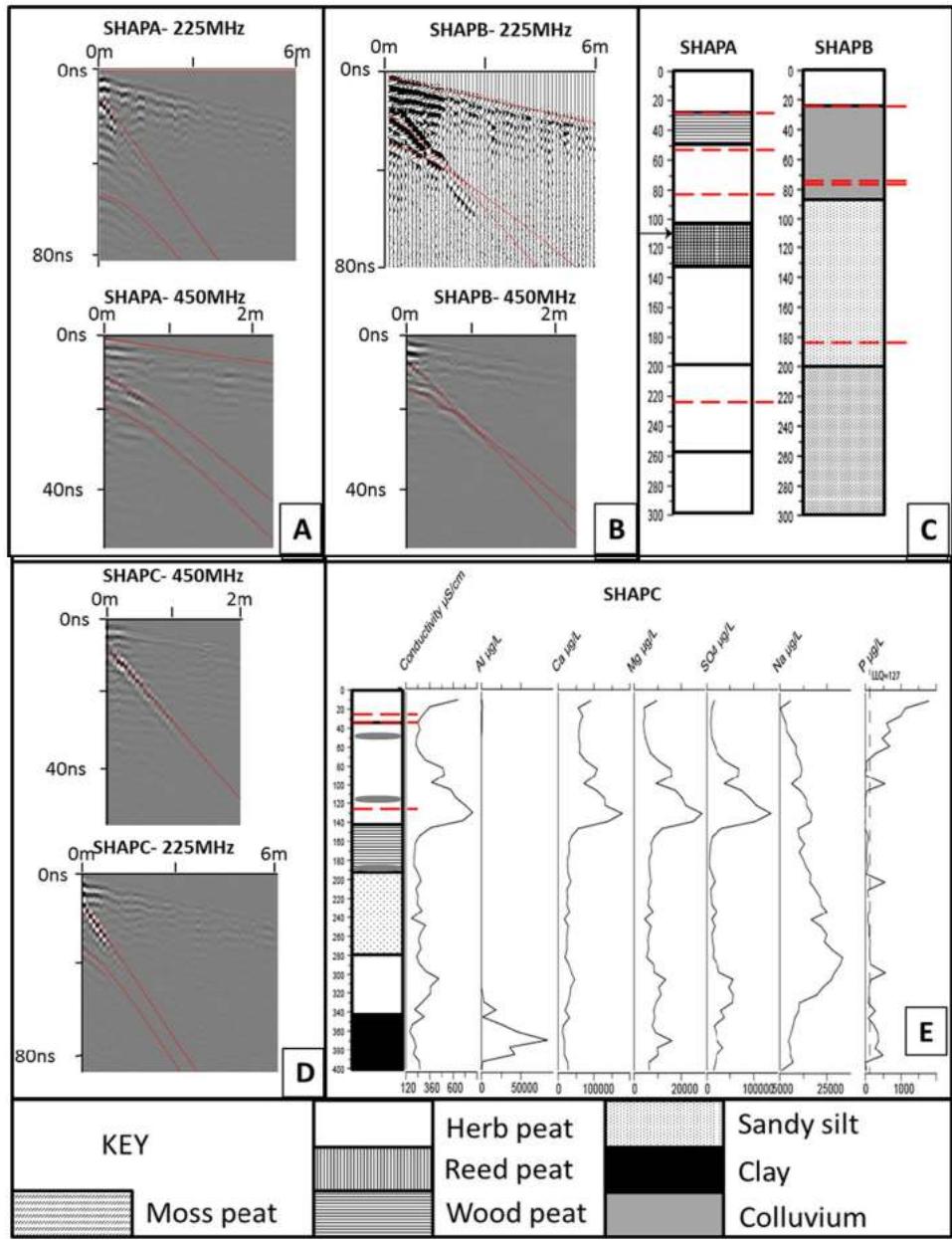
#### **At Castlegar (Site 1)**

Anomalies interpreted as trackway material in the 200 MHz data time slices at 38.4–62.4 ns (0.64–1.04 m) suggest the trackway has an east to west orientation linking the East sighting to the northernmost West trackway sighting (Figure 3.6D).

Another linear anomaly at 48–67.2 ns (0.8–1.12 m) suggests a Northeast to Southwest orientation linking the East trackway sighting with the Southernmost West trackway sighting (Figure 3.6E).

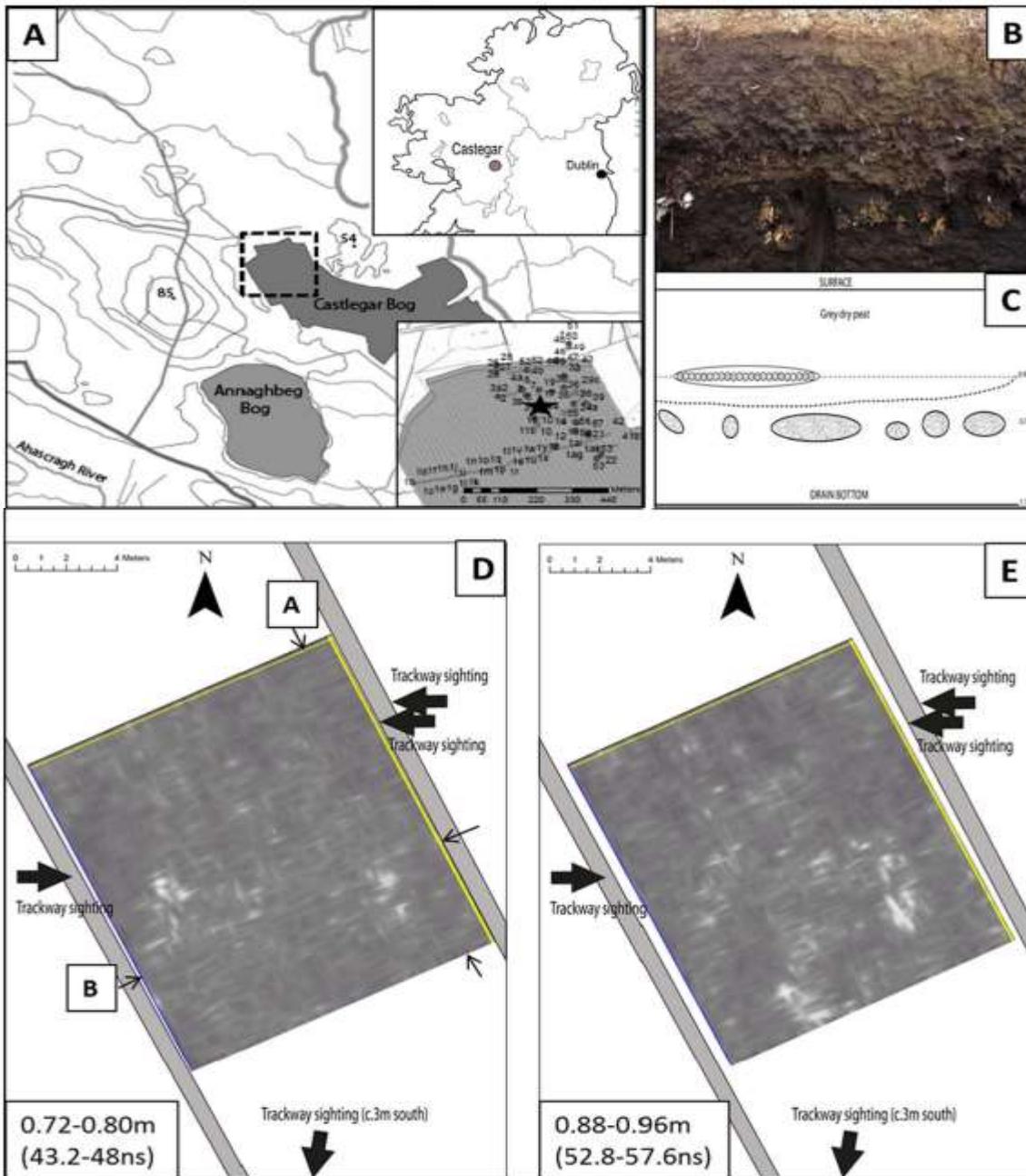
The most plausible explanation is that there are two features, one overlying the other as suggested in the section created by an adjacent drainage ditch (Figures 3.6B and 3.6C).

In the core at 0.96–1.04 m there is a sharp dip in moisture content with an associated increase in bulk density and calcium carbonate content, this is at a similar depth as round woods identified at 0.92–1.00 m. There is also a significant change in sediment properties to near surface conditions at 0.72–0.80 m (Figure 3.7C). This adds strength to the argument for two separate structures, one overlaying the other. Both appear to sit on or in stratigraphic horizons in the peat sequence (Figure 3.7B).



**FIGURES 3.5**

**A;** CMP profiles at SHAPA. **B;** CMP profiles at SHAP B. **C;** Borehole logs from SHAPA and SHAPB.  
**D;** CMP profiles at SHAPC. **E;** The geochemical profile and borehole log at SHAPC



**FIGURES 3.6**

**A:** The location of Annaghbeg and Castlegar bogs, Ireland, with locations of archaeological sightings in the west arm of Castlegar bog from Rohan (2009) inset on the right corner. The location of the survey grid is indicated by a black star. **B and C:** Photo and schematic of the East trackway sighting suggesting two separate structures. **D and E:** time slices ( $15 \text{ m} \times 12 \text{ m}$ ) of the data collected, the borehole was taken at the point where the two intersect. Black indicates high amplitude and white indicates low amplitude.

Also, a core inserted at a depth of 1 m reveals a highly waterlogged ombrotrophic (moss) peat which has an EM velocity of 0.033 m/ns (Figure 3.7A). In addition to the trackways four potential stratigraphic boundaries are seen in the GPR data (Figure 3.7B).

Chemical analysis down the core gives a more complete understanding of the sequence.

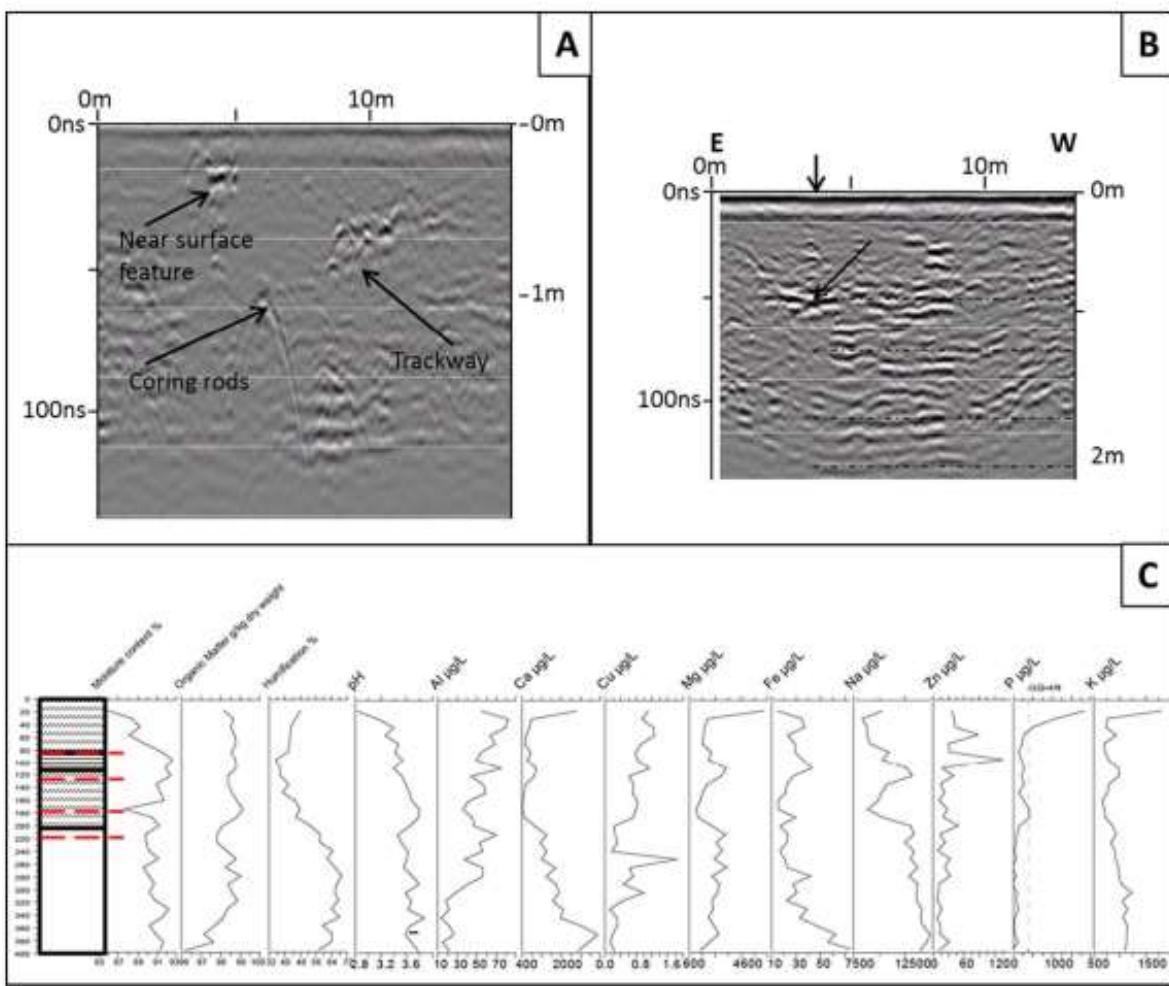
The **geochemical analysis** show general trends outlined above with high iron and calcium (with high pH) at the base of the sequence introduced from the underlying geology in groundwater. The Ca:Mg ratio is 1:1 at 2.08 m indicating the depth of the fen (herb) to bog (moss) transition.

This is the deepest of the stratigraphic horizons indicated by the GPR at 130 ns (2.17 m) (Figure 4.7B and C). High concentrations of aluminium, copper and zinc at 0.08–0.32 m are indicative of redox processes at the water table. The two points in the core where concentrations vary from the general trends **are 0.96–1.12 m**, where there is a rise in phosphorus concentration to 424.36 µg/L (values similar to those seen on the surface and breaking the correlation with concentration of potassium), **and 0.56–0.72 m**, where there is a peak in concentration of a range of elements (Al, Ca, Cu, Fe, K, Mg and Na) (Figure 3.7C). These two depths are at the depths of anomalies interpreted as trackways in the GPR data (Figures 3.7B and 3.6D and E).

Between 1.25 m and 1.75 m there is a higher than average concentration of sulphate (Figure 3.7C), the top and base of this unit are shown in the GPR data (at 75 ns and 105 ns; Figure 3.7B) but no significant change in sediment properties was observed when describing the core.

### **At Caldicot (site 4) and Marsal (site 5)**

For Caldicot (Figure 3.8A) and Marsal (see Milton, 2015), the alluvial clay rich sites, the GPR results were severely depth limited due to attenuation of the EM wave (Figure 3.9). The velocity



**FIGURES 3.7**

**A:** Profile collected for calculation of velocity, the coring rods were inserted at a depth of 1 m (location is indicated by small arrows in Figure 4.6D). **B:** 200 MHz GPR profile intersecting the trackway, dashed lines indicate potential stratigraphic boundaries (location is indicated by small arrows in Figure 4.6D). **C:** The geochemical and physical profile of the core, red dashed lines show location of stratigraphic boundaries in GPR profile.

of the EM wave in these clay contexts was calculated as 0.05 m/ns, giving a dielectric permittivity of 35.95 (within the range given by Mussett and Khan, 2000 for wet clay) for both sites.

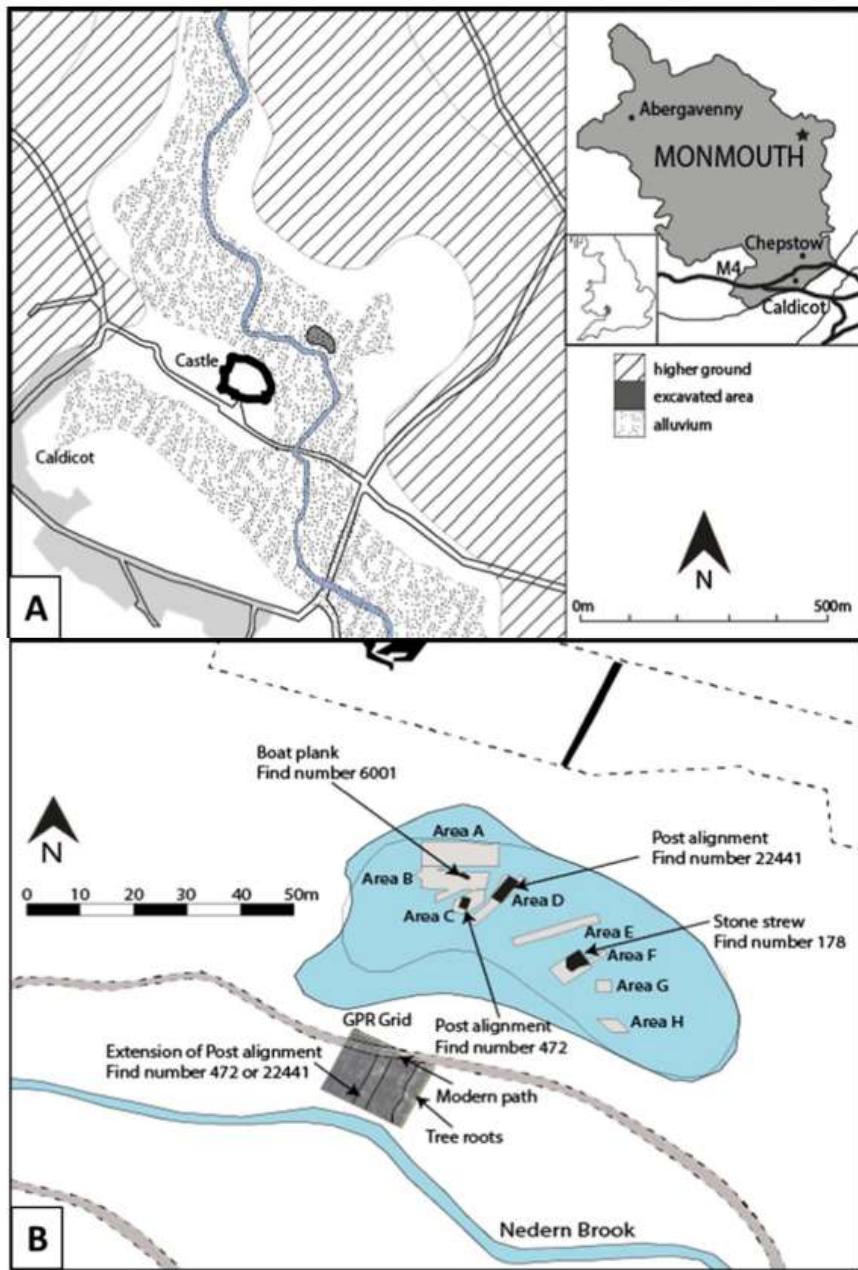
However, there is less confidence in this value due to attenuation making the reflection from the corer (at 1 m depth) less clear (Figure 3.9B). Despite this, at both sites near surface features were identified (to a depth of no > 1 m).

At Caldicot this included a modern trackway consisting of gravel and sand, wood roots and a possible Iron Age structure (Figure 3.8B and 9A). But at Marsal these were interpreted as post medieval earthworks, the occupation horizons in association with a palaeo-channel which were the target of prospection were observed in the boreholes at a greater depth than the GPR could penetrate (Riddiford et al., 2012).

However, **geochemical analysis** allowed the depth of deposits associated with a saltwater spring to be identified (Milton, 2015).

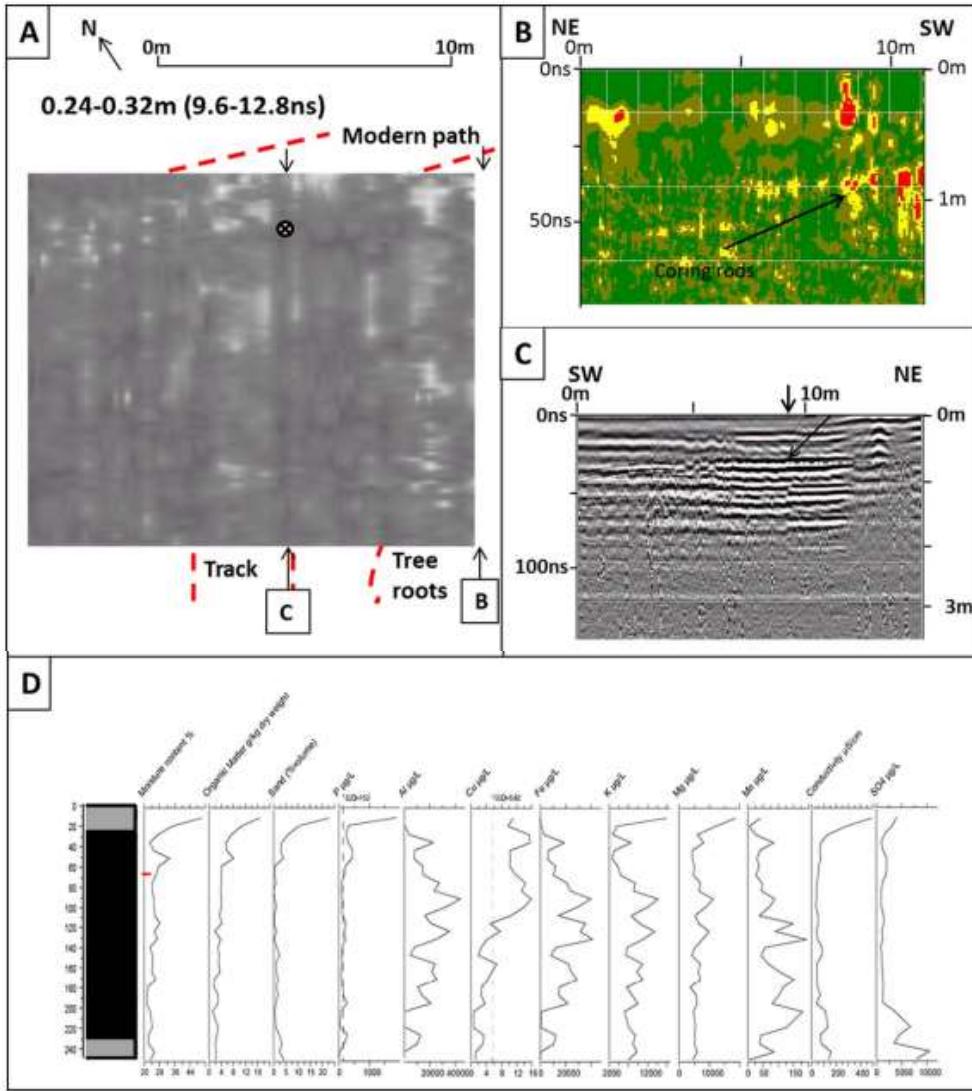
At Caldicot anomalies in approximate alignment to the structure excavated in Area D were observed at 0.16–0.56 m (Figures 3.8B, 3.9A and C). This is interpreted as an extension of the Iron Age post alignment found during the excavations and for which Mansfield (2009) identified a northern extension (Figure 3.8B). The cause of this anomaly appears to be a layer of organic material holding higher water content than the surrounding clay (Figure 3.9D). This fits with the faintness of the GPR signal in the data block. Mansfield (2009) suggested a stone strew could also be the cause of the anomaly in her data but this is likely to have resulted a much more distinct signal with small hyperbola caused by individual elements similar to that seen for the modern path in this data set (Figure 3.9C).

There is also a peak in phosphorus to 449.77 µg/L at 0.32–0.48 m, this along with the presence of charcoal flecks and a crumb structure supports the interpretation of this feature as a palaeo-sol. The peak in concentrations of aluminium, iron, zinc, copper, potassium, magnesium and manganese at 0.16–0.32 m may be associated with the Iron Age structure but could also indicate the depth of the water table (Figure 3.9D).



**FIGURES 3.8**

**A;** The location of the lake and castle at Caldicot, Wales. **B;** The location of the GPR grid in relation to the structures revealed in the lake excavation (Nayling and Caseldine, 1997) and anomalies in GPR data collected to the North of the lake by Mansfield (2007)



**FIGURES 3.9**

**A:** A time slice of the GPR data grid showing anomalies interpreted as a modern path, trackway and tree roots. The core was collected at the point where the modern path and trackway intersect. **B:** The GPR profile used for calculating velocity, the cores were inserted at a depth of 1 m. **C:** A GPR profile intersecting the location of the borehole, large arrow indicates the borehole location. **D:** The geochemical and physical profile of the core, red dashed lines show location of stratigraphic boundaries in GPR profile Black indicates high amplitude and white indicates low amplitude in A and red shows high amplitude in B.

**Table 3.3A: Velocities (m/ns) and Dielectric Permitivities (F/m) calculated for the Wetland Sediments encountered during the Research**

Sediment	Highly water logged		Wet		Dry	
	EM velocity	Dielectric permittivity	EM velocity	Dielectric permittivity	EM velocity	Dielectric permittivity
Ombrrophic peat	0.033	81.05	0.033	81.05		
Fen peat	0.042- 0.015	50.95	0.047- 0.051	40.69-34.56	0.067	20.23
Wood peat			0.040	56.18		
Colluvium			0.057	27.66		
Clay			0.05	35.95	0.05	35.95
Sandy clay			0.073	16.87		

**Table 3.3B: Comparison of Moisture Content from Gravimetric and Dielectric Permittivity**

Site ( $K_2$ )	Average measured water content for the surface meter (%)	Average measured water content for the surface meter ( $m^3/m^3$ )	Moisture content calculated by Topp ( $m^3/m^3$ )	Moisture content calculated by CRIM ( $m^3/m^3$ )
Annaghbeg (81.05)	93.57	0.91	0.97	1.01
Castlegar (81.05)	90.11	0.76	0.97	1.01
Shapwick (50.95)	81.34	0.48	0.48	0.56
Caldicot (35.95)	28.62	0.48	0.48	0.56
Marsal (35.95)	27.28	0.36	0.48	0.56

Table 3.3C: The Reflectivity of Wetland Sediments

Overlying material	Underlying material	R value
Dry fen peat (20.23)	Colluvium (27.66)	0.27
Saturated fen peat (50.95)	Silty sand (16.87)	0.27
Ombrotropic peat (81.05)	Colluvium (27.66)	0.26
Ombrotropic peat (81.05)	Colluvium (27.66)	0.26
Saturated fen peat (50.95)	Colluvium (27.66)	0.15
Clay (30.95)	Dry fen peat (20.23)	0.14
Clay (30.95)	Dry fen peat (20.23)	0.14
Ombrotropic peat (81.05)	Saturated fen peat (50.95)	0.12
Ombrotropic peat (81.05)	Wood (56.18)	0.09
Saturated fen peat (50.95)	Clay (35.95)	0.09
Dry fen peat (20.23)	Silty sand (16.87)	0.05
Saturated fen peat (50.95)	Wood (56.18)	- 0.02
Dry fen peat (20.23)	Silty sand (16.87)	- 0.08
Clay (30.95)	Saturated fen peat (50.95)	- 0.09
Clay (30.95)	Wood (56.18)	- 0.11
Dry fen peat (20.23)	Wood (56.18)	- 0.25

**Table 3.3D: The Range of Some of the Soil Solution Concentrations in the Core Samples at each Site**

Site	Marsal	Caldicot	Shapwick	Castlegar	Annaghbog
Al ( $\mu\text{g/L}$ )	63.22–698,653.79	10.17-44,175.40	<0.01-83,003.97	13.57-82.22	35.20-180.91
Ca ( $\mu\text{g/L}$ )	6395.52-42237.79	3806.69-61,068.00	11711.89-178184.01	420.53-3482.80	464.86-7640.68
Cu ( $\mu\text{g/L}$ )	2.27-354.92	0.68-15.85	0.15-61.15	0.13-1.85	<0.01-3.01

## **CHAPTER FOUR**

### **CONCLUSION AND RECOMMENDATION**

#### **4.1 Conclusion of the Study**

The research presented a range of velocities of the electromagnetic wave through different wetland sediments, including peat, clay, and silt minerogenic sediments. The water content and dielectric permittivity of different types of sediment were found to be highly variable, with peat having the capacity to hold more water than minerogenic sediments due to the pore structure of the sediment. The lack of correlation between the theoretical moisture content calculated from dielectric conductivity and the water content measured from gravimetric means on bulk samples taken was demonstrated.

The results provide valuable information for the calibration of Ground Penetrating Radar (GPR) data for monitoring wetland sites preserved in-situ and for identifying sediment types that produce strong reflectors.

As the results have shown, the geochemical analysis from the borehole material, can bridge the gap between geophysics results and archaeological interpretations to allow the successful application in wetland conditions. This can be used by curatorial, commercial and academic stakeholders for wetland heritage management and research. Nevertheless, the results presented here, despite being more accurate than those currently found in the literature, are still in need of refinement and it is hoped that future work will address this

Thus, the research contributes to a better understanding of the properties of wetland sediments, which can be used for various applications such as archeology, environmental management and paleoecology.

#### **4.4 General Conclusion**

Conducting geophysical surveys in wetland environments presents unique challenges and requires careful characterization of the sediment types to achieve accurate results.

The geochemical analysis also help to bridge the gap between geophysical results and archaeological interpretations. This study provides valuable insights into the potential of GPR for detecting wooden structures and colluvium layers in wetland environments and highlights the need for further research and refinement of geophysical methods in these challenging conditions. Overall, the results have important implications for wetland heritage management and research and can be useful for curatorial, commercial, and academic stakeholders.

#### **4.3 Recommendation**

The use of a comprehensive approach for conducting geophysical surveys in wetlands, as described in the paper is highly recommended to be used. This includes characterizing the deposits prior to the survey, using a range of dielectric permittivity associated with different sediment types, and analyzing borehole material to bridge the gap between geophysics results and archaeological interpretations. These techniques have the potential to be a valuable tool for wetland heritage management and research for curatorial, commercial, and academic stakeholders.

It is important to note that while the results presented in the paper are more accurate than those currently found in the literature, they are still in need of refinement. Future work should address a broader range of sediment types and site conditions, including full descriptions of sediments and

independent analysis of velocity fields and moisture content to allow more detailed modeling of GPR responses in different conditions.

Additionally, focused geochemical studies (analysis) on wetland sites subject to full excavation and interpretation could greatly improve the potential of employing these techniques as a means of interpreting different deposit types.

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