

Water penetrating radar (WPR) in archaeology: A crannog case study

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ABSTRACT

WPR has had limited use in freshwater archaeology and can provide superb 2D data over sites with appropriate water type and depth, such as exists in this case study at Castlewellan Lake, Northern Ireland. Here, a submerged crannog (Prehistoric, usually Bronze Age to Medieval human structure in water) is only shown on one historic map, yet is not presently visible nor on other historic/recent maps. This work used a desktop study, sonar and WPR to characterise the submerged structure as a crannog. The asymmetry, bathymetric position, upper surface (rock slabs) and general topography of the crannog are determined, yet the variable makeup of its interior and sides allow numerous theories and possibilities for further, probably non-invasive investigation. The limits, problems, data processing and uses of WPR for archaeology in this environment are described, some of which may be useful in other studies of freshwater archaeology, including crannogs, flooded dwellings, walkways/jetties and military archaeology.

1. Introduction

1.1. Freshwater geophysics

The adaptation of ground penetrating radar (GPR) to surveying freshwater (WPR) has been limited, due to occasional poor results such as conductive water and unsuitable deployment (type of vessel, antenna frequency: see [Ruffell and Parker, 2021](#)), as well as a misconception that radar does not work on water (see the discussion at <https://sensoft.ca/gpr/the-water-myth/> for an example). WPR has, however found favour in engineering (bridge scour assessment: see [Gorin and Haeni, 1989](#); [Forde et al., 1999](#)), palaeoecology (sedimentation rates, siltation: see [Lachhab et al., 2015](#); [Fisher et al., 2007](#)) and forensic search applications: see [Ruffell and Parker \(2021\)](#), as well as in studies allied to archaeology, such as tephrochronology ([Lowe, 1985](#)). The uses of WPR in archaeology are limited, with (for example) [Qin et al. \(2018\)](#) providing a focused search for historic Chinese ceramic kilns in a reservoir and [Ruffell and Parker \(2021\)](#) using case studies of flooded 18th century trackways and a crannog (different to that described here). This is primarily due to the abundance of terrestrial archaeology vs. that beneath freshwater; the common use of sonar, as well as other geophysics (magnetometry, CHIRPS [Compressed High-intensity Radar Pulse] and divers; lack of expertise and the effort required in boat/radar deployment, positioning and safety. Conversely, the building of dams,

land subsidence/water inundation, increased flooding and the preponderance of human activity near water (especially freshwater), make aquatic archaeological important. Remote sensing and geophysics are relevant for the correct location, characterisation, preservation and retrieval of sites and artefacts, especially if threatened by human activity or degradation. Given the above, the aim of this work is to consider whether WPR provides an effective and useful tool in freshwater archaeology, especially when used in conjunction with sonar, taking the search for an enigmatic crannog in County Down (Northern Ireland, UK) as a test case.

1.2. Crannogs (Lake Dwellings)

Crannogs (from the Irish, *crannóg*) are generally Bronze Age to Medieval artificial structures, built in lakes and estuaries throughout Scotland, Wales and Ireland ([Armit, 2003](#); [O'Sullivan, 1998](#)) and they are interpreted to be defensive structures, similar to the Prehistoric pile dwellings of the German/Austrian Alps. Some date from the Neolithic and occur as late as the 17th Century ([Lynn, 1983](#)) and were either extensions of promontories or wholly constructed in water: with changing water-levels, this can be hard to differentiate. Whilst some crannogs are wholly water-inundated, some (as in this case study, see below) emerge or are submerged through time via human damming/drainage, subsidence and climate change-induced increases in water

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volume (Cavers, 2006). Commonly comprising wooden supports with stone interiors and exteriors, that must have taken considerable effort to construct (Garrow and Sturt, 2019), crannogs provide a rich source of contextualized archaeological information: many are complex (O'Sullivan, 1998) remaining largely undisturbed and/or without significant excavation (Garrow and Sturt, 2019). As a result, there is an abundant published literature on Irish and Scottish crannogs (Crone, 1994; Garrow and Sturt, 2019; Henderson and Sands, 2012; O'Sullivan, 1998; O'Brien et al., 2005). Due to their construction on promontories or in shallow water, many crannogs are known from historical and recent observation: however, in natural lakes (with no change in water level) or where flooded before accurate mapping, crannogs have been accidentally discovered in the course of other archaeological work (e.g. Lagore, County Meath, Ireland: see Wood-Martin, 2021) or through geophysical investigation (Ruffell and Parker, 2021) – one of the drivers behind this research. Here, we outline a case study involving the location and characterization of a crannog (unknown age) in Northern Ireland as an example of using WPR: this provides us some results for interpretation, translation to other sites and how water depths over 10 m may be explored in future studies.

2. Methods used –Sonar, WPR, GPS, Depth-sounding

2.1. Sonar

Sonar comprised initial visual scanning using a Starfish2000 device, which suffered high reflectance scatter from fish and weed. Consequently, we found it more effective to gather sonar using small (7 cm diameter) commercial fish finder devices simultaneously to obtaining WPR data (in summary, the radar is in or behind the boat [see below] and the sonar hangs over the side). For this, we used a Deeper™ Smart Sonar Pro + 2 and a Deeper™ Smart Sonar CHIRP + 2: the latter gathers data in both shallow (-50 cm) and deep (80 m) water and has some sediment-penetration capability, providing visual comparison of outputs to WPR. Descriptions of hydrographic survey validation and uses of the Deeper™ Sonar devices, may be found in: Bandini et al. (2008); Giambastiani et al. (2020) and Ruffell et al. (2021). The Deeper™ Smart Sonar CHIRP + 2 used here was programmed to gather data in narrow-beam (15°) boat mode for GPS location, vertical imaging and bathymetric mapping. No post-acquisition processing was conducted and the manufacturers bathymetric map outputs were used.

2.2. WPR (water penetrating radar) – Equipment

Conventional ground penetrating radar Mala Geoscience^{MV} systems were deployed comprising either a 160 MHz high dynamic range shielded antenna and GX control monitor or 50, 100, 200 (unshielded) and 500 (shielded) antennas, linked to a Pro-Ex Control Unit and monitor. The latter were deployed in the same manner as described by Ruffell and Parker (2021: their Fig. 1), with antennas in three orientations: 200 and 500 MHz in parallel broadside [PBs] and parallel endfire [PEf] in the base of a rubber inflatable boat (with foot-slats removed) or 50 MHz and 100 MHz as in-line endfire, water-proofed and towed by the same boat, with an electric MinKota electric trolling outboard engine. Readers interested in modes of WPR deployment and the technicalities of vessel type, may read Ruffell and Parker (2021) for full details. Initial trials with a 50 MHz rough terrain antenna (for deep imaging) and 160 MHz high dynamic range (HDR) shielded antenna array showed some success, whereafter 100 MHz, 200 MHz (unshielded) and 500 MHz (shielded, largely unsuccessful due to water depths) were used for their lightweight nature and (in the case of 200 MHz) versatility. Where possible, WPR was gathered in low wind conditions on a constant engine throttle speed of 2 knots. The desktop study (below) and preliminary site visits were conducted for two reasons: i) these indicated no significant floating or upstanding objects that may cause out-of-plane reflection artefacts on radar data; ii) Health and Safety risk assessments of boat handling, flotation, emergency contacts also included sailing hazards, such as submerged trees, discarded fishing tackle and other lake users.

2.3. WPR data acquisition

An assumed radar wave velocity of 0.033 m/ns was used, where the dielectric constant is $D = 83/\alpha$ meters (α is the coefficient of attenuation) at 8 °C (winter) to $D = 81$ at 15 °C (summer): the lake water is of neutral pH (see below). The combination of refractive focusing of the radar wave at the air to water interface (creating a narrow radar beam of 5° to 10°) and slow propagation (a 100 MHz wavelength is about 33 cm in freshwater, yet 3 m in air), allows good penetration and resolution of radar waves. The time window (how long each radar wave takes from transmission, reflection to receiver, or two-way travel time) differs for each antenna frequency, so is shown on radar profiles (below). Two issues arise: first is survey speed, which has to be slow enough to allow radar transmission and reflection, but this causes the generation of

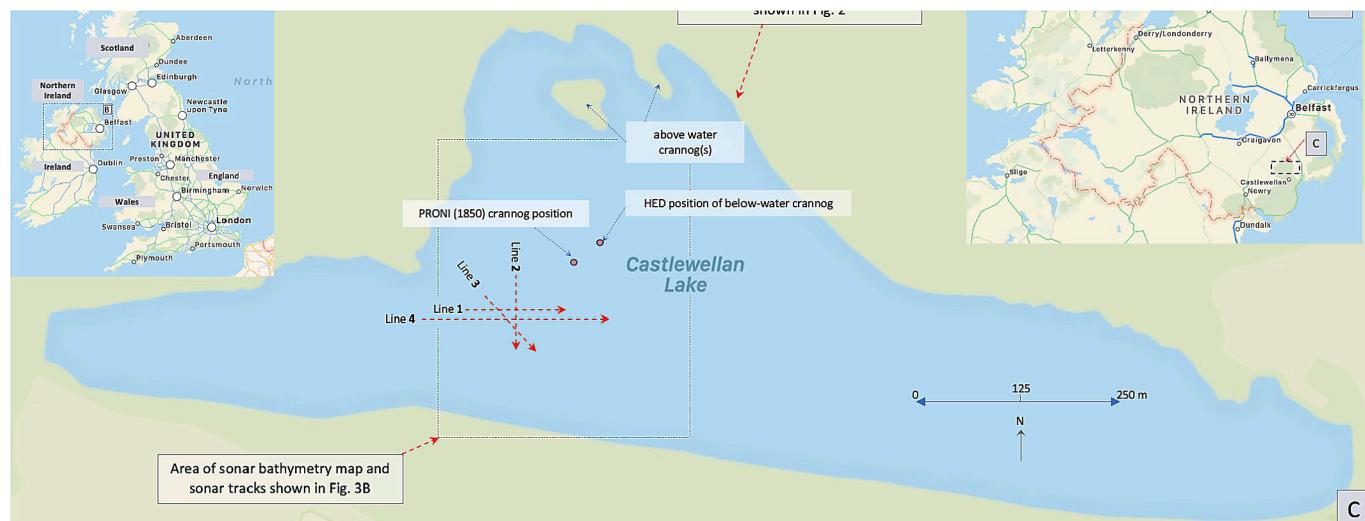


Fig. 1. A: location of the study area in the United Kingdom and Ireland: crannogs are common in Scotland, Ireland and Wales (bold). B: Location of the site and lake in the north of Ireland (Castlewellan Country Park approximate area in dashed box). C: map of Castlewellan Lake with key features (WPR lines, recorded locations of crannogs with sources: PRONI = Public Records Office for Northern Ireland; HED = Historic Environment Division, Department for Communities). Basemaps modified from AppleMaps under terms of use: <https://www.apple.com/uk/legal/internet-services/maps/terms-en.html>.

surface and water-bottom multiples and second the assumption of the lake waters being homogenous, when changes in dissolved/suspended solids and temperature thermocline may alter this. If measured, such depth changes in velocity may allow a layer-cake velocity correction, beyond the scope of this work.

2.4. WPR – Data processing and interpretation

WPR data were viewed unprocessed (raw on figures) during each survey. Initially, we show uninterpreted data to assess antenna frequency/orientation and processing, gradually focusing on increasing interpretation of 200 MHz lines over the identified feature and longer (~200 m line length) 100 MHz WPR for context.

WPR data gathered here had air–water multiples (ringing in some literature) on all frequencies used, which were suppressed during processing using background removal on site in Mala's built-in software or following each survey using the software package ReflexW. Manual gain was applied to 200 MHz and 500 MHz data, as this amplifies deeper radar reflections and can eliminate the unwanted effect of increasing noise with depth. Background removal can suppress the horizontal ringing from multiples by calculating the average radar pulse from the entire radar profile to be subtracted from each radar wave (Goodman and Piro, 2013). Such background removal can, however, remove subsurface horizontal reflectors. Otherwise, unprocessed data from the study location was clear enough to allow the interpretations described. Castlewellan Lake has some stream catchments from mixed deciduous parkland and is a recreational boating facility, from which we conclude that the waters are of good quality, providing clear WPR data.

2.5. Positioning – GPS

WPR data were recorded using a time-trigger, with start/end and direction change points marked using both the in-built GPS on the 160 MHz antenna or a hand-held Garmin eTrex 60+ (2–3 m lateral accuracy in this open environment) when using the 100, 200 and 500 MHz antennas. The same device was used to pre-load coordinates of published crannog positions (see below), the used the GoTo Function and initiate the survey. The footprint of a radar beam increases as an elliptical cone from the length/width of the antenna at surface, imaging an increasing area of lake bed and subsurface sediment with depth. Differential GPS, whilst accurate for the start and end points of a survey, is pointless when a radar reflection may be metres in front, behind or either side of the survey: lower frequency antennas have a proportionally larger footprint.

2.6. Depth verification

Sonar and WPR data were compared on site to check each was measuring similar depths. WPR was verified and adjusted using a plumb-bob and (over shallow water) with van Walt fibre-glass peat probes, gently tapping on firm lake floor or probing into soft sediment. Such probes come in 75 cm lengths, making them ideal for boat deployment, and can be positioned to check they are vertical.

3. Site and area background - (Site Location, Geology, Topography, Hydrology, History)

A desktop study was undertaken to derive what extant textual records could be found: geological/topographic maps showing the lake and surroundings were brought into QGIS for comparison and focusing of any water-borne survey. The study site is centered on a natural lake (raised by damming in the late 19th Century for aesthetic purposes) at Castlewellan Country Park in County Down, Northern Ireland: Fig. 1).

The lake is ~ 0.57 km², is 1.75 km long (east to west) and from 0.5 km to 0.2 km wide (north to south), with an above-water raised island in the northern embayment (Fig. 1) and two occasionally isolated islands adjacent (depending on lake levels). The maximum depth recorded by

Griffiths et al. (2015) is 22 m. The solid geology of the area (from Mitchell, 2004) comprises erosion-resistant late Caledonian (~410 million years old) Newry Granodiorite (a fine-grained granite) to the west, with Lower Palaeozoic (430 to 415 million years old) greywackes (metamorphosed sandstones and shales) of the Gala and Hawick groups, forming more subdued topography to the east (Fig. 2A): the north-south/northeast-southwest trending boundary of these two rock types has a bearing on our interpretation (see below).

Both are intruded by erosion-resistant (possible elevated ground north of the lake in Fig. 2B) Palaeogene (~55 million year old) intrusive dykes. Superficial sediments comprise Pleistocene diamictite tills (Mitchell, 2004) in low ground, with solid geology close to surface in upstanding areas to the north and northwest (Fig. 2B) of an east–west trending glacial valley, which became Castlewellan Lake (Fig. 2). The lake is known to be at least ~ 20 m deep (Griffiths et al., 2015), with no major fluvial inputs excepting small streams. Water quality was measured by us to assess radar wave permeability (which can be diminished with increasing conductivity), with a conductivity of 2200 µS/cm at 15 °C, nitrates at 50 mg NO₃/l; chloride at 14 mg Cl/l; sulphates at 220 mg SO₄/l; iron at 220 ug/Fe/l, these values allow us to apply a standard freshwater radar wave velocity for depth conversion. Blooms of poisonous blue-green algae occur in springtime, survey times avoided this on advice from the Department of Agriculture and Rural Affairs, Northern Ireland: the lake is known to have good-quality water otherwise, being home to the rare upland water crustacean *Mysis salemaai* (Griffiths et al., 2015), demonstrating the good water quality, confirming low conductivity and ideal for WPR surveying.

The castle at Castlewellan (from the Irish: *Caisleán Uidhilín* 'Hugelin's Castle' or 'McQuillin's Castle') Lake was built in a Scottish baronial style by the Annesley family from 1856 to 1858 (Mullen, 2005) on the site of a previous church with nearby pre-existing buildings known to be at least of Queen Anne style (early 1700s), along with the possible location of the original castle, called Caisleán an Mhuilinn, ('Caisleán' in Irish often refers to a stone building not a true castle).

Directly south of Castlewellan Castle, the shores of the lake have been raised and reinforced, testament to the Annesley family increasing the lake level sometime following construction. Consequently, the First Series Ordnance Survey of Ireland map (1832–1846: Fig. 2C) shows no castle, and intriguingly, no crannog – whilst the Second Series (1846–1862: Fig. 2C) shows the early footprint of the castle and crannog (1846–1862, recorded as 1850). Later maps 1905–1957 and 1957–1986 do not show the crannog. This suggests either poor mapping in the First Series, or that the inundation of the crannog is not wholly due to the artificial raising of the lake level. Regardless, the Second Series record of the crannog is not mapped before or after: nonetheless, there are eyewitness and personal accounts (from the authors) of a feature emerging in periods of dry weather, so its location is recorded both by the Department for Communities (Northern Ireland) HED (Historic Enquiries Division, 2021) of the and the Public Records Office for Northern Ireland (PRONI, 2021), although the location is recorded differently by each (Fig. 1C).

4. Results

4.1. Sonar

Individual sonar lines were gathered east–west through the entire lake, with the area of the previously-recorded location of the submerged crannog surveyed in detail (Fig. 3A): water depths in these locations proved to be 8 to 10 m, with no indication of shallower water at their mapped positions. To the south of these HED and PRONI records, a 5 to 15 m wide platform at 1 m depth was observed (Fig. 3B and C): gentle pressure from peat-probes indicated flat rock at this location (probe did not wedge between stones), marked by GPS for further investigation by WPR. Sonar depth data from the Deeper device showed a consistent asymmetry – steeper with a forebulge (Fig. 3C) and over 10 m water

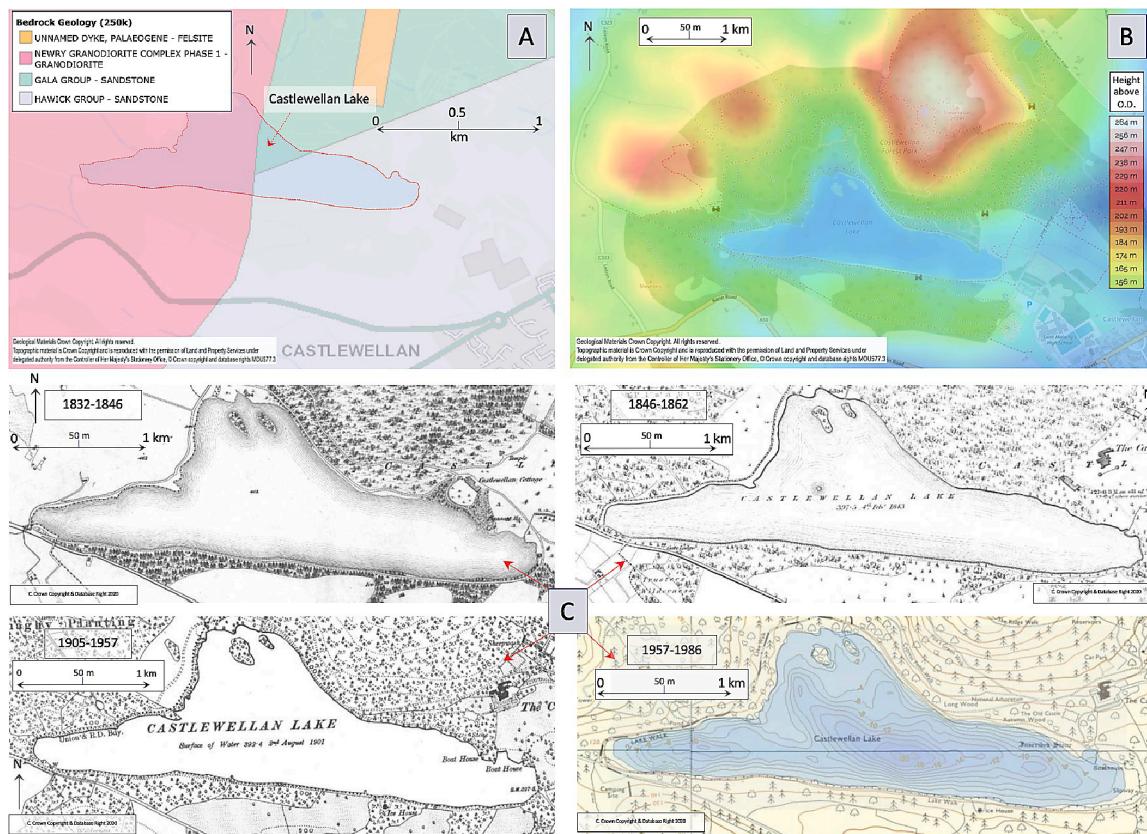


Fig. 2. Desktop study data. A: solid geology, with Castlewellan Lake highlighted (red dotted line), note the north – south oriented boundary between erosion-resistant granodiorites to the west (some uplands) and subdued topography of Gala/Hawick group(s) greywackes to the east. Data (including key) from Geological Survey of Northern Ireland GeoIndex (https://mapapps2.bgs.ac.uk/GSNI_Geoindex/home.html). B: topography, with uplands to the north, no major fluvial inputs and two mapped crannogs in the northern embayment. Data modified from Open Source data at <https://en-gb.topographic-map.com>. C: Historic maps of the area and lake, with no crannog mapped on three, yet visible on the 1846–1862 Series (during the time of the castle construction). Data from PRONI: <https://www.nidirect.gov.uk/campaigns/public-record-office-northern-ireland-proni> and HED Historic Map Viewer (background mapping): dfcgis.maps.arcgis.com. Bathymetry from: Agri-Food & Biosciences Institute (Northern Ireland) after original mapping supplied by Robert Rossell, DAERA with thanks, overlain on the 1957–1986 map.

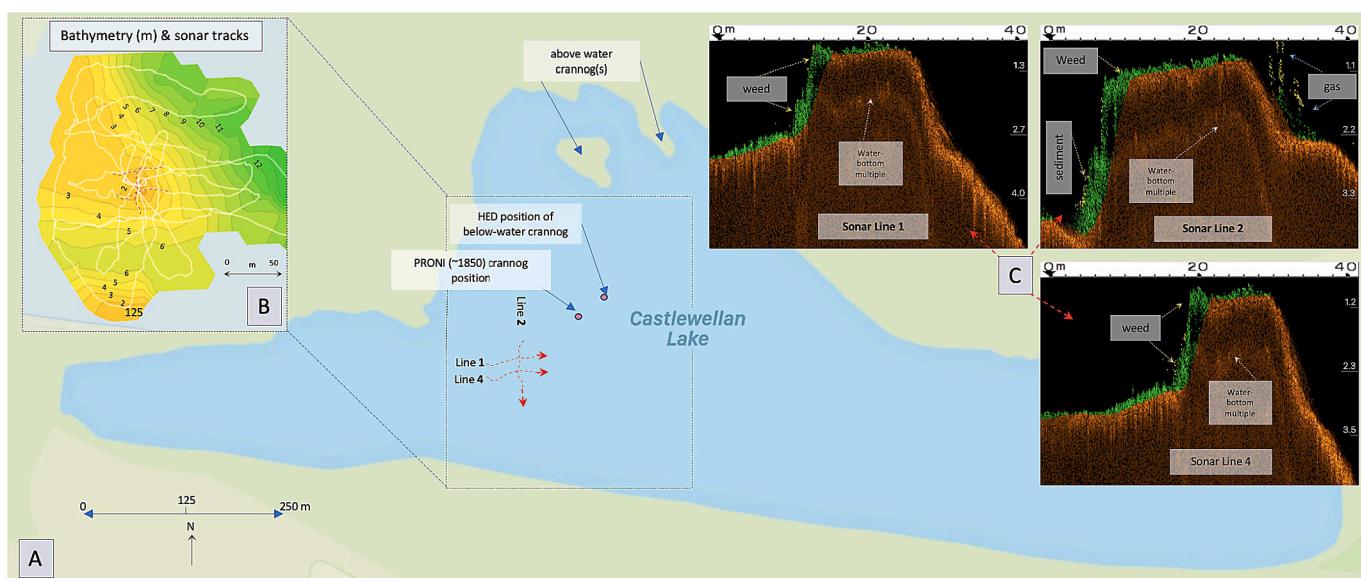


Fig. 3. A: map of selected sonar profiles (seen in inset C) in relation to mapped locations of crannogs. B: Sonar bathymetric map over the shallow area located in wider sonar tracks. C: selected portions of the DeeperPro sonar output, showing the form of the upstanding feature, hereon interpreted as a crannog. The upper two sonar profiles (inset C) are .
adapted from Ruffell et al. (2021)

depths to the east, remaining shallow to the west, southwest and northwest of the suggested location(s), shown as red dots on Fig. 3A. A 6 m deep channel was recorded to the south, midways between the upstanding feature (presumed crannog) and southern shoreline of Castlewellan Lake (Fig. 3B).

4.2. WPr

Following pre-survey trials with the 50 MHz Rough Terrain Antenna (RTA) and 160 MHz antenna, we assessed the effect of antenna orientation and processing using a 100 MHz RTA and 200 MHz unshielded antenna on the north–south transect (Line 1, Figs. 1 and 4) across the GPS-marked shallow water (from sonar and plumb-bob/probes). Both parallel broadside and parallel endfire antenna configurations imaged the upstanding feature (hereon, ‘crannog’) in exceptional clarity, with good sediment penetration at 200 MHz to 4 m (total) depth and water-bottom to 8 m depth, when surveys were halted (hence the asymmetry of line lengths on Fig. 4).

100 MHz data penetrated to over 7 m sediment + water depths, when meaningful reflections were lost (Fig. 4B) and surveys halted. Parallel broadside WPR data shows the sides of the crannog more clearly than unprocessed (raw) parallel endfire – reflecting the longer footprint of the latter, coincident with antenna orientation and boat movement direction. Parallel broadside orientations and processed endfire show the crannog width, probably an accurate depiction of the feature, albeit gathered in time-trigger mode, when even minor gusts of wind or a decrease in battery power for the engine may have resulted in a loss of spatial accuracy. We have intentionally left the data on Fig. 4 uninterpreted, to show the effects of background removal in diminishing the water-bottom multiples that can dominate WPR data (see Delaney et al., 1992; Sellmann et al., 1983; Sellmann et al., 1992) and the minimal improvement to depth penetration/clarity made in increasing gain (Fig. 4). Water-bottom multiples were most apparent on 100 MHz RTA Endfire (Ef) data, again reflecting the greater (elongate) footprint ahead and behind the antennas and boat movement direction, allowing this ‘ringing’ in the data to reverberate for longer than in parallel broadside mode, confirmed by the multiples continuing further eastwards (boat movement direction) at increasing depths from the slope of the crannog. Increasing background removal in the data caused the crannog to become vague (Fig. 4D), although when examined in detail, does

accentuate internal reflectors or WPR opacity (see below). From these 200 MHz and 100 MHz data, we were able to erect a scheme of radar facies for further interpretation (Table 1).

Given that 100 MHz RTA Ef data showed good penetration but less clarity over the crannog compared to 200 MHz data, the latter are displayed on a west to east transect across the crannog (Fig. 5, Line 2), compared to a selected sonar profile and one 500 MHz WPR line. As in Fig. 4 (Line 1), the 200 MHz clearly data show the internal structure of the crannog, which we have taken a stage further to reflect the development of our interpretations, using Table 1 as a guide. Endfire data shows the crannog as slightly wider than on broadside, again mirroring the orientation footprint, but consistent with the feature being elongate north to south (~20 m N-S long, ~10 to 15 m E-W wide). A prominent subaqueous elevation (here termed forebulge) on the northern flank of the crannog is seen (Fig. 5A–D), with bright hyperbolae in and on the crannog’s northern side, here suggested to be rocks, possibly armouring for defence or shoring-up the steep sides.

Opaque WPR data (below water) is suggested to be fine-grained/water-saturated (likely thixotropic from probing) sediment; laterally-reflective WPR data is interpreted as sediment layers (natural or anthropogenic) and speckled/hyperbola-rich WPR character may be mixed boulders, cobbles, silt and water (basically, rubble), as in Table 1. Examination of WPR data in isolation could lead the interpreter to consider the opaque, or ghost-like nature of the forebulge (labelled ‘fine sediment, ?thixotropic’ on Fig. 5B) as an out-of-plane reflection: however, the same feature occurs at the same geographic position on sonar (which does not suffer such out-of-plane features), and determined as resistant sediment when probed, and thus is real. Discontinuous, bright reflections occur along the flat-top to the crannog (also see on other data), where flat stones were indicated on tapping across the surface with the fibre-glass peat probe. Validation of the WPR shape of the crannog is provided by the sonar profile (Fig. 5E), whilst 500 MHz data, gathered to image the nature of the crannog top in detail, did not penetrate the water sufficiently to be of further use (shown here to demonstrate this).

In order to examine the sides of the crannog and negate any bias in survey line orientation, northwest – southeast oriented data was also gathered using the 100 MHz RTA in deeper water around the flanks of the crannog: one example is provided in Fig. 6 (Line 3). Here, the lateral extension of the crannog is at 2 to 4 m depth, broadening into an apron

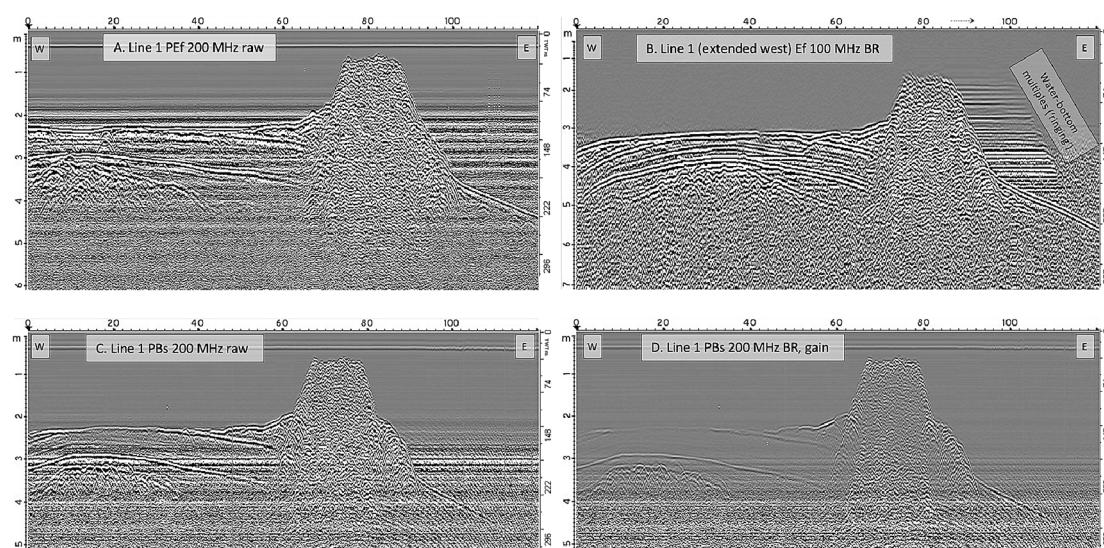
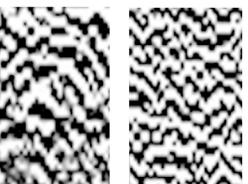


Fig. 4. Line 1. Uninterpreted selected 200 MHz lines and one 100 MHz WPR line to show the effects of antenna orientation, frequency and processing. PEf = parallel endfire; Ef = endfire; PBs = parallel broadside. BR = background removal. A: note excessive multiples (ringing) in raw data. B: multiples apparent on the east side of the crannog: boat movement was west to east (arrow), causing this continued reverberation. C: parallel broadside data suffers less multiples than parallel endfire data, due to antenna footprint along direction of survey (as in 4B). D: background removal limits multiples to 4 m+, gain has little effect; reflections become vague, but strong reflectors apparent. Depth conversion of 0.033 m/ns is crude, as dissolved solids at 2 to 3 m depth and a thermocline may occur.

Table 1

Typical WPR interpretation facies and reflectors from the crannog and surrounding sediments.

WPR characteristic	WPR Profile
Left – bedrock, multiple hyperbolas. Bright texture. Right – ‘rubble’ crannog infill. Opaque texture.	
Hyperbola-rich crannog sides, possible armouring. Bright texture.	
Opaque layers on lake floor, adjacent to crannog sides, likely thixotropic sediment.	
Object in sediment with multiple below or out-of-plane sediment surface object.	

of surrounding sediment. Thus the flat-top is no longer seen, but evidence of construction is apparent, with analogous rocks (?armour) on the north and north-western side, along with the forebulge, both seen on Figs. 4 and 5. A rubble core is interpreted, with layered sediment either side, which on the northwest appears to abut the crannog flank, and draped over on the southeastern side, with a sharp contact between layered sediment and possible rubble core.

Similarly to Line 3 (Fig. 6) we wished to both place the identified feature into context, as well as seek any other, deeper-water yet upstanding features using 100 MHz RTA data. Thus long (150 to 500 m) west to east WPR lines were gathered over the area, one 225 m long example shown as Line 4 (Fig. 7). Such lines proved particularly useful in showing the effects of processing (gain and background removal) as well as the western-edge shallow water (2 to 3 m depth) and steep-sided eastern edge of the crannog, adjacent to deeper waters (7 + m, where penetration was diminished, thus no data here is presented on Fig. 7).

We also take interpretation of the crannog further in Fig. 7, by focusing on the structure and laterally compressing the WPR to accentuate continuous, strong reflectors. These are shown in dashed red, continuous weaker reflectors (mainly within the crannog) in turquoise and steep discontinuities in dashed yellow on Fig. 7. This sideways compression of the data forces the crannog sides to appear vertical, albeit it nearly-so (75° to 80°), but aids in stratigraphic interpretation. The bright, parallel and sub-horizontal reflectors seen on other data (Figs. 5 and 6) on the crannog top, also occur on the shallow, gently-sloping western side: these could be slabs of rock, slipped from the crannog or as a firm base: if lake water-levels were lower during the time of use, this could this be a pathway or track.

5. Discussion

5.1. The crannog

This work has made some interpretations that merit further research. Firstly, the asymmetric nature of the crannog: it is shallow to the west, with a trough or channel to the south and steep to the east. This is roughly in line with the mapped boundary between erosion-resistant granodiorites to the west and more subdued, greywacke topography to

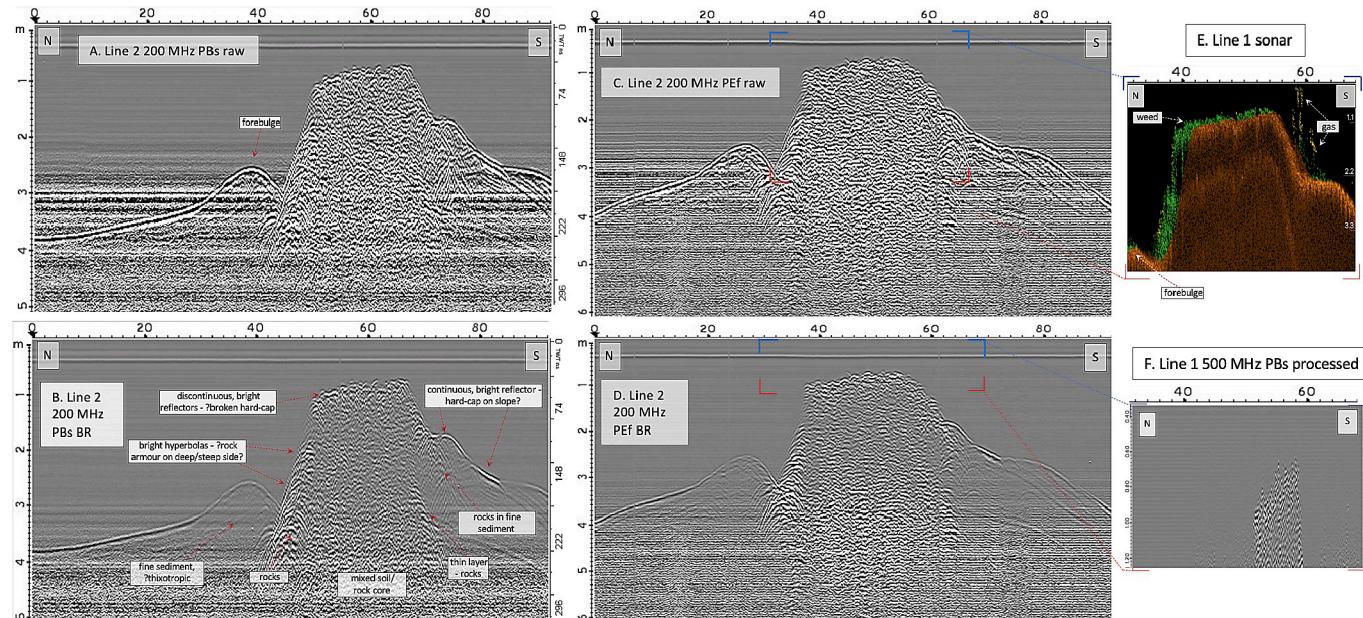


Fig. 5. Selected north – south 200 MHz profiles over the crannog, with comparable sonar and example 500 MHz data: Line 2 (Location on Fig. 1). A: multiples obscure data below 3 m, yet the crannog shape and internal structure, together with forebulge are clear. B: Interpretation of processed (background removal = BR) data in Fig. 5A. C: parallel endfire (PEF) 200 MHz data with inset to show (approximate) location of sonar data in Fig. 5E. D: Parallel endfire data to compare with broadside data and show location of the one 500 MHz profile (Fig. 5F) gathered.

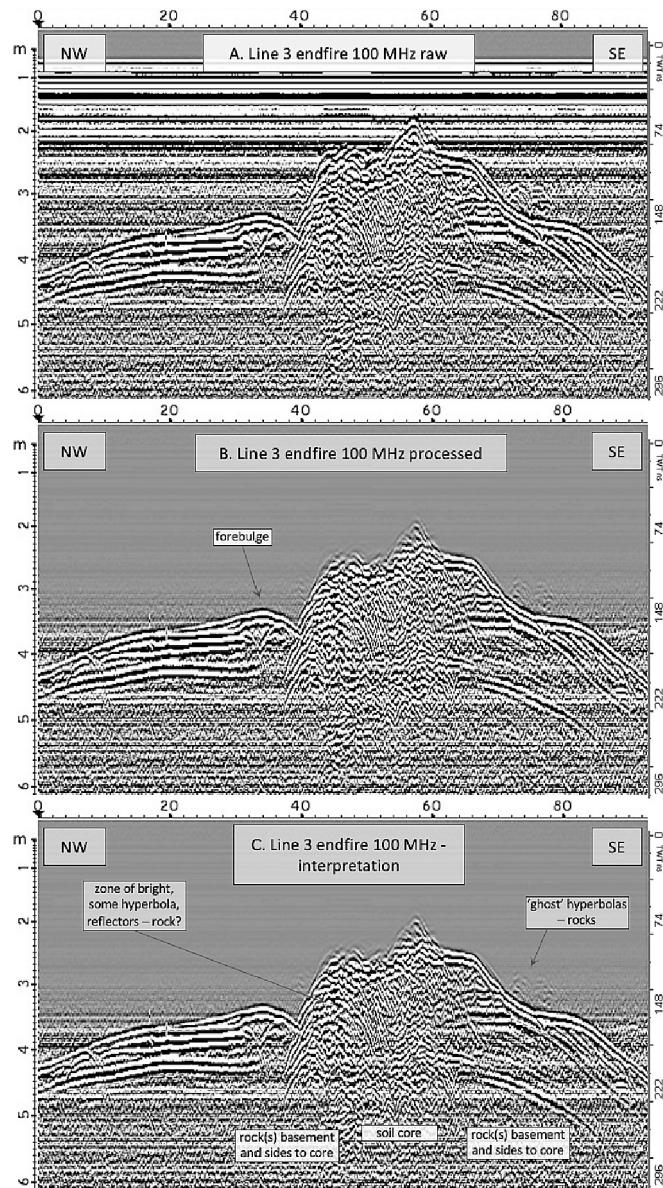


Fig. 6. 100 MHz endfire data, gathered southwest (off centre) of the crannog in a northwest – southeast transect on Line 3 (location on Fig. 1), to show that the feature has some similar construction-related features common to the crannog itself. A: Excessive water-bottom multiples occur, crannog flank construction and surrounding sediment clear. B: Background removal only applied; previous lines show that gain has minimal effect thus advantage in application. C: Further interpretation than in Figs. 4 and 5 to provide the reader with confidence in how we developed our understanding and theories in text.

the east, and thus may have a geological control, with the rock-armoured crannog positioned at the interface between shallow and deep waters, providing an access route. The crannog is also linear, roughly north to south, along the same orientation as the geological contact (granodiorite to greywacke) and thus shallow waters to the west and deeper to the east. This places the surveyed crannog in a north/north–north-east orientation with the other, emergent crannogs seen in Figs. 1, 2 and 3. A review of other crannogs, to see if symmetric ones have no underlying geological/bathymetric influence and those similar to this, do, would improve our understanding of where they were constructed. Secondly, the external nature of the crannog is interpreted to be rock armouring on the steep/deep eastern side, adjacent to the forebulge. Armit (2003) discusses how some crannogs were constructed with a mixture of timber and rock, thus some form of armouring is

possible here: this maybe a slipped mass or outer defence. The depth and radar frequencies used preclude us conjecturing on how much rock and timber is present at this site, which a dive team would resolve. A similar approach to that taken here, maybe useful in investigating other crannogs, or indeed other freshwater sites (submerged dwellings, piers, jetties; ship wrecks; accidents/military archaeology), especially given this work's preamble on increased water levels through human engineering and raised water-tables/water levels through flooding.

5.2. Geophysics (especially WPR)

Aside from some focused case studies (e.g. Qin et al., 2018), this is the first study of its type and obvious improvements can be made in subsequent work. Nonetheless, examination of the WPR textures and reflections within the crannog shows more variation than included here: two possible reasons are the complexity of these structures (O'Sullivan, 1998) and limitations in interpreting WPR data. On the latter, we suspect that the good transmission of radar waves in freshwater must be balanced by their slow movement vs. acquisition speed (boat movement ~ 2 knots), increasing the possibility of out of plane reflections appearing amongst those that are in plane: 3D WPR surveys in the future may alleviate this issue. These include (i) the issue of survey speed and positioning, which maybe better-controlled by dGPS-triggering of the radar; (ii) further analysis of radar frequency, antenna orientation, further use of high dynamic range and hyperstacking radar systems and processing in different freshwater archaeological environments. Should WPR be desirable in freshwaters over 10 m deep, the lowering of borehole antennas to the lake/riverbed may be trialled; (iii) more use of appropriate, complimentary geophysical techniques such magnetometry for suspected metal/ore remains; CHIRPS for deeper imaging/non-freshwater (polluted, brackish, saline); sidescan sonar where weed/gas bubbles/rocky substrates are limited or absent, amongst others.

6. Conclusions

The enigmatic historical and recent records of a crannog in the lake studied are resolved here by combined use of a general location, rectified in GIS and successfully searched for, then correctly located by sonar and WPR, both recorded by GPS for the update of records and further non-destructive study. Of the 100, 200 and 500 MHz antennas used here, and the 50 MHz 160 MHz HDR antenna trialled, for 1 to 5 m water depths, the 200 MHz antenna proved ideal in either parallel broadside or parallel endfire mode due to focusing of the radar beam and slow transmissivity in freshwater. For wider lateral and deeper (7 m+) context, the 100 MHz RTA antenna was found to be useful. In our reconnaissance surveys, 50 MHz antennas only achieved a few metres more of water penetration depth compared to 100 MHz; 500 MHz (for detail of the crannog top in shallow waters) did not have quite enough penetration to be useful. Comparing raw and processed data was found to be beneficial to interpretation, where raw data was dominated by water-bottom multiples, yet had good sediment and crannog (internal) reflections, processed data diminished these multiples, made the reflections vague, yet accentuated the WPR facies of sediment and archaeological radar sequences (*sensu stricto* in the sequence stratigraphic meaning).

The submerged Castlewellan crannog is asymmetric in two ways: first with a rocky steep eastern and northern side, adjacent to deep water with gentle inclination to the west, secondly, the crannog is wider north to south, narrower east to west – which is consistent with the sonar map (Fig. 3B) and its bathymetry. It appears to have a complex construction, some areas made of rock (northern side, 'armouring'; internal 'pinnacles', as on Fig. 6C), or founded on bedrock, others with rubble, some with layering and finally a mix of surrounding sediment types, some of which terminate abruptly against the crannog sides, others drape over. The flat top of the crannog is certainly rock, given the flat/bright reflectors and probe indications: there maybe slabs of rock here, as the

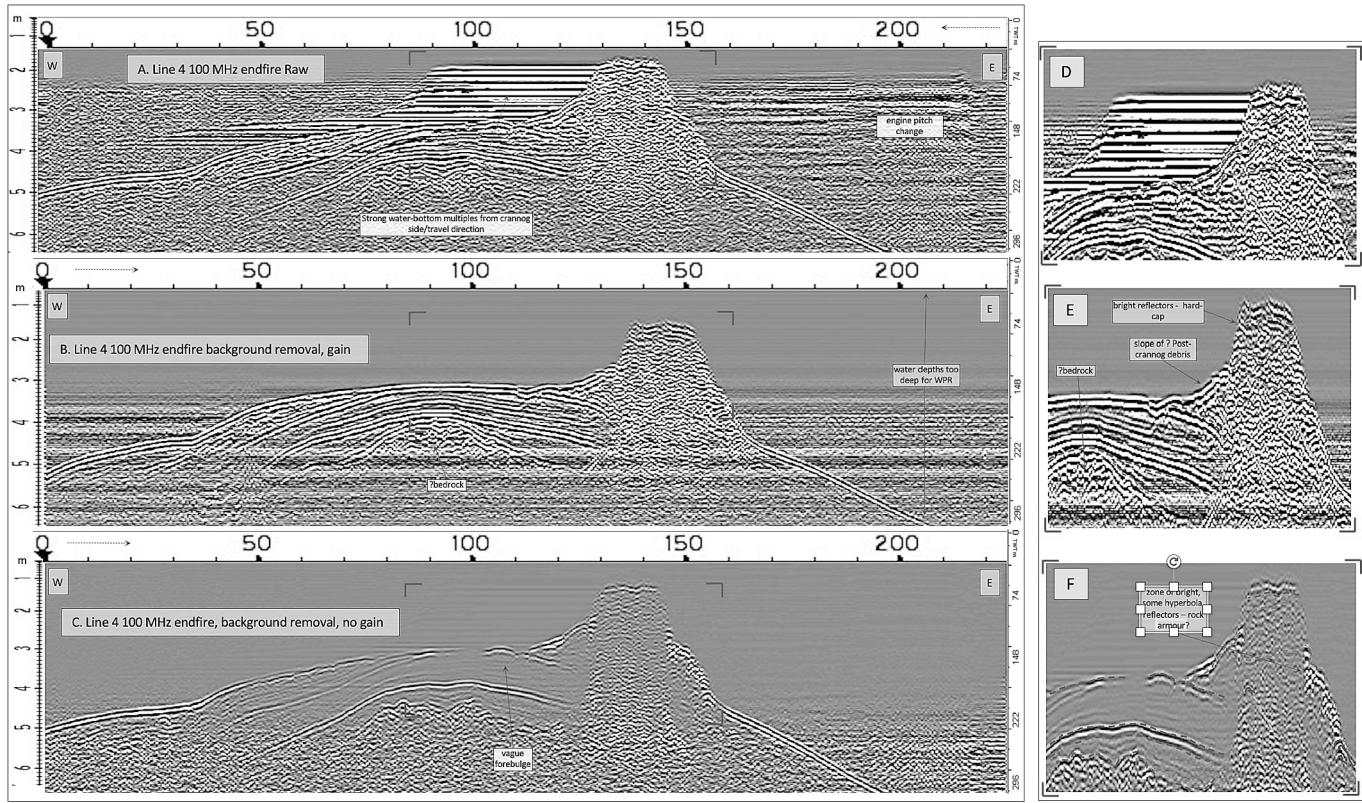


Fig. 7. Line 4. Long west to east line, overlying Line 1 (locations on Fig. 1), to show context and depth on 100 MHz data. Portions of each (red and green boxes) expanded, laterally-compressed and interpreted. A: note survey was east to west (arrowed), hence water-bottom multiples from the crannog sides propagate in this direction. B: background removal has diminished water-bottom multiples, gain has accentuated air-water multiples. C: processing (background removal) has decreased multiples; the draped sediments become opaque, but reflectors with strong amplitudes accentuated. D, E, F: the artificial lateral compression of data alters the vertical to horizontal scale, but accentuates reflections such as the crannog top, sides and core for interpretation.

probe did not get wedged between boulders/cobbles and the preponderance of Lower Palaeozoic greywackes with a strong, slaty cleavage in the area. More conjectural is whether this bright, flat radar reflection seen on the shallow, southern slopes of the crannog (Line 2, Fig. 5) could also be slabs and thence why they are here – fallen/slid from the top or laid intentionally? They are certainly not natural. As with all geophysics, the theories (above) will only be tested by a dive team and more advanced geophysical imaging such as sidescan sonar and 3D WPR.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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