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Citation: Bates CR, Bates M, Gaffney C et al (2019) Geophysical investigation of the neolithic Calanais landscape. Remote Sensing. 11(24): 2975.

remote sensing

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Article

Geophysical Investigation of the Neolithic Calanais Landscape

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Received: 3 November 2019; Accepted: 6 December 2019; Published: 11 December 2019

Abstract: The northern and western isles of Scotland have proved fertile ground for archaeological investigation over the last 100 years. However, the nature of the landscape with its rugged coastlines and irregular topography, together with rapid peat growth rates, make for challenging surveying. Commonly, an archaeological monument or series of monuments is identified but little is known about the surrounding areas and, in particular, the palaeo-landscapes within which the monuments are located. This situation is exemplified by the standing stones of Calanais in Lewis. Here, surrounding peat bogs have buried a significant portion of the landscape around which the stones were first erected. This project identifies remote sensing geophysical techniques that are effective in mapping the buried (lost) landscape and thus aid better contextualisation of the stone monuments within it. Further, the project demonstrates the most appropriate techniques for prospecting across these buried landscapes for as yet unidentified stone features associated with the lives of the people who constructed the monuments.

Keywords: geophysics; neolithic; calanais; stone circle

1. Background

The Tursachan at Calanais in the Outer Hebrides of Scotland is a World Heritage site and one of the most iconic Neolithic stone monuments in the UK. The main site in the Loch Roag area of Lewis is associated with a number of stone circles (Figure 1). Today, the landscape is dominated by open moorland, extensive peat, and rough agriculture. The mild climate is moderated by the Gulf Stream, but the west coast is exposed to North Atlantic storms. Unlike the Neolithic landscapes of Scotland's Northern Isles, those of the western Isles remain relatively unexplored and poorly documented [1]. This is partially a result of a low archaeological research intensity but also the widespread blanket peat and lower levels of agricultural development that lessen chance finds in the area. The peat and Holocene rising sea levels also serve to preserve the Neolithic and older, buried landscapes. Investigating these landscapes thus requires remote sensing technologies to map the archaeology on land and marine geophysical techniques to see through water and sediment accumulations on to preserved landscapes offshore.

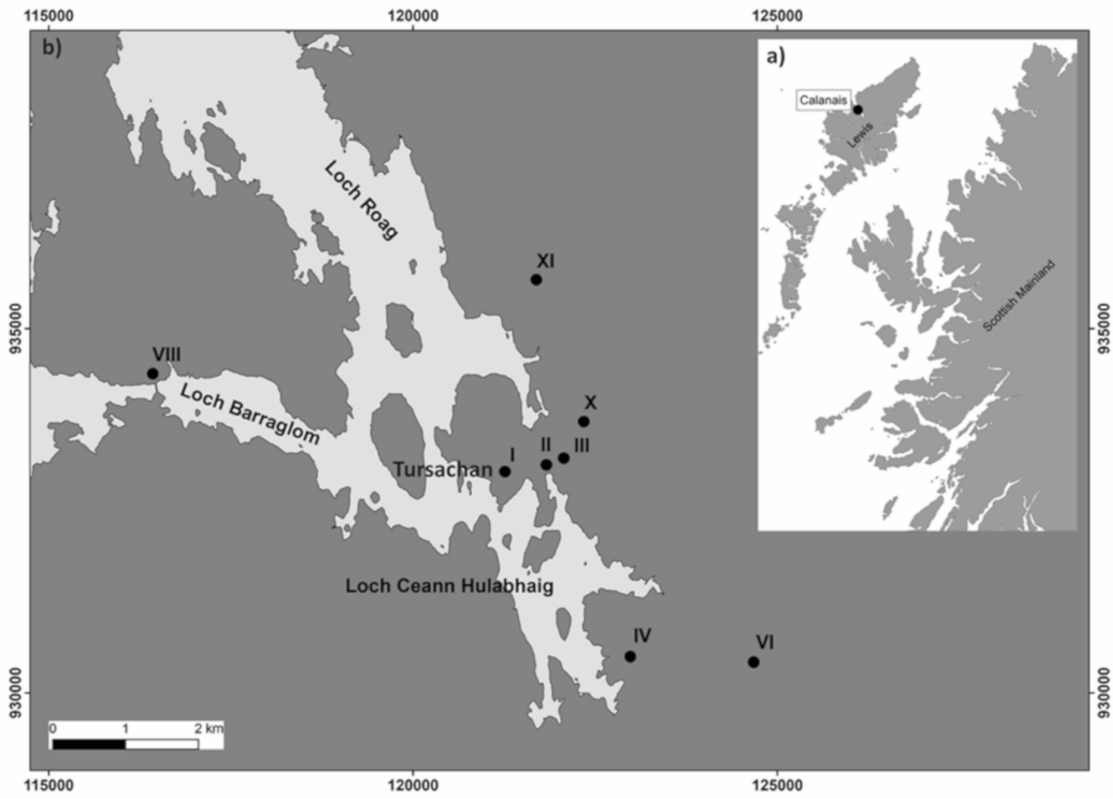

Figure 1. (**a**) Location map of Calanais, Isle of Lewis, Scotland; (**b**) location of the main Calanais sites including the Tursachan (Site I) and Site XI, the site of geophysical investigation.

Previous direct archaeological investigation and remote sensing research has included studies of settlement sites and some, limited, studies on monumental architecture. Early studies include that on Eilean Domhnuill in Loch Olabhat on North Uist [2]. This site, on a small islet in the loch, is joined to the mainland by a thin causeway and possesses multiple Neolithic occupation levels. Finds at the site have included pottery within well-preserved waterlogged deposits. The site is similar to others found throughout the Hebrides and may represent a characteristic settlement for this area [3,4]. Finds on similar islet sites have been reported by local divers and most recently have been investigated by the Universities of Southampton and Reading in loch Olabhat [5]. Here, well-preserved pottery finds support the suggestion that islet sites may not be exceptional in these landscapes but might be of more frequent occurrence. Investigations on two of the islets show the nature of construction where natural features have been enhanced to create a platform. The relatively small size of the platforms has led to speculation that the sites may have a more ceremonial purpose rather than habitation.

Cairn sites are known across the Hebrides and may be associated with two basic forms, Clyde and Hebridean [6]. The typical Hebridean chambered cairn is of circular design with a simple passage leading to the outside. Occasionally, long and also square examples are recorded, and these may reflect reuse from the early Neolithic to the Bronze Age [2].

Stone circles, however, are the dominant feature of the Neolithic landscape with the Tursachan, the Calanais Great Circle being the best known. In the loch Roag area, over 15 other sites have been identified as possible satellite circles to the main Tursachan (Site I, Figure 1b) [7]. The sites have been divided into the "low stone circles" and the "high stone circles" based on their elevations [8] and are labelled as Calanais Sites 'I' to 'XIII'. The Tursachan has been the subject of archaeological interest since the peat was first cleared from around the stones on the orders of a local notable, Sir James Matheson, in 1857. Subsequent distinguished visitors include General Pitt Rivers who recorded the monuments and made careful sketches of individual stones. At this time, there was much speculation as to the astronomical significance at the site.

In the last 50 years, more stone monuments have been discovered within 20 km of the site, but it was not until the late 1970s that a systematic investigation was initiated at the main site. These investigations were undertaken by Patrick Ashmore, who concluded that monumental building began with a single monolith followed by a ring of stones. This was followed by erection of timber structures and a chambered cairn. Pottery associated with the site include domestic and fine Early/Middle Neolithic Grooved Ware suggesting widespread contacts with mainland Britain. Radiocarbon dating suggested that the ring of stones and chambered cairn were erected between 2900BCE and 2600BCE [9]. Investigation around the main site, and in fact investigations further afield within the Loch Roag area, have remained relatively sparse with the exception of a series of excavations undertaken by the University of Edinburgh which are yet to be published.

Richards [7] conducted a number of investigations at sites around Calanais as part of the Great Stone Circles Project. This research programme aimed not only to enhance our understanding of individual sites, but also to review the wider landscape in terms of provision of material for building the circles. The investigation at Na Dromannan (Site X) was particularly useful as it demonstrated an unusual site where stones had been erected on an area with little or no soil cover and where the circle stones had to be propped up using mounds of packing stones rather the usual practice of cutting notches into the ground.

2. Geology

The dominant bedrock of the Loch Roag area is > 1.6Ga banded Lewisian gneiss. This is part of a suite of tonalitic to granodioritic gneiss that contain a wide variety of ultramafic, mafic, and acidic bodies as both intrusions and inclusions [10]. The gneiss typically shows distinctive banding (foliation) of biotite and hornblende minerals, which sometimes occur as distinct cm or dm "augen" or eye-shaped concentrations. Richards [7] suggested that this texture could be employed to classify and indicate the provenance of individual standing stones. Unfortunately, the variability in gneiss textures shows no first-order regional patterns [11] in natural exposures. Locally, foliations tend to weaken the rock causing disintegration along banding planes. These weaknesses are exploited by natural weathering, but it has been noted that the major fracturing and breakup of the bedrock surface happens as a result of pre-glacial weathering and where glacial erosion results from fast palaeo-ice flow [12]. Thus, the bedrock surfaces around the Calanais site contain material that has been weathered over many tens to hundreds of millennia and not just the few millennia since these monuments were constructed or since the last glacial maximum [13].

The fracturing, breakup, and weathering patterns, resulting from ancient tectonic evens and many younger glacial episodes, have left their mark on the gneiss and formed a typical ice-eroded landscape of crag and tails, elongated ridges, and bedrock hollows filled with small lochs. In places, the bedrock is partly overlain by glacial till, which weathers to orange-brown colour in bedrock hollows but shows a greenish shade where fresh. Soil types include peaty gleyed podzols with iron pan above. These are typical of peat profiles, which have been modified where they have been artificially improved.

3. Environmental Change

Investigations of the palaeo-environments within the landscape investigated here suggest that prior to construction the landscape was one where woodland covered over half the area during the early postglacial period. This was dominated by birch (Betula) and Corylus with Salix, Populus, and *Sorbus aucuparia* also present [14]. Blanket peat began to spread from c. 3900BCE and became a major aspect of the (non-cultivated) landscape as woodland decreased. This was likely the result of an increase in grazing livestock rather than cutting and burning [15]. A noted rise in cereal pollen follows to peak between 1400 and 1100 cal BCE, after which the landscape is dominated by peat growth. Concurrent with the change in vegetation, the coastal corridor experienced the final impacts of flooding as sea level rose to present day elevations, and this would have been felt particularly across the sheltered Loch Roag as waters enveloped shallow bathymetry and a large intertidal area t [16].

Sea level change across Scotland has been highly variable over the last 15,000 years. For the Outer Hebrides, the recent review by Shennen et al. [16] shows a rapid rise to approximately –5 m OD by approximately 5500 BCE followed by a gradual rise since then. This analysis is based on recent modelling and a comparison to available sea level index points from around the UK coast. While this represents our current best estimates of relative sea level position, the authors point out the need for consideration of coastal processes when considering local impact. Such factors can often override model predictions: This is especially true for areas where strong tidal currents may play a significant role. The bathymetry offshore from Calanais, which is associated with rock-cut channels and submerged reefs, could have produced major controls on vertical and horizontal shifts in local coastal patterns. Detailed bathymetry and sub-bottom profiling are therefore necessary to understand the history and impact of sea level change.

4. Previous Geophysical Investigations

Geophysical remote sensing surveys, and in particular earth resistance survey, have been conducted at a number of Hebridean stone sites and proved successful for the identification of both buried stones and stone sockets where present. Earth resistance survey was undertaken by Patrick Ashmore as part of the 1979–1988 investigations of the main Calanais site [9]. These surveys used a twin probe resistance arrangement with 0.5 and 1.0 m spacings on 20 m grids. While the results showed a number of important buried features, the probe spacing and line spacing likely caused a spatial aliasing to some of the results. Despite this, anomalies were associated with the standing stones and pits within which they were sunk. Areas near exposed bedrock were generally indicated by higher resistivity, with areas of deeper burial by the peat showing generally lower resistivity. Lower resistivity was also associated with the impact of compaction from informal paths around the site. Magnetic susceptibility survey was also conducted by Ashmore at some local sites, for example at the Na Dromannan stone circle (Calanais Site X). However, results did not indicate any anomalies that might be associated with buried stone, burnt stone, or concentrations of charcoal. Earth resistance surveys were also conducted around the Clach an Trushal stone, western Lewis, where subsequent investigation showed a number of discrete anomalies associated with broken monoliths, packing stones, and pits [7].

In this part of the Hebrides, no marine geophysical investigations have had a focus on mapping submerged sites or landscapes. A few surveys have been conducted however on freshwater lochs using single beam sonar (echosounders) around potential, early crannog sites [5].

5. Geophysical Methods

The methodology applied in this study was chosen with the aim of further understanding the Tursachan within the wider Neolithic landscape. The geophysical study had three main objectives;

- To test remote sensing, geophysical techniques that could be used onshore to reconstruct palaeo-landscapes,
- To map sites of stone monuments (including stone circles) and structures that are presently covered by peat,
- To determine appropriate methods for mapping drowned landscapes and to determine if there are sediment sequences preserved offshore of comparable to those onshore at the monuments.

The Airigh na Beinne Bige (Calanais Site XI) was chosen as a test site as it contained all the elements of a typical Lewis landscape. The site is set on an exposed rocky outcrop surrounded by blanket peat bog. The site has one remaining standing stone that is thought to have been part of a stone circle, the remaining stones being either removed or buried by the peat. The site is located approximately 2.5 km to the north of the Tursachan on a bench or platform on the south facing slope of Airigh na Beinne Bige. It was first reported by Tait, [8] and subsequently by Ponting and Ponting [17]. At the eastern end of the site are the remains of two structures of unknown age. These are probably field houses, known locally as sheilings, and are indicated by piles of stone. There are suggestions that a third sheiling may nestle against the rock lip on the northern margin of the bench. The commanding aspect of the location is such that it is the only point from which every other site of the Calanais complex is visible. The visual characteristics of the site were considered by Richards et al. [7] but without further evidence of the nature of the site, no firm conclusions were drawn as to the significance of the location.

The Loch Roag area to the west of Tursachan was chosen as an appropriate site to test methods for offshore surveying to include both remote sensing geophysical methods and ground truth sampling methods. The Loch Roag area contains an intricate network of narrow and shallow channels with small islands protecting sheltered bays in which there is the potential to preserve sediment sequences. The loch is relatively shallow (<40 m deep) with a large intertidal area consisting of rocky reefs, boulder beaches, sandy bays, and mud flats. Both peat bogs and cultivated land extend along a gentle land gradient for the most part, to the high tide mark, although there are occasional steep cliffs rising up to 15 m. The Allt Gleann nan Culaulhean and Abhainn Ghriomarstaid flow into the loch. The latter is one of the most important salmon rivers in Scotland. At the mouth of the rivers, and along subsidiary rivers, especially on the eastern shore of the loch, there is considerable evidence for stone fish traps of unknown age.

6. Remote Sensing of Buried Terrestrial Landscapes

Geophysical methods are well-tested and tried in the reconstruction of buried palaeo-landscapes (e.g., Durrington walls and Stonehenge Hidden Landscape Project 2010–2016, [18]), and have proven most effective where there is a marked contrast in geophysical properties between the old landscape and the material that has subsequently covered it. In the Outer Hebrides, limited surveys have been utilised on machair, multi-period sites [19], but upland locations have only rarely been surveyed. Electrical, electromagnetic, and magnetic methods have been most successful in archaeological studies where there has been the choice of technique depending on the physical properties of the material and the amount of (geophysical) noise [20]. In particular, a benefit of these studies is that they have discriminated buried materials within the soil such as stones and walls when there is a high contrast in moisture and/or magnetic content between the buried material and surrounding sediments. Geophysical noise that can lead to misinterpretation of the geophysics includes modern anthropogenic features such as buried pipes and cables but can also occur from natural causes such as changes in the geology and physical phenomena.

For this project, a combination of electrical, electromagnetic, and magnetic techniques was chosen because of the need to cover larger areas of ground in detail. Furthermore, techniques were chosen that would have the highest chance of mapping the contrast between the (saturated) peat and boulder clay, both of which are relatively electrically conductive, and the resistive bedrock of Lewisian gneiss. Specifically, the techniques listed in Table 1 were used with different objectives associated with each technique, and the areas of survey are illustrated in Figure 2.

Table 1. Geophysical survey equipment.

Method.	Equipment	Type of Cover	Aim
		LAND	
Electromagnetic surface mapping	GF Instruments CMD Explorer and MiniExplorer	Land, 2D surface	Mapping thickness of sediment (peat) overlying bedrock for palaeo-landscapes reconstruction, mapping buried features such as stone and pits
Earth Resistance mapping	Geoscan Research RM15D	Land, 2D surface	Location of shallow buried features such as pits and stones
Electrical (2D) resistivity imaging	Lund SAS 3000 Terrameter	2D cross section	Measurement of sediment (peat) thickness
Magnetic Gradiometer surface mapping	Bartington 601	2D surface	Location of shallow buried features such as pits and stones

Table 1. *Cont.*

Method.	Equipment	Type of Cover	Aim
		MARINE	
Multibeam bathymetry	ITER Systems SwathPlus 468	2D surface	Mapping high-resolution bathymetry
Sub-bottom profiling	Tritech Seaking/IXBlue profiler	2D cross section	Mapping buried landscape surfaces

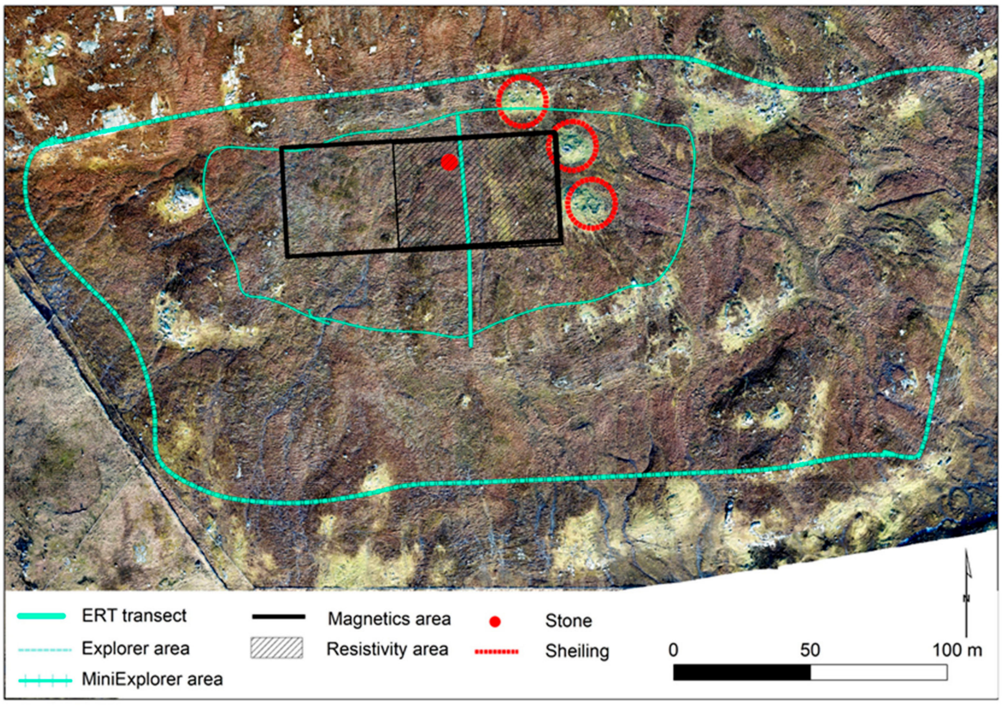

Figure 2. Location map of geophysical survey projected drone-derived image of Calanais Site XI showing sheilings and single standing stone location together with survey extents for geophysical methods.

7. Remote Sensing of Submerged Landscapes

Seismic geophysical methods have proved highly successful for mapping submerged buried palaeo-landscapes at different scales on the continental shelf surrounding the UK. Over very large areas of the southern North Sea, the re-processing of seismic data originally acquired for hydrocarbon survey has shown the extent of the preserved Holocene and earlier landscapes that are known in the south as Doggerland [21]. In the Northern Isles, a similar approach using very high-resolution seismic has been used to demonstrate complex flooding histories near archaeologically significant sites such as the World Heritage monuments on Orkney [22]. Key to this work is the combination of careful seismic analysis with judicial placing of cores for palaeo-environmental analysis, and the tying together of results from the present-day offshore areas to those onshore. Crucial for this is the ability to acquire data in the intertidal zone using very high-resolution sonar.

8. Results

8.1. Electromagnetic Ground Conductivity

Electromagnetic measurements were made across the site using a CMD Explorer and CMD Mini-Explorer (CF Instruments) both operated in vertical coil orientation. These instruments simultaneously measure both ground conductivity and inphase (magnetic) values for three coil separations giving exploration depth ranges of approximately 2, 4, and 6 m depth for the Explorer and 0.5, 1, and 1.5 m for the Mini-Explorer. The instruments were deployed together with position provided by a Trimble G6 GNSS. Line spacings of approximately 3 m were acquired across the site using the

Explorer in order to map landscape changes, and with a line spacing of 0.5–1 m for the Mini-Explorer around the upstanding stone in order to map potential stone socket locations. Both were operated with a sample interval of 0.3 s for both. This resulted in sample points spaced at approximately 30 cm intervals along lines. The results were downloaded and analysed by extrapolation into contiguous surfaces using gridding routines in a geographic information system. The results are shown as contour plots in Figure 3a for the conductivity and inphase from the CMD Explorer for Coil 3 and in Figure 3b from the Mini-Explorer Coil 3. Results for Coils 1 and 2 for both instruments are given in the Supplementary Materials.

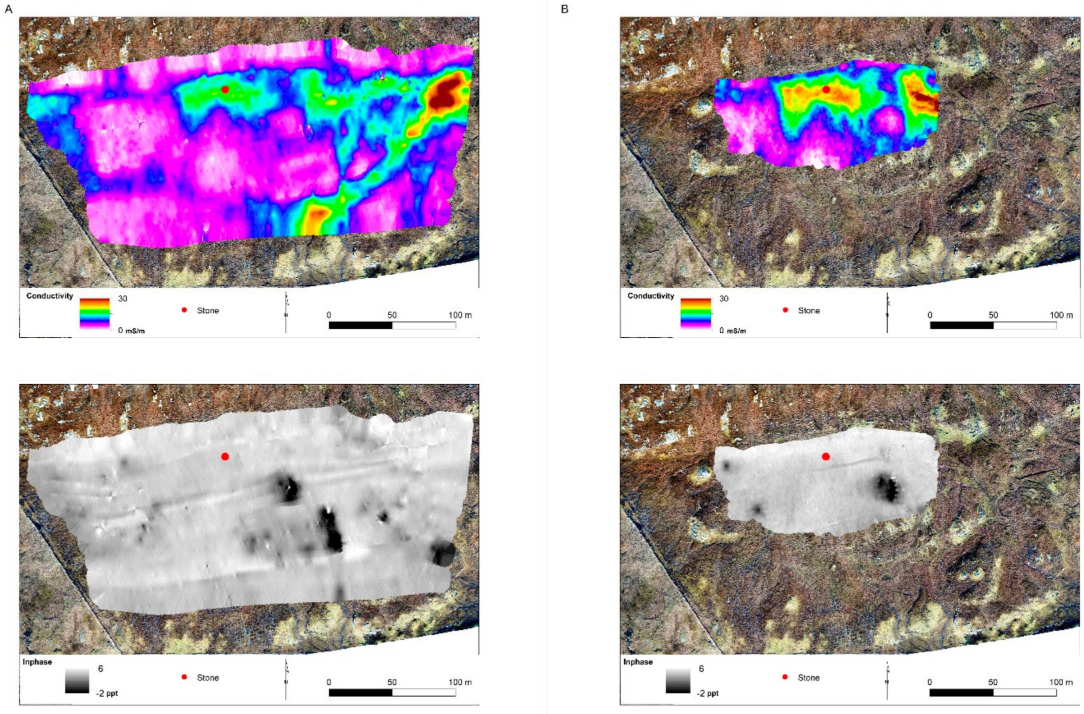

Figure 3. (**a**) Ground conductivity and inphase for CMD Explorer Coil 3. (**b**) Ground conductivity and inphase for CMD Mini-Explorer Coil 3.

Results show general agreement between each instrument with ground conductivity values higher (>10 mS/m) across the peat and soils and conductivity lower over exposed bedrock (<10 mS/m). The area immediately around the single extant stone shows as a higher conductivity signature, particularly in the Mini-Explorer data. Inphase results show anomalies associated with the larger sheiling site and at two other location at the western end of the survey site. At these western locations, there was no indication of stonework at ground surface, but shallow buried bedrock is likely to exist here.

8.2. Earth Resistance

Surface earth resistance measurements were made on a 20x20 m grid pattern with readings taken every 0.5 m although time and weather only permitted the eastern part of the site to be covered. The RM15 was deployed in both the Wenner and Double Dipole array; probes were spaced at 25 cm giving an approximate maximum exploration depth of 10–15 cm in order to test very near surface disturbance within the peat. The data were uploaded, and grids joined to cover the site over the area where peat was thickest and where there was the chance of buried features. Figure 4 shows that high values of earth resistance correlate to the exposed rock and likely near-surface presence of rock. Low values were associated with the saturated peat and clay soils. A reasonable correlation was noted between these results and those of the Mini-Explorer for Coil 1.

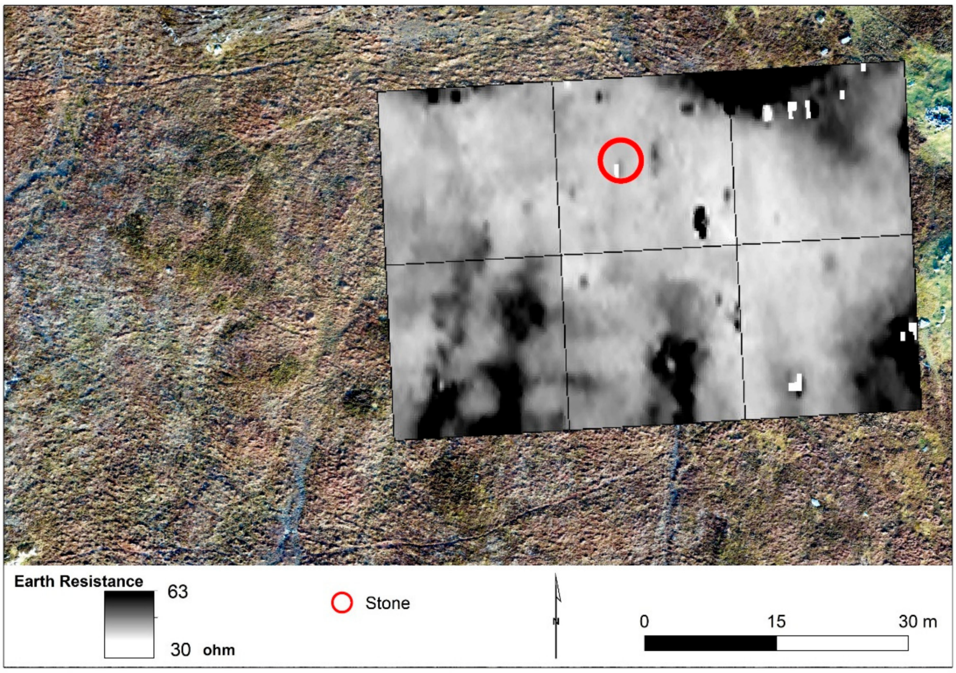

Figure 4. Earth resistance—Wenner Array.

8.3. Electrical Resistivity Tomography

A single line of electrical resistivity tomography (ERT) measurement was acquired across the site using and ABEM Terrameter 4000 (ABEM Inc.) along an approximately north-south transect. An electrode spacing of 0.5 m was used with 88 electrodes in roll-along acquisition with a modified Wenner array. The data were processed using Res2DINV (Geotomo Software) with a smoothness-constrained Gauss-Newton least-squares inversion method. The pseudo-section results are shown in Figure 5a with the section spliced into the appropriate topographic location together with the ground conductivity results from the CMD Explorer in Figure 5b. The section shows generally lower resistivity at depth to the north, and high resistivity to the south. From the ground surface to approximately 0.5 m depth, intermediate resistivity (100–150 ohm.m) was measured. To the north, across the peat area, the lower resistivity corresponds to the high conductivity areas shown by the CMD Explorer. Here, the data did not indicate a maximum depth to bedrock but suggest a thickness of greater than 3 m. Within the south section of the line, higher resistivity at depth also corresponded to lower conductivity recorded by the CMD Explorer, thus corroborating the interpretation of an association with the gneiss bedrock.

8.4. Geomagnetics

The geomagnetic survey was conducted using a Bartington Grad 601 (Bartington Instruments) fluxgate magnetometer with twin sensors on a 20x20 m grid with 1.0 m line spacings surveyed in an E-W direction and 8 samples/m inline. The grids were joined to give full coverage over the main site area (Figure 6a). Magnetic signatures can be classified into three types, the first two of which show generally low magnetic responses.

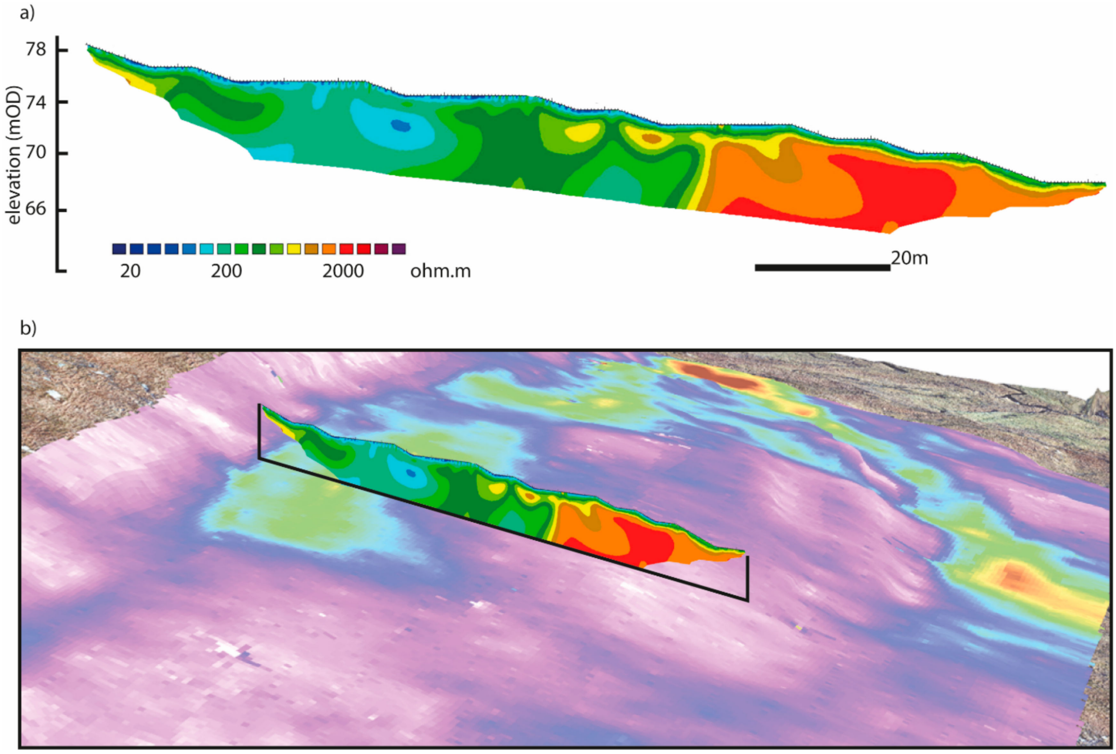

Figure 5. (**a**) Electrical resistivity tomography (ERT) measured along a north-south transect through the main site; (**b**) resistivity section integrated with 3D surface representation overlaid with ground conductivity signatures acquired using the CMD Explorer and Coil 3 data.

Across the site, single, scattered positive anomalies can be seen, shaded black. These are typically sub-metre in size and have no feature at the ground surface with which to relate them to. However, their size and a comparison to typical data from other sites suggests that these may be associated with small buried features. The second type of anomaly are paired positive/negative bi-poles (black/white pairs). Overall, the orientation of the positive/negative pairs show no consistent orientation, and this suggests a non-induced signal i.e., not a soil filled pit, but the presence of magnetized material. Thirteen of these pairs fall into a roughly circular pattern across the site and one is associated with the only extant stone (Figure 6b). The circular pattern is approximately 30 m in diameter and is interpreted as an integral archaeological feature associated with the remaining standing stone. The third type of anomaly includes two sets of linear positive/negative anomalies approximately 20 m long; one located at the middle of the grid where there is no surface feature and the other to the east side of the grid. The former anomaly falls at the centre of the circular arrangement of positive/negative anomalies and the eastern anomaly is located to the east side of the larger sheiling. These features are interpreted as indicative of past lightning strikes.

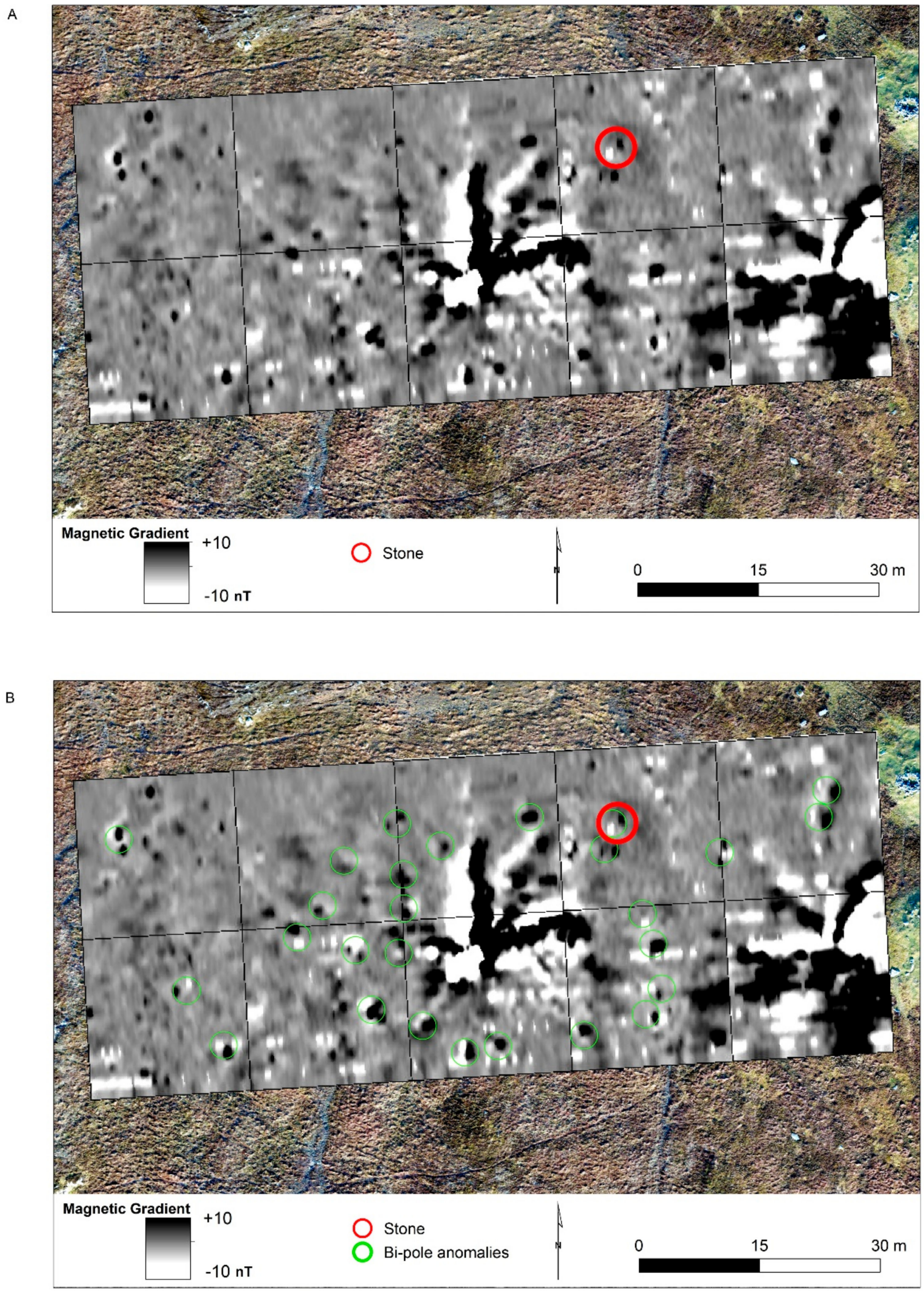

Figure 6. (**a**) Bartington Grad 601 magnetic gradient results acquired on 0.125x1.0m grid; (**b**) Magnetic gradient with bi-pole anomalies highlighted.

8.5. Submerged Landscape

A preliminary bathymetric survey was conducted on the southern, inner Loch Roag using a SwathPlus 468kHz sonar (Iter Systems) to measure the bathymetry and seafloor type. The results (Figure 7) showed a narrow, submerged valley of maximum depth 10 m truncated by a series of submerged, shallow rock lips. The southern end of the valley, closer to the inlet of the Chriomarstaidh river, shows a rapid shallowing to less than 3 m water depth around two submerged, isolated mounds located along an abrupt, northeast–southwest-oriented break of slope.

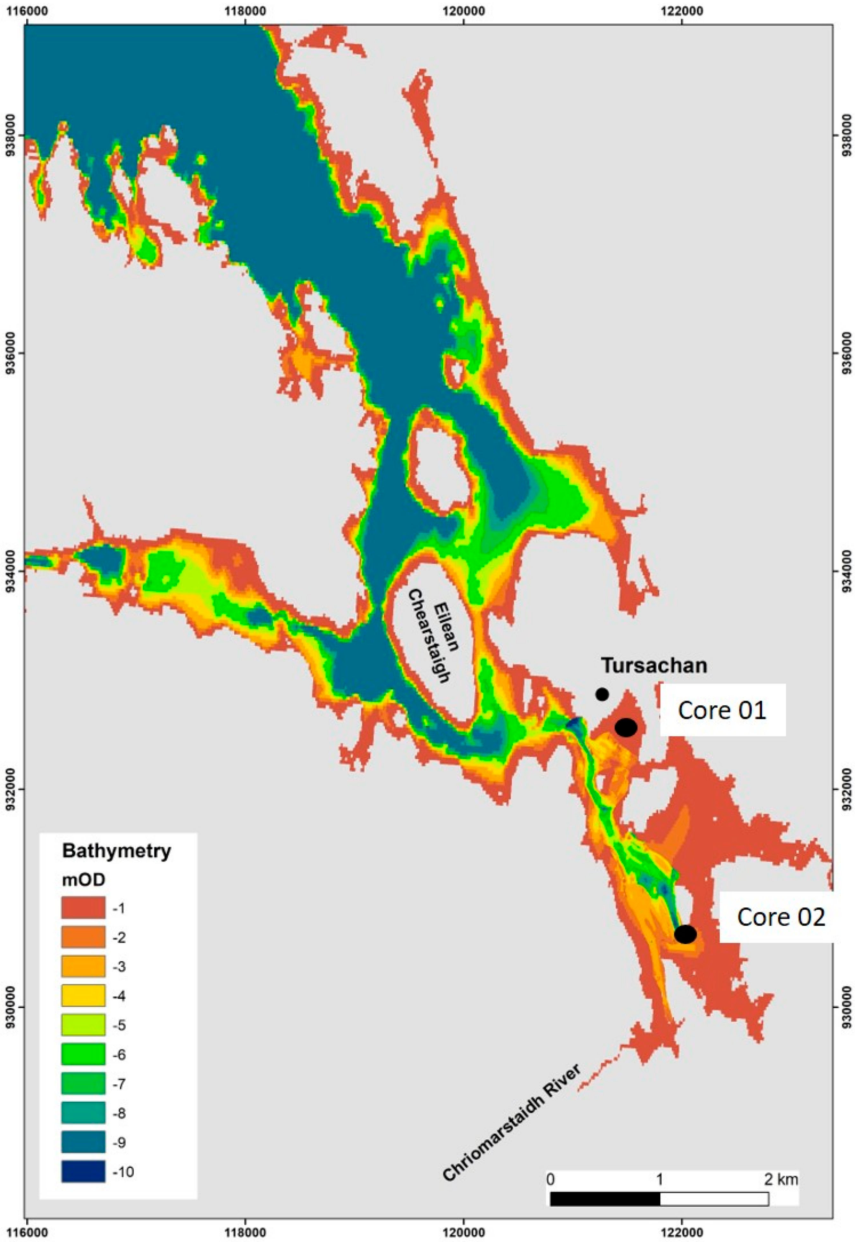

Figure 7. High-resolution bathymetry map of loch Roag showing core locations.

Sub-bottom profilers were obtained with both a Tritech SeaKing parametric sonar (Tritech Ltd.) and an IXBlue Echoes 1000 parametric sonar (IXBlue Ltd.). Survey lines were acquired in the inner loch and also at strategic locations between some of the narrow, shallow channels between the outer islands.

The sub-bottom seismic profiles showed thick sequences of preserved sediments, with multiple internal layering overlying strong basal reflectors. Examples of the sub-bottom sequences are shown in Figure 8a,b along west–east transects through core locations. Five seismic units representing a complex history of multiple sedimentation and erosion events are noted. The deepest surface is interpreted as basement and is marked by a strong reflector that is likely associated with the gneiss bedrock. Above this, a thin sequence of sediment fills the base of channel features and hollows. No clear reflectors are seen within this unit and it is interpreted as the remains of till overlying the bedrock. The top of this unit is again marked by a strong reflection event and the start of a package of sediment 1–3 m thick showing strong internal refection events that are sub-parallel to the underlying surfaces. The impression here is one of sediment draping across a palaeo-landscape rather than sediment infilling a basin or loch. These sediments are abruptly truncated with an erosion surface above, and they are marked by a lack of coherent internal reflectors. Within this sequence are a number of point reflectors with small hyperbola. These features represent seismic energy reflecting from buried material that is stronger than the surrounding sediment and are likely to be small boulders. The other substantial feature mapped during survey were places where all internal structure was lost due to the presence of gas in the sediment. The gas is derived from decomposing organics, probably peat layers, deeper in the sediment sequence.

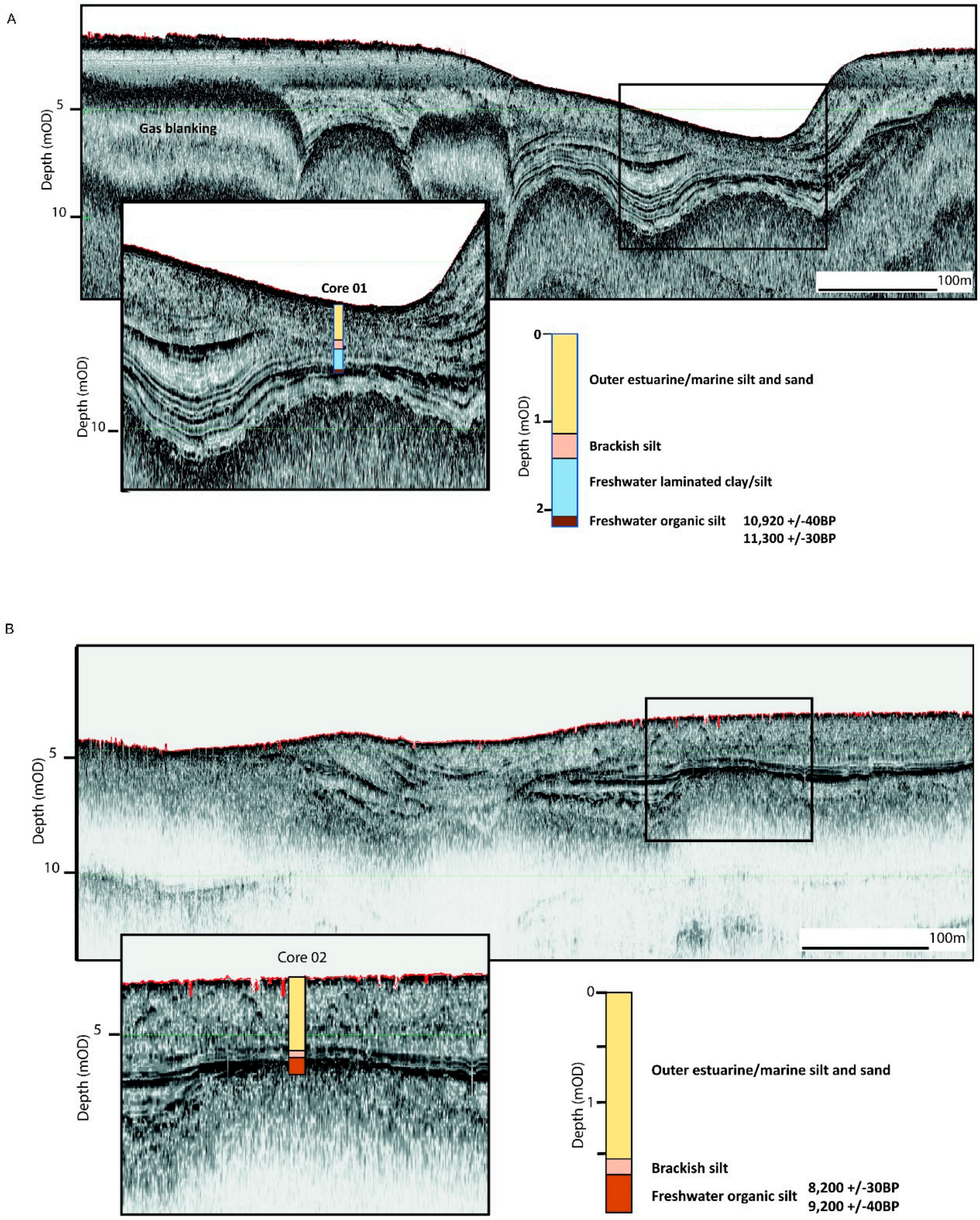

Figure 8. (**a**) Sub-bottom seismic section acquired east to west through core site 01 south of the Tursachan. (**b**) Sub-bottom seismic section acquired east to west through core site 02 in southern Loch Roag toward the inlet Chriomarstaidh river.

8.6. Core Samples

Two cores were acquired at specific locations in order to ground truth the seismic data and for the recovery of material for palaeo-environmental analysis and dating (Figure 8a,b). Core 01 showed a lithology consisting of organic silts at the base of the core (–8.15 to –8.25 m) overlain by a series of interbedded grey clay-silts (–7.40 to –8.15 m). The lowest interval (–8.10 to –8.22 m) contained organic silt, rich in distinctive plant debris: Cladocera (water-flea) valves and in the lowest part, charophyte oogonia. The data suggest a shallow weedy freshwater loch as the initial phase. The interval –7.60 m down to –8.07 m is represented by a curious deposit, leaving virtually no residue. The clay is light grey to white in colour and devoid of fauna apart from some small plant stems or possibly rootlets with a few small charophyte oogonia. This may represent a shallow freshwater body subject to drying out. The sample at –6.50 to –6.52 m contains rare *Elphidum williamsoni,* indicative of brackish water conditions. At –7.80/–7.82 m, there are a few brackish foraminifera possibly indicative of a storm event or overtopping of what might have been a low coastal barrier prior to full marine access.

At –7.43/–7.45 m the core contains an interval with many stones perhaps indicating a major high-energy event, possibly catastrophic, that could represent the first full marine incursion. Above –7.40 m silts and sands rich in marine shells were present. However, at –7.10/–7.12 m, the deposits contain brackish sediment-dwelling ostracods (*Leptocythere* spp.) perhaps indicating that this location was somewhat confined. Above this the sediment contained a rich microfauna of foraminifera, ostracods, and molluscs. The foraminifera are outer estuarine/marine in aspect and many of them cling or are attached to seaweeds and sea-grass—miliolids, *Ammonia batavus, Cibicides lobatulus*, and various species of *Elphidium. Eggerelloides scaber* is also particularly common—this is a detritivore, a subtidal agglutinating species which extends into slightly brackish waters in estuaries and is often epiphytic on sea-grass. The ostracods include *Celtia quadridentata* and *Robertsonites tuberculatus* (two "northern" forms) amongst others.

Core 02 showed a basal sequence consisting of brown organic silts between –2.03 and –1.42 m that is rich in organic matter. The upper part of this sequence shows an influx of minerogenic material prior to a return to organic rich sediments. This is overlain by grey clay silts and organic sands. The base organic silts are rich in plant debris with some distinctive seeds, insects, and the crushed valves of Cladocera (water-fleas). This sequence represents a freshwater body, although proximity to the sea is indicated by the presence in the basal sample of brackish foraminifera, probably suggesting that the coastal loch was subject to overtopping as a barrier was breaking down. The uppermost two samples, from –0.40 to –0.82 m, contain a fairly rich and diverse microfauna and some molluscs, but lack some of the species seen in Core 01, most notably miliolids and *Cibicides lobatulus.* Nevertheless, *Ammonia batavus* and *Eggerellolides scaber*, in particular, are again very common. The faunas at –1.20/–1.22 m include only one ostracod, *Pontocythere mytiloides*, and that preserved only as an organic shell, probably indicative of decalcification. There are some fish remains in the –1.30/–1.52 m interval that are not seen in Core 01, but the microfauna is represented only by a few, almost entirely decalcified, foraminiferal shells. There are no white clays in this sequence.

Dating of the organic sediments in both cores has been achieved through plant material and the full results of the dating are given in the Supplementary Materials. The dates from core 01 (–8.24 m and –8.15 m) suggest that the basal organic sediments belong to the Late glacial interstadial and the earliest part of the Younger Dryas. The presence of sediments devoid of faunal and floral remains between –8.15 m and –7.60 m, which is consistent with a return to severe cold climate conditions. By contrast, the organic sediments in core 02 have dates belonging to the Early Holocene (sensu Walker et al. [23]).

9. Discussion

Land and marine geophysics have been successfully applied, together with ground truth investigations, in the reconstruction of palaeo-landscapes at many coastal locations in the UK. Preliminary data collected in the Calanais landscape suggest that a combination of techniques will be equally effective at both revealing buried features beneath the peat and also for reconstructing the wider palaeo-geography of the area.

The results from marine survey have demonstrated that significant submerged sediment sequences exist in sheltered loch locations, and that these can be used to target coring to support our understanding of the sequence of rising sea-levels. Based on the bathymetric surveys to the south, west, and north of the Tursachan, the modern bathymetry and buried land surface indicate that a drowned valley landscape was present in the past represented by a series of freshwater lochs joined by rivers flowing over a set of lips or waterfalls. The dates obtained from cores demonstrate that wetland sequences were accumulating in the area at elevations below present-day sea level and during the Early Holocene. At this time, coastal conditions must have existed close to the core site given the presence of brackish water forams even in the lowermost samples from the borehole. However, the model most accurately represents the ancient land surface where rock is exposed on the seafloor today without sediment cover. Furthermore, rock barriers or lips on the seafloor represent minimum depths to ancient land surfaces, and if they had once been covered by till or gravel/cobble banks, then they may have acted as greater barriers to the encroaching sea in the past.

Throughout most of prehistory, access to the marine environment from the Tursachan would have been through a channel between Eilean Chearstaigh and Great Bearnaraigh with the site of Cleitir (Calanais Site VIII) marking not a narrow channel to the open sea but rather a narrow causeway, that would have been exposed at low tide from the main island over to Great Bearnaraigh. Flooding of the valley immediately to the south and southeast of Tursachan would only have occurred when sea levels over-topped the shallow lip immediately to the west of the site at –2 m OD. The dating evidence from the core suggests that occurred at approximately 8.2 ka (around the Early to Middle Holocene boundary), thus significantly before the stone circles were built but probably not before the first people had started to use the landscape.

At Calanais Site XI, a combination of the surface electromagnetic conductivity measurement and electrical resistivity tomography provided methodologies that showed areas of extensive peat build-up over the highly resistive bedrock. Using electromagnetic surface techniques, it was relatively easy to cover ground rapidly and, when combined with 2D ERT data, mapping peat thickness over large areas can be achieved. Neither technique proved particularly useful for mapping very small buried (stone) features. However, some anomalous signatures were observed with the inphase portion of the electromagnetic data and these could be correlated with larger accumulations of stone. The Mini-Explorer and Earth Resistance surveys also demonstrated a correlation to exposed rock at the surface and perhaps with shallow buried rock. Neither technique showed a clear signature in association with the extant stone at the site.

The surface geomagnetic results proved of great interest. A characteristic bi-pole spot anomaly was associated with the standing stone at the site and another 12 paired anomalies were mapped forming an approximate circle extending from this stone. Bi-pole anomalies in magnetic data have been noted previously, for example by Aspinall [24] during an investigation of the recumbent stone circle at Rothiemay, Banffshire. It is noted that these anomalies are relatively small in magnitude and thus likely non-metallic in origin. Further, the positive/negative bi-pole orientation is random. Such a random distribution suggests that they are inherently magnetic rather than exhibiting an induced magnetic behaviour. It is postulated that these anomalies are associated with further buried stones or the pits that were associated with the stones.

If these were settings for stones, or buried stones, prior to the extensive peat formation indicated from this research, exposures of bedrock would have dominated this landscape even more that they do today, with the steep slopes providing ample source material for the stone circles. Richards [7] has suggested that the use of texture could be a way to classify and determine the origin of the stones: that is to link individual stones to particular quarry sites. Field observations on variability in textures of the gneiss, including the foliation and later quartz fracture infilling, note that such features are ubiquitous to the geology across the landscape. Consequently, classifying the stones by form (eroded vs. 'quarried' faces) and texture alone will not provide a unique answer to their potential source outcrops. With the ample supply of stone across the landscape the need for (human) transportation of material widely would not have existed and therefore the conclusion that Richards reaches ' … that the high stone circles appear to be constituted of the stone up on which it once stood' is likely to be correct for many of the monuments.

The two linear bi-pole features identified during magnetic survey are of particular interest. Such patterns are typically associated with large lightning strikes. One set is located at the centre of the 13 positive/negative pair anomalies interpreted as a buried stone circle. At this location, there are no visible features that might be associated with a lightning strike such as stone fragments, plasma spatter, lichen, or moss death, or any upstanding feature that might act as a lightning attracter. The other pattern is located to the west of the sheilings on the east side of the grid. This second anomaly is not as clear as the first and may result from interference with the magnetic signatures associated with the large piles of stone at the surface here.

Lightning strikes have been previously been recorded in geophysical data as magnetic anomalies, although these mainly occur within datasets recorded in arid areas such as the southwestern United States [25]. Similar features have also been recorded in geomagnetic data in the UK, but they are not common. Their occurrence within magnetometer datasets on archaeological sites in the UK is equally sparse with only two examples recorded in the literature from Wales [26,27]. Strikes typically manifest as linear di-polar anomalies that can form large (metres to tens of metres) anomalies due to skin currents induced in the struck surface. Lack of recognition of such features within archaeological surveys may be due to the fact that acquisition data density is often too limited to recognise such features [28], or it may be that they are ignored as they are not anthropogenic. Whilst the presence of strikes should be carefully reviewed, especially if magnetic methods are to be used to define properties of stone, it is not impossible that lightning strikes may have cultural significance, and this is worth discussing in respect of their presence at Calanais Site XI.

Where strikes do occur in Britain, they are frequently associated with large upstanding features: such as high buildings, tall trees, or posts, as described by Macki et al. [29]. Lightning is well-established not to strike uniformly on a landscape. This is mainly because primary and return strokes, in both cloud-to-ground and ground-to-cloud directions follow current "leaders", which typically are dm - m wide and "jump" by approximately 1–10 m laterally between adjacent segments. Lightning thus effectively searches for and locates positions of charge build-up or, for effective discharge/grounding, places on a land surface. Persistent features such as trees, stones, or conductive minerals will tend to be struck multiply over time. At Site XI, no upstanding feature exists today although the site itself is very exposed. It is noted that the exposure is a significant characteristic of the site and that this has been referred to, in an archaeological context, when considering the site's visual qualities [7]. In discussing the presence of strikes at Site XI, it should also be noted that lightning energy is immediately dissipated by heating where ground has a high-water saturation. As this is almost always the condition of peat, it is reasonable to assume that the size of lightning strike recorded in this survey must be associated with either the underlying rock or low saturation boulder clay layer on top of the rock. When lightning hits relatively dry rock surfaces, it also does not penetrate downward; rather, skin currents extend outward along the free surface to a distance proportionate to the current density.

These characteristics of strike require the detected signal at Calanais XI to have occurred before the peat had accumulated. The spatial size and intensity of this 'fossil' lightning magnetic signature also suggests that it may represent multiple, repeated strikes (whether in a single storm or cumulated over time), and also for it to have a relatively high current density. In the Western Isles, significant peat accumulation began from approximately 5900 BP and, therefore, for the lightning strike signature to have been preserved, it most likely predates this, and therefore provides a terminus ante quem for the strike. More than a decade of satellite-detected lightning strike frequency by the TRMM satellite (OTD and LIS detectors) indicates that the modern lightning strike frequency on Lewis is ca. 0.1–1 strike per square kilometre per 10-year interval, and is the lowest non-zero pixel value in its survey record [30]. The Calanais XI survey site covers ca. 0.05 sq km and so the expected occurrence of randomly distributed lightning on the landscape, if pre-peat lightning frequency were similar to that of the past 15 years, would be 1 strike per 200–2000 years. Within 1 sq km of the site, there are exposed rock outcrops in crags and cliffs, and the rugged relief of these exposures is not suited for magnetic surveying. It is possible, therefore, that that the modern (and the ancient) uniform-frequency lightning strikes expected for the Calanais XI location would also have struck these outcrops. In that case, a fossilized, buried, pre-peat significant lightning strike at Calanais XI would seem even less likely in the absence of an unrecognized attractor within the stone circle. The multiple strike inference, given the scale and magnitude of the central dipole anomaly, would increase this non-uniform strike attractor inference many fold. It is not possible to determine if the strikes occurred before or after the stone circle had been constructed but the presence of the strikes here is none the less intriguing.

There is at least a possibility that the strikes were associated with a feature of the landscape, such as a tree, or large, natural rock, that no longer exists. If such features had some cultural significance to the people on the island, then the stone circle might memorialise such a feature or simply record a natural event that was noticed and judged significant by contemporary communities. A comparison could be made with studies mapping lighting strikes at the Buffalo Slough Mound Group in Dakota where historical evidence, supported by archaeological and geophysical data, suggest that lighting was an important aspect of the Dakota world view; 'construction of mounds on lighting prone landforms may have been purposeful, and that landscape modifications within mound complexes increased the probability of strikes' [29]. Even without any upstanding feature, it is recognized that the site of Calanais XI is exposed and might preferentially attract lightning. The construction of a stone circle, deliberately located in a dominant position above the Calanais monument complex, might enhance the chances of such events. In such a situation it would be difficult, and perhaps not even useful, to determine whether these, or other, characteristics of the landscape were most significant in the decision to construct a stone monument on this position, as all may have been important to the contemporary inhabitants of Lewis. However, the archaeological literature increasingly recognises the symbiotic role between culture and nature in the past [31] and, if that were the case at Site XI, this survey demonstrates the benefit of exploring buried landscapes of the western Hebrides through careful use of different remote sensing techniques. Aside from landscape development, the results suggest that prospection may also lead to novel insights into the perception of natural phenomena by past peoples that cannot be inferred by any other means.

10. Conclusions

The results set out within this article demonstrate that reconstructing palaeo-landscapes can be accomplished in these challenging environments through surveys that employ a range of remote sensing technologies, together with an appropriate methodology to ground truth the results. Such an approach, linked with a full appreciation of the cultural aspect of the landscape, offers the potential to unlock new information about multi-periods of occupation in these frequently neglected areas. Furthermore, the insights from geophysical survey at Site XI support previous speculation relating to the construction of a stone circle on this location. These survey also provided, for the first time, information on a natural phenomenon, lightning, and suggests that such events may have had a profound significance to those communities who lived on the island and constructed the Tursachan and other monuments within the Lewis landscape.

Supplementary Materials: The following are available online at http://www.mdpi.com/2072-4292/11/24/2975/s1.

Author Contributions: The survey on Lewis was initiated and organised in the field by C.R.B. and M.B. survey and coring were undertaken by C.R.B. and M.B. Magnetic and resistance survey was undertaken by C.R.B., C.G. with V.G., T.D.R. undertook magnetic studies. Reporting was undertaken by All the Authors.

Funding: This research was funded by Scottish Enterprise.

Acknowledgments: The research was conducted in conjunction with the Calanais Visitor Center. Field work was undertaken with the help of Donald McArthur, Victoria Harvey, Melanie Chocholek, Siobhan Killingbeck, James Killingbeck, Iain Oliver, Fanny Bessard, Sarah Boyd.

Conflicts of Interest: The authors declare no conflict of interest.

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