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Lake and crannog: A 2500-year palaeoenvironmental record of continuity and change in NE Scotland

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ABSTRACT

Wetland environments have been important resources for human habitation since prehistoric times and in parts of northern Europe these have witnessed the construction of artificial islet settlements, known as ‘crannogs’ in Scotland and Ireland. This paper presents a high-resolution multi-proxy palaeoenvironmental study from the Loch of Leys, Aberdeenshire, Scotland, the site of a recently excavated crannog that provides a chronological context for its inhabitation. The combined datasets demonstrate that the first occupation from AD 20–210 coincided not only with a transitional phase from lake to wetland (mire) but also with the timing of the first major Roman campaigns in northeast Scotland. Techniques including microfossil analysis, geochemistry, IR-spectroscopy and physical properties integrated with archaeological and historical records have helped to better define both natural changes that took place in the wetland environment and human activity (agriculture, fires, metal working) spanning the Roman Iron Age through to the present. This has allowed a better understanding of the responses of existing Iron Age communities to Roman military activity (e.g. through continuity or change in land use) as well as the resources exploited in frontier zones during the Roman and post Roman eras. This has wider significance not just for Scotland but also for other parts of Europe that had similar frontiers and conflict zones during the Roman period.

1. Introduction

Wetland environments have been foci for human settlement and economic activity ubiquitously across the globe and through time. In parts of northern Europe, a particular form of wetland settlement developed involving the construction of artificial small islets, on which one or a few dwellings were built, known as crannogs in Scotland and Ireland. Some crannogs show similarities to the pile dwellings found in the Alpine and Baltic regions of continental Europe (e.g. Menotti, 2015; Pranckėnaitė et al., 2021), although unlike crannogs these tend to be located on or very close to the shore; crannogs in contrast are typically found tens to even hundreds of metres from the nearest shore (Stratigos, 2021). There are around 1200 crannogs in Ireland and over 600 crannogs recorded in Scotland and only a single example in Wales at Llangorse lake (Fig. 1). The majority of Irish and Scottish crannogs have never been excavated and most that have were done so in the 19th century (e.g. Burnett, 1851; Grigor, 1863; Munro, 1882; Stuart, 1866). Munro is particularly renowned for his early work on Scottish crannogs (Munro, 1882, 1890), but these early excavations lacked modern recording and have insecure and unreliable dating. For Munro and his contemporaries, chronology was largely a mystery, but a general Roman period and later phasing was accepted. This was only overturned with the first radiocarbon dates on crannog material (Guido, 1974). Since then radiocarbon dates obtained from structural timbers or other contexts have allowed the age of crannogs to be pushed back into the Neolithic in the far northwest of Scotland (e.g. Armit, 1996, 2006; Garrow and Sturt,

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2019). This is comparable to other wetland chronologies across continental Europe. In the circum-alpine region, pile dwellings are generally Neolithic to early Iron Age (Menotti, 2015) and late Bronze Age to early Iron Age in the south-east Baltic region (Pranckénaité, 2014, Pranckénaité et al., 2021). For the rest of Scotland, however, crannogs tend to be much younger spanning the Iron Age and Medieval periods, with activity known in a few cases to extend into the 17th century AD (e.g. Crone, 2012; Dixon et al., 2007; Henderson et al., 2006; Stratigos and Noble, 2014, 2018, 2021). Crannogs in Ireland appear to have at least some Neolithic phases, with many showing Bronze Age construction. In contrast to Scottish crannogs there is very limited Iron Age construction, with Irish crannogs only being built again in significant numbers from around AD 400 (Hencken, 1942; Newman, 1997; Fredengren, 2002; Brown et al. 2021).

Advances in radiocarbon dating, re-evaluation of 19th century crannog excavations in Scotland, as well as fresh multi-proxy investigations, have yielded a wealth of new information regarding crannog use and occupation (e.g. Cavers and Henderson, 2005; Cavers, 2010; Crone, 2012; Dixon et al., 2007; Henderson et al., 2006; Miller, 2004; Stratigos and Noble, 2018; Stratigos, 2017, 2021), but despite this, the exact purpose of building and living on crannogs and other wetland sites across Europe, has never been widely agreed upon, and it is likely they had various purposes ranging from defence, economic, ritual, resource proximity (e.g., Gackowski, 2000; Pydyn, 2007; Pranckénaité, 2014; Crone and Campbell, 2005). Understanding the purpose and use of wetland sites can only be fully achieved through interdisciplinary collaboration. This includes the synthesis of archaeology with multi-proxy palaeoenvironmental datasets. In continental Europe there have been some good examples of how this can be achieved (e.g. De Marinis et al., 2005; Menotti, 2015; Pranckénaité, 2014), whilst in Scotland interdisciplinary research has demonstrated that many artificial islets were occupied by people engaged in farming and other domestic tasks (e.g. Barber and Crone, 1993; Cavers and Crone, 2018; Clapham and Scaife, 1988; Crone, 2000; Miller, 2004; Robertson and Roy, 2021). This has been the overwhelming focus of the limited palaeoecological work on crannogs in Scotland to date – attempting to articulate the types of activities taking place in and around crannogs to elucidate their purpose or more occasionally define site formation processes. Pollen and plant macrofossil analysis has been the primary focus of this work (e.g. Miller

Fig. 1. Crannog distribution in the United Kingdom: Data compiled from: the Irish National Monuments Record Copyright Government of Ireland. The content of this application is owned and operated by National Monuments Service, Government of Ireland. This copyright material is licensed for re-use under the Creative Commons Attribution 4.0 International license, The Historic Environment Division of Northern Ireland. This copyright material is licensed for re-use under an Open Government License. Historic Environment Scotland Canmore data. This copyright material is licensed for re-use under an Open Government License. Scottish sites also include data from Cavers (2010); Lenfert (2013); Stratigos (2017, 2021). Llangorse crannog location data from Lane and Redknap (2020).

et al., 1998) but more recently, soil micromorphology and faecal lipid analysis have been applied to excavated contexts (Cavers and Crone, 2018; Robertson and Roy, 2021; Mackay et al., 2020).

The impact of crannog and other artificial island construction on its environment is less well known. Limited investigations include those of Tipping et al. (2000) who broadly sketched out the environmental context of Buiston Crannog; Craig (2018) who identified a decrease in diatom biodiversity due to increased eutrophication caused by crannog activity at White Loch of Myrton, Dumfries and Galloway and Fonville (2015) who used a multi-proxy palaeoenvironmental approach to explore the impacts of crannog and other wetland occupation at Cults Loch, Barhapple Loch and Black Loch of Myrton in south-west Scotland. Eutrophication and a decrease in pH of loch waters was identified at some of these sites whilst disturbance was identified at all sites. Research into the environmental impacts of crannog construction has been more common on Irish crannogs (e.g. Brown et al., 2005; O'Brien et al., 2005; Fonville, 2015), including sedimentary DNA analysis coupled with a suite of other palaeoenvironmental proxies which have revealed erosion caused by construction and occupation, the replacement of woodland with agricultural land, as well as eutrophication caused by the addition of nutrients from the crannog, particularly nitrogen and phosphate (e.g. Brown et al., 2021). Craig (2018), Brown et al. (2021), O'Brien et al. (2005) and Fonville (2015) again put emphasis on the importance and rich potential of using multi-proxy analysis to better understand wetland dwellings in Ireland, Scotland and beyond.

Some crannog excavations have recently been conducted in eastern Scotland (e.g. O'Grady, 2016; Stratigos and Noble, 2018); however, the majority of excavated Scottish crannog sites are located in western and central Scotland where most of the earlier antiquarian investigations were conducted, but even these western and central locations only make up a small proportion of well excavated sites. This means the environmental impact that underpinned social, political and economic activities on crannogs in Scotland remains poorly understood, with the chronology of occupation only broadly sketched out with just a few radiocarbon dates from a handful of contexts across a small number of crannogs (Stratigos and Noble, 2018). The challenge posed by chronological uncertainty is critical, as crannog interpretation has usually hinged on placing any specific crannog into its contemporary settlement landscape which is best achieved through palaeoenvironmental analyses. Furthermore, the impact of the construction and occupation of the crannog itself on its immediate wetland environment are often not fully resolved solely through analysis of excavated contexts from the crannogs. Fine resolution palaeoecological analysis can fill in some of these knowledge gaps, particularly when compared with available archaeological and historical archives. The aim of this paper is to explore the wetland environment and settlement history at the Loch of Leys in north-eastern Scotland, to better understand the phases of occupation and types of land-use in the locality, but also how these fit into the wider context of crannog occupation in the region and beyond. This will be achieved through high resolution multi-proxy analysis of a sediment core from the Loch of Leys, which will then be compared with archaeological and historical data from the nearby crannog which spans the Roman Iron Age through to the Medieval period. Palynology will not only help to determine past environments and land-use but combined with archaeology can identify periods of continuity, change or land abandonment. Geochemistry and other types of sedimentary analysis including the use of novel techniques such as, colour analysis and attenuated total reflectance-Fourier transform infrared spectrometry (FTIR-ATR) will provide information on metalworking and catchment changes associated with human-induced erosion, fires, eutrophication as well as natural catchment changes and the internal dynamics/characteristics of the sedimentary archive. The integration of the palaeoenvironmental datasets and archaeological evidence has wide international significance since the Loch of Leys crannog is situated beyond the northern most frontier of the Roman empire and was occupied during this period of Roman activity. The integrated datasets therefore seek to provide an interpretation of continuity and change in land use across a time period spanning the Roman and Post Roman eras that in Scotland has little information, and thus will enable comparisons with other frontier and beyond frontier regions of the world. The advantage of using this type of approach is that the combination of proxy methods can be used to unpick complex questions around environmental change and human activity, which would otherwise be unachievable.

2. Study area background

The Loch of Leys (Figs. 2 and 3) is located about 2 km north of the town of Banchory in Aberdeenshire in north-east Scotland (57°04′12.9″N 2°29′19.2″W. Grid ref: NO704978; and about 73 m O.D. The surrounding geology consists predominantly of andesitic igneous rocks with glacial and alluvial deposits of clays, gravels, and sands. About a kilometre to the east of Loch of Leys the geology changes to predominantly granites (British Geological Survey, 1996).

Due to drainage of the loch in 1850 (which followed an earlier lowering of the loch in the early 18th century), the area is currently an open fen occupying ~0.7 km^2 with substantial areas of reed and *Juncus* dominated grassland. The crannog is located slightly southeast from the centre of the former loch. Apart from large willow and birch trees ringing the crannog, the mound today is dominated by grassland with a small area of exposed stonework (Stratigos, 2017). To the north and east of the former loch are conifer plantations, probably planted in the mid-1800s (Robertson's 1822 map does not show pine plantations, but plantations are there on the 1st OS edition in 1864), whilst to the south and west is farmland and the northern fringes of the town of Banchory.

2.1. History & archaeology

The earliest documentary reference to the Loch of Leys crannog suggests the Wauchope family was in possession of the island prior to AD 1323. At Crathes castle there are several transcripts of a charter granted by Alexander II in AD 1247 to Robert of Wauchope, for homage and service of the lands of Tulimacboythne, which includes the boundaries of the Loch of Banchory (Loch of Leys) (Burnett, 1901: pp. 8 & 152). In March 1323 the land was taken by Robert the Bruce, likely as a punishment for the Wauchope's support of Edward I (Bailey et al., 2000: pp. 225–226) and granted to the Burnard family (later to become Burnett) as a reward for being faithful to him during the wars of Independence (Burnett, 1901: p. 6; Bailey et al., 2000: pp. 225–226). Alexander Burnard was known as the first Laird of Leys. The island then remained home to the Burnett family until the late 15th or early 16th century, after which the family moved to Crathes castle in 1543 (Shepherd, 1996).

The first excavations at the Loch of Leys crannog were conducted by James H Burnett in 1850 (Burnett, 1851; Munro, 1882). Burnett identified that the foundations of the crannog were surrounded by oak piles, which projected up to 1 m above ground. Several artefacts from the crannog and surrounding loch bed, including the bones and antlers of a red deer, a millstone/quern stone, coins, bronze kitchen vessels and two log boats: one small vessel and one flat-bottomed boat, were recovered (Burnett, 1851).

Further excavations and a survey were undertaken in 2016 to

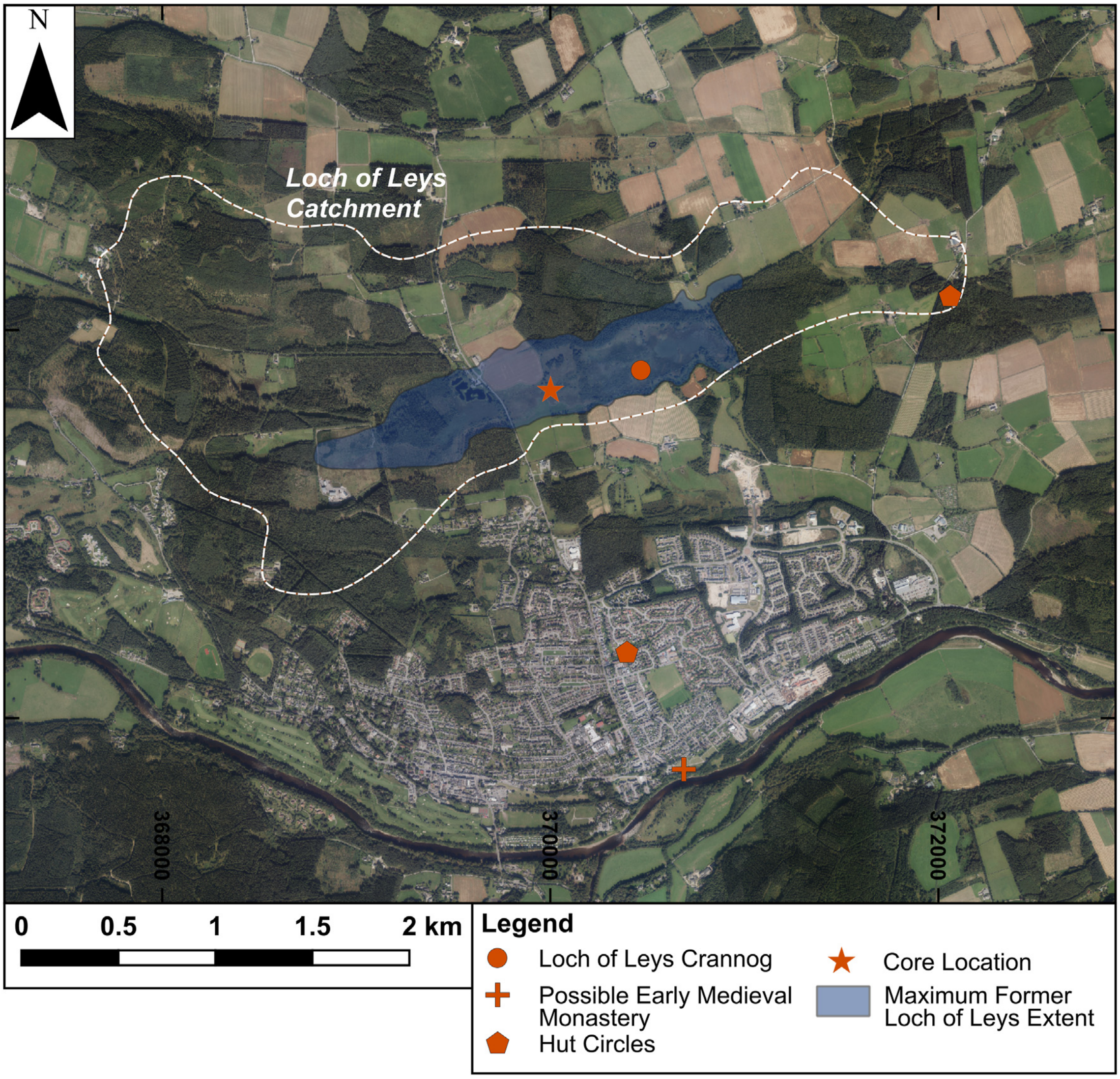


Fig. 2. Site and crannog location with catchment and local archaeological sites. Catchment derived from 5 × 5 m Ordnance Survey interpolated Digital Elevation Model. Site location of Tillybrake and Drumshalloch Woods hut circles and possible early medieval monastery. Site location information from Historic Environment Scotland Canmore data. This copyright material is licensed for re-use under an Open Government License. Core and crannog location from Stratigos (2017). ***Note that the possible early medieval monastery is not at the present St Ternan's church, it's on the other side of Banchory and indicated by the presence of some incised cross slabs and an iron hand bell found during the construction of the rail line. https://canmore.org.uk/site/36675/banchory-ternan; https://canmore.org.uk/site/36663/banchory-54-station-road-north-garden-wall-cross.

date phases of construction and occupation at the crannog, establish the condition of organic remains and to help establish the extent of the former loch levels (Stratigos, 2017). Two radiocarbon dates obtained from the excavation indicated phases of use during the Roman Iron Age and the early Medieval period (Table 1). The later date of cal AD 890–1010 came from a charcoal sample from the uppermost portion of the surviving organic matrix of the crannog. The earlier date of cal AD 20–210 came from a higher stratigraphic position and could be intrusive; but it has been interpreted as representing activity on the crannog, although in a secondary context (Stratigos, 2017; Stratigos and Noble, 2018). Radiocarbon dates from crannogs in the early centuries AD are relatively common (Crone, 2012). Until recently, late first millennium AD activity on crannogs in Scotland was less forthcoming (Stratigos and Noble, 2021). The nearest well-preserved crannogs to Loch of Leys are found at Loch Kinord, located 26 km to the west, where two crannogs also have radiocarbon evidence for construction and use in the last centuries of the first millennium AD. Castle and Prison Islands in Loch Kinord both have evidence of mid- and late- 1st millennium AD construction and occupation that might have continued through to the 11th-12th centuries. This evidence was found at both of the Kinord crannogs with documentary and excavation evidence suggesting use of Castle Island until the mid-17th century AD (Stratigos and Noble, 2014, 2018). The combination and overlap of documentary evidence, recent excavations and radiocarbon dating from the Loch of Leys and Loch Kinord sites is relatively unusual for crannog sites. This means that the palaeoenvironmental record generated in this investigation can be used to put the documentary evidence in context and adds strength to this study in that the combination of evidence will be considerably important in terms of understanding the interaction between people and environmental change whilst the crannog was in use.

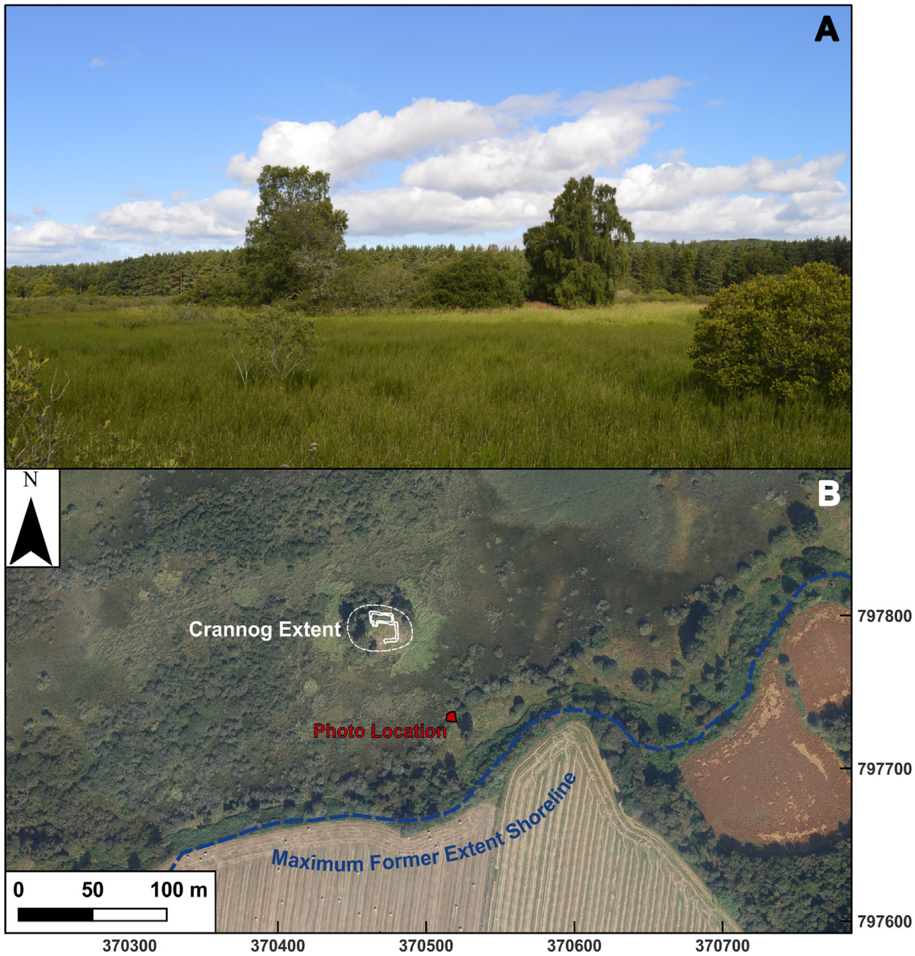


Fig. 3. Site and Photo: A: Loch of Leys crannog looking north from near the former southern shoreline of the loch. B: Satellite imagery of the crannog in its immediate context. This copyright material is licensed to GetMapping accessed via EdinaDigimap.

Table 1
^{14}C results from the Loch of Leys sediment core and crannog. Top five dates are from the sediment core. The two bottom dates are from the Crannog excavation, contexts 103 & 108 (Stratigos, 2017).

Lab code	Location	Sample Type	Depth (cm)	^{14}C age BP	Error ±	δ^{13}C (‰)	AD age (2σ)
SUERC-82572	Core	Peat-humic acid	48	1715	30	−28.8	AD250–390
SUERC-82571	Core	Roundwood	73–74	886	30	−27.4	AD1040–1220
Poz-91194	Core	Peat-humic acid	115–116	1435	30	Not provided	AD570–655
Poz-91196	Core	Peat-humic acid	155–156	1535	30	Not provided	AD425–595
Poz-91197	Core	gyttja-humic acid	205–206	2390	30	Not provided	730–400BC
Poz-83362	Crannog	*Betula* charcoal	Con-103	1095	30	−23.4	AD890–1010
Poz-83364	Crannog	*Betula* charcoal	Con-108	1910	30	−25.9	AD20–210

3. Methods

3.1. Sampling strategy

An initial desk based stratigraphic survey using GIS was undertaken by Stratigos (2017) to estimate the maximum extent of the palaeoshoreline of Loch of Leys, which is proposed to be at 74 m ODN. A topographic survey using dGPS was also made of the crannog mound. Seven cores were taken on a 20 m transect from the south-east corner of the mound with scheduled monument consent (SMC) to establish the sedimentation history of the loch and test for surviving archaeological material related to the crannog. These sediments were extracted using a gouge-auger and indicated relatively shallow sediment accumulation in the shallower water in the vicinity of the crannog and thus this location was not selected as a core location for paleoenvironmental analysis.

For this investigation a 3.5 m core was extracted using a Russian 5 cm diameter peat corer from the former loch sediments. These sediments offered the possibility to analyse continuous sequences using multi-proxy palaeoenvironmental data, including pollen and non-pollen palynomorphs (NPPs), loss on ignition (LOI), geochemical analysis, quantitative colour, and attenuated total reflectance-Fourier transform infrared spectrometry (FTIR-ATR), to better understand human occupation at the crannog site. The process of sediment extraction included the recovery of 50 cm sediment segments with a 10 cm overlap. The core is located at NO

70001 97690, approximately 500 m south-east of the crannog. Although close to the Burn of Bennie drainage ditch the core location should be minimally impacted by the ditch as it is approximately 13 m to the south. The location was selected because it was as close to the deepest part of the basin as to obtain the longest record covering the use of the crannog, and avoided sediments impacted by shrub vegetation, particularly willow on the shallower sediments. Accessibility was also important; to be as close to the crannog as possible and not within the scheduled monument consent (SMC) area.

Sediments were sub-sampled every 5 cm in the top 30 cm and then every 2 cm until 2.1m, incorporating the early Medieval period and part of the Iron-Age. The sub-samples were analysed at the same depths for pollen, NPPs, geochemistry, colour & FTIR-ATR, representing 285 samples in total. The core was lithologically described using Troels-Smith (1955). Older sediments between 2.10 and 3.5 m have not been analysed in this investigation.

3.2. Radiocarbon analysis

Due to the limited availability of macrofossil remains most of the samples selected for radiocarbon analysis are peat and gyttja (Table 1). Five samples were submitted to the SUERC and Poznań radiocarbon laboratories. These included three bulk peat samples (5 g each), one gyttja (5 g) and a terrestrial macrofossil (twig). The radiocarbon ages were calibrated using the CALIB 8.2 calibration program (Stuiver et al., 2021) and Intcal20 (Reimer et al., 2020). Modelled ages are based on Bayesian modelling results in Oxcal using the Oxcal program (Bronk Ramsey, 2009, 2020). The Poisson-process deposition model was then used to produce an age-depth model (Fig. 4) (Bronk Ramsey, 2009, 2020; Bronk Ramsey and Lee, 2013). Sedimentary boundaries have been incorporated into the model to help constrain the dates within the different sediment sequences.

It should be noted that the use of bulk sediments and gyttja for radiocarbon dating are not always reliable given that carbon from uncertain provenances can cause age errors (Grimm et al., 2009; Grimm and Jacobson, 2004). Only the humic acid content was measured in this investigation, therefore an age slightly older or younger than actual remains possible (Shore et al., 1995) and thus some caution should be applied to their interpretation. A hard water effect is, however, unlikely given that the surrounding geology is comprised of igneous rocks (British Geological Survey, 1996). Radiocarbon dates are presented in the main text by their calibrated age ranges AD/BC. For simplicity, however, the figures are represented by the median value of the modelled ages.

3.3. Sedimentary analysis

A combination of different types of sedimentary analyses have been used including Loss on Ignition, Colour, Vibrational spectroscopy and Elemental composition analysis. The combination of analyses has been key to strengthen any interpretation around changes driven by lake processes and then those more likely to be in response to human activity.

3.3.1. Loss on ignition (LOI)

Loss on ignition has been used to examine fluctuations in organic carbon. Increased LOI can identify the natural stages of loch terrestrialization whilst fluctuations or a decline may be associated with increased wetness or erosion linked to natural or anthropogenic changes in the catchment. LOI was conducted on the sediments between 20 cm and 210 cm at 2 cm intervals following the conventional methods outlined in Heiri et al. (2001).

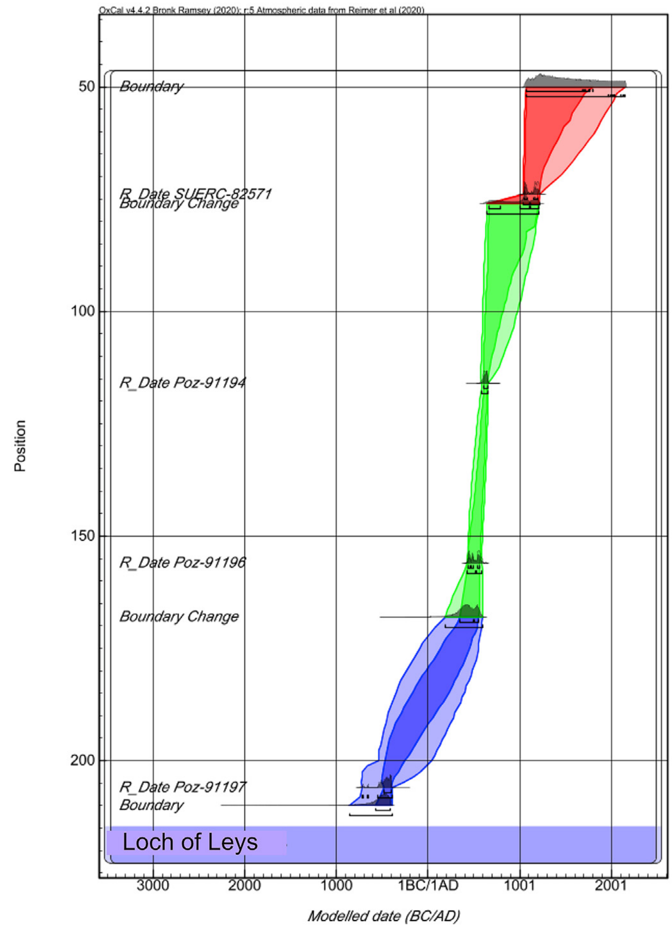


Fig. 4. Loch of Leys Bayesian age/depth model.

3.3.2. Colour

Quantitative colour determination provides information on stratigraphical changes, which are usually related to changes in composition and geochemical processes occurring in the sediments (see for example, Sanmartín et al., 2015; Martínez Cortizas et al., 2020). Both the colour and FTIR-ATR (described below in 3.33) are novel types of analysis that have been used successfully in this investigation to not only identify changes in environment, but these proxies have been useful in validating other proxy-data to provide a more robust interpretation of the results. Colour was quantitatively determined in finely milled (<50 μm) samples with a Konica-Minolta CR5 colourimeter for solids. CIELab colour space was used; this provides five parameters: luminosity (L, black is 0 and white is 100), the green (negative values) to red (positive values) component (a*), the blue (negative values) to yellow (positive values) component (b*), chromaticity (C*) and hue (h).

3.3.3. Vibrational spectroscopy

FTIR-ATR is a non-destructive, quick technique that provides compositional (organic and inorganic) and structural information of many materials, and it has been applied in palaeoenvironmental research for both soil/sediment and peat molecular characterization to better understand both natural and anthropogenic causes of environmental change (e.g. Cocozza et al., 2003; Artz et al., 2008; Tinti et al., 2015; Martínez Cortizas et al., 2021). Vibrational spectroscopy was done on well-homogenized finely milled (<50 μm) samples using an Agilent Technologies Cary 630 FTIR-ATR, measuring in the mid-infrared region (4000-400 m^{-1}) at a resolution of 4 cm^{-1}, with 100 scans per sample. Spectra were processed with the {*andurinha*} R package (Álvarez Fernández and Martínez Cortizas, 2020). In total 35 representative absorbances were selected to perform a principal components analysis (PCA; see below).

3.3.4. Elemental composition analysis

Geochemical analysis can be used to detect traces of metals which might indicate a metalworking, but also environmental changes including fluctuations in wetness/water levels and terrigenous inwash associated with erosion. All samples were finely milled to <50 μm and analysed by ICP-MS at the RIAIDT facility of the Universidade de Santiago de Compostela (Spain). Samples were digested with 1 mL of HNO_3 2% (Hiperpur, Panreac) and 0.5 mL H_2O_2 (Panreac) in a microwave system (Milestone Ethos1) at 190 °C for 30 min. After digestion, MilliQ water was added to a final volume of 5 mL. Elements were analysed by ICP-MS (Agilent 7700x) equipped with an introduction system with a Micromist glass low-flow nebulizer, Scott spray chamber with Peltier (2 °C), and a quartz torch. Concentrations for 23 major, minor and trace elements were determined. Calibration standards were prepared in a matrix – matched acid solution with the concentrations for Al, Fe, Mg, Na, K, Ti, Rb, Sr, Y, Mn, Cr, Cu, Zn, Ni, As, Pb, U, Cd, Zr and Se (Multi IV-MERCK) between 0.2 and 10 000 μg/L, and for Ca, P and S (Panreac) with concentrations from 1 to 100 mg/L. Samples were analysed together with five procedural blanks. All samples and blanks were analysed in triplicate, with Ir 20 μg/L as the internal standard. Calibration curves were constructed daily by analysis of fresh standard solutions. In all cases, linear responses were obtained with correlation coefficients higher than 0.999, and a relative standard deviation (RSD) lower than 5%. To monitor the overall performance of the system, two reference materials - BCR277R (estuarine sediment, measured 4 times) and SQC001 (metals in soil, measured 2 times) were analysed along with the samples obtaining good percentages of recovery (80–100%).

Data was clr-transformed (to avoid the close data effect) before statistical analysis. The main geochemical signals were extracted by applying PCA on the correlation matrix using a varimax rotation, a solution that maximizes the loadings of the variables on the components. This solution provides clearer depth/age patterns and helps to identify the underlying (latent) factors affecting peat/sediment composition (e.g. Küttner et al., 2014; Martínez Cortizas et al. 2020, 2021).

3.4. Pollen and NPPs

To reconstruct the Loch of Leys vegetation history to understand patterns of land use change, pollen and non-pollen microfossils (NPPs) were prepared using the conventional methods outlined in Moore et al. (1991), including the additional step of density separation (Nakagawa et al., 1998). A representative minimum sum of 500 total land pollen (TLP) (cf. Birks, 1980) was counted for all subsamples where possible. Only 5 samples fell below this count: one with a count of 250, the others 300. Identification was aided by reference keys in Fægri et al. (1989), Moore et al. (1991), Beug (2004) and Reille (1999), and supported by a modern type-slide reference collection housed at the University of Aberdeen. Since *Myrica* and *Corylus* are difficult to separate (Edwards, 1981), these species have been grouped as *Corylus avellana*-type. Cereal-type pollen are classified as grains ≥38 ųm and with an annulus ≥8 ųm (Moore et al., 1991; Andersen, 1979; Beug, 2004). Based on the size dimensions, the cereal-type grains identified likely belong to either *Hordeum*, *Triticum* or *Avena,* although it should be acknowledged that some wild grasses can be incorporated into this group as well (Tweddle et al., 2005). Cereal type pollen are grouped together to increase visibility. Pollen grains belonging to arable weeds from both *Polygonum persicaria* and *Polygonum aviculare* were identified but only as single sporadic occurrences, therefore it was decided to also group these taxa together. Damaged grains were divided into four main categories (broken, crumpled, corroded/degraded-identifiable and corroded/degraded-unidentifiable), adapted from Delcourt and Delcourt (1980). Broken and crumpled categories would have been influenced by mechanical mechanisms such as breakages during transport; corroded/degraded categories would have been influenced by chemical weathering, such as oxidation processes (Moore et al., 1991). The pollen and spore data are expressed both as a percentage of total land pollen (TLP) and as concentrations, with spores and aquatic taxa excluded from the TLP sum. Pollen percentages can be influenced by the proportional representation of other taxa. Wind pollinated plants produce abundant pollen grains that can mask the percentage representation of low pollen producers, particularly local herbaceous taxa. Concentration values are therefore useful since the individual pollen values are independent of each other (Mulder and Janssen, 1999) and may therefore identify more clearly changes in low pollen producers, particularly plants associated with disturbance, pastoral and arable economies. Pollen concentrations have been calculated using the *Tilia* software version 2.0.41 (Grimm, 1991–2015). All samples had a consistent weight of 2.1 g and a *Lycopodium* spike (1 tablet containing 12,542.4 grains; Batch number 124961). However, *Lycopodium* counts between 2 and 60 cm were in single figures, and therefore have not been included in the concentration calculations. Concentration graphs can be found in the supplementary material. NPPs were also counted during routine pollen analysis and were identified using Bakker and van Smeerdijk (1982), van Geel (1976, 1978), van Geel et al. (1981, 1983, 1986), Haaster (1984), Kuhry (1985, 1997), Pals et al. (1980) and Van der Wiel (1982). NPPs are expressed as a percentage of total NPPs and also include whole fragments of diatoms, and fragmented head capsules of chironomids. Rare types are indicated by a cross (+), where one cross is equal to one pollen grain or NPP. Microscopic charcoal particles greater than 10 ųm were counted and are represented as total counts. The pollen diagram was constructed and delineated using CONISS software as part of the *Tilia* and *Tilia*.graph version 2.0.41 package (Grimm, 1991-2015).

The pollen catchment area has also been taken into consideration. Regional pollen representation will be impacted by topography, size of basin and whether there are any incoming streams/rivers (Jacobson, and Bradshaw, 1981). The Loch of Leys has a catchment of 492 ha, most of which lies to the west and north of the loch (Fig. 1). There are no major incoming streams or rivers. To the east is the Hill of Drumshalloch; to the south is the Hill of Banchory; to the north-west is the Hill of Brathens and to the north are several larger hills (Craigbeg, Myrie Hill, Cateran's Howe Covert) with the highest at 283 m a.s.l., all are within 1–5 km of the Loch of Leys-Regional pollen transported by hydrological pathways can have a significant impact on lake pollen records (Pittam et al., 2006), but given the lack of major rivers and close proximity of the surrounding hills the size of the catchment is relatively small for a lowland loch of this size. The pollen in the core therefore likely represents a relatively constrained catchment source area around the Loch of Leys.

4. Results

4.1. Radiocarbon analysis

Table 1 presents the radiocarbon results. Age ranges are based on 95.4% (2σ) confidence limits. The gyttja sample at 205–206 cm produced a calibrated age of 730−400BC. All samples produced ages in chronological order spanning the Iron Age through to the Medieval period except at 48−49 cm. At this depth a peat sample produced an inverted calibrated age of AD250−390. This could potentially be due to several reasons including modern disturbance during the construction of a nearby (13 m away) ditch, erosional in wash induced by fire (a rise in microcharcoal is recorded at 52 cm, described in 4.6) or contamination.

Besides the chronology of the core, the radiocarbon results also highlight changes in sedimentation accumulation rates. Fig. 4 represents the Bayesian Poisson-process deposition model (Bronk Ramsey, 2009, 2020) applied to the calibrated ages. The model suggests increased sediment accumulation between 168 and 115 cm.

4.2. Sedimentary analysis

4.2.1. Stratigraphy and LOI

4.2.1.1. Stratigraphy. The macroscopic stratigraphy of the core is represented in Table 2:

4.2.1.2. Loss on Ignition. The LOI results are presented in Table 3 and in Fig. 6:

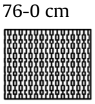
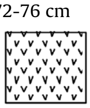
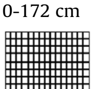
To summarise the stratigraphy and LOI results, gyttja is present between 210 and 172 cm. The dark brown colour suggests it was formed within a low energy environment. The gyttja coincides with a sharp rise in organic content (LOI: 40−66%) between 186 and 174 cm (*c.* 5BC-AD300). It is then superseded by woody peat after 172 cm and LOI continues to increase (65−90%) with fluctuations. Organic content (LOI) increases and reaches 90% between 115 and 70 cm (c. AD515−1180). To some extent the stratigraphic changes and LOI appear to coincide with increased sediment accumulation rates represented in the Bayesian age/depth model between 168 and 115 cm (Fig. 6). Above 70 cm sediments change to a *Phragmites* clayey peat and coincide with a gradual decline in organic content suggesting wetter conditions.

4.2.2. Colour

The colour results (Fig. 5) enable a more precise identification of the stratigraphical changes, which are associated with the stages of evolution of the loch and are further supported in the FTIR-ATR, elemental and LOI datasets. The depth records of colour parameters suggest the core can be divided into four main sections: Section I (210-178 cm, *c.* 510BC to AD200), characterised by higher luminosity and hue values (Fig.SM_2) and stable values of the colour components (a*, b*) and chromaticity (C*); however, between 188 and 182 cm (*c.* 25BC and *c.*AD100) a slight lowering of hue and luminosity is recorded. Section II (178-108 cm. *c.* AD200 to AD675): luminosity and hue decrease steadily while the colour components and chromaticity remain almost stable; Section III (108-52 cm, *c.* AD675 to AD1470): characterised by the lowest luminosity and hue values and high frequency variations in the colour components and chromaticity; and Section IV (upper 52 cm, *c.* AD1470 to modern): increase in luminosity and to a lesser extent in hue, while the colour components and chromaticity are still quite variable. The described sections fit with changes in LOI and agree approximately with visual macroscopic colour descriptions taken in the field. The CIELab sections have been used to describe the results.

Luminosity is highly correlated to hue (r = 0.96) but poorly correlated to the colour components (a* and b*) and chromaticity (C*); while b* is highly correlated with chromaticity (r = 0.97). Although a* and b* show no correlation for the whole set of samples, they are in fact correlated in every section, lending support to the stratigraphic CIELab sections identified. Luminosity and hue are also highly correlated to LOI (r = −0.93), which points to changes in organic matter and inorganic matter content as the primary control of colour changes (see Fig. SM_2).

Table 2
Stratigraphy from the Loch of Leys sediment core. Stratigraphic changes based on Troels-Smith (1955).

76-0 cm 	Dark Brown fibrous *Phragmites* clay rich peat. Th2[1]Ag2 Nig 2, Strf 0, Sicc 3, Elas 2, Lim 0
172-76 cm 	**Dark Brown woody peat.** Tl2[2]As2Ag++ Nig 3, Strf 0, Sicc 2, Elas 3, Lim 0
210-172 cm 	**Dark Brown gyttja.** Sh2[4]As2 Nig 3, Strf 0, Sicc 1, Elas 4, Lim 0

4.2.3. Vibrational spectroscopy (Cp-IR)

The spectra of the samples and the standard deviation spectrum can be seen in supplementary material (SM_Fig. 1).

35 main absorbances were identified (SM_Table 1) that characterize the organic and inorganic phases of the gyttja/peats of Loch of Leys. The PCA extracted six principal components that account for almost 99% of the total spectral variance: Cp1-IR 69%, Cp2-IR 11%, Cp3-IR 9%, Cp4-IR 5%, Cp5-IR 4% and Cp6-IR 1%. These are represented in Fig. 6. Component Cp5-IR is related to the variation of the 786 cm^{-1} vibration which is quite unspecific (it may correspond to both organic and inorganic compounds) and Cp6-IR is related to minor residual variance of OH vibrations (3220 cm^{-1}, SM_Table 1), and are not considered further.

The first component, Cp1-IR, shows large to moderate positive loadings for absorbances characteristic of the organic matter (carbohydrates: 490-600 cm^{-1}; lignin and aromatics: 600−700, 1200-1650 m^{-1}; lignin plus nitrogen compounds: 1500-1600 cm^{-1}; aliphatics: 2850 and 2919 cm^{-1}; and OH vibrations: 3220 cm^{-1}) and negative loadings for absorbances typical of minerals (silicates: 447, 1049-1094 cm^{-1}; clay: 3617-3712 cm^{-1}) (SM_Table 1). The component is related to the relative content of organic matter versus mineral matter and is positively correlated with the LOI (r = 0.92, slightly non-linear relationship).

The record of Cp1-IR scores shows low (i.e. predominance of inorganic matter) and constant values below 182 cm (*c.* 510BC to AD100). From 188 cm (*c.* 25BC) values begin to increase with a sharp increase between 182 and 176 cm (*c.* AD100 to AD250) indicating higher accumulation of organic matter. This is followed by a more gradual rise until 170 cm (*c.* AD385). Values remain almost constant until 108 cm (*c.* AD650) where they increase abruptly until 92 cm (c. AD820) and remain at high values (i.e. highly organic materials) until 52 cm (*c.* AD1470). From 52 to 46 cm, (*c.* AD1470 to AD1500s) a rapid decrease occurs, and scores stabilize to values comparable to those of the bottom section (i.e. predominance of mineral matter).

Cp2-IR is characterised by large loadings of carboxylate absorbances (1700-1733 cm^{-1}; SM_Table 1), so it reflects changes in organic acids/degree of oxidation of the organic matter. Scores are quite homogeneous at the base of the core, between 210 and 182 cm (*c.* 510BC to AD100), but show a series of peaks at 158, 140, 102, 74 and 46 cm.

Cp3-IR shows large to moderate loadings for absorbances of biogenic silica (1094-1226 cm^{-1}; SM_Table 1) (Swan and Patwardhan, 2011; Leiva-Dueñas et al., 2020) and it most

Table 3
Loss on Ignition results from the Loch of Leys sediment core.

0–36 cm	A sharp increase to 85% before declining to below 70%.
36–70 cm	Declines to 72%, although fluctuations occur.
70–115 cm	Gradually increases and reaches its highest organic content (above 90%).
115–150 cm	Displays a gradual decline from 78% to 65%.
150–162 cm	Rises to 78%
162–172 cm	Increases to 75% but dips to 68% at 162 cm
172–186 cm	Shows a sharp rise from 40% to 66% between 186 and 174 cm but dips to 60% at 172 cm.
186–210 cm	Is generally low between 40% and 47%

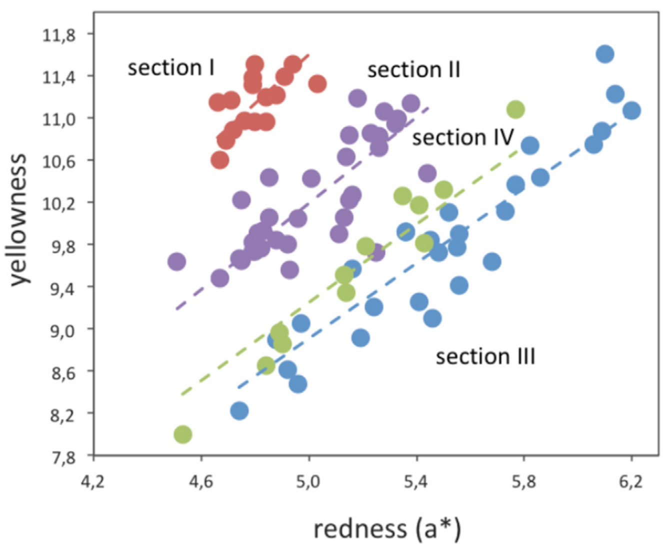


Fig. 5. Depth records of the colour parameters. Sections I to IV are based on observed changes in the colour parameters. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

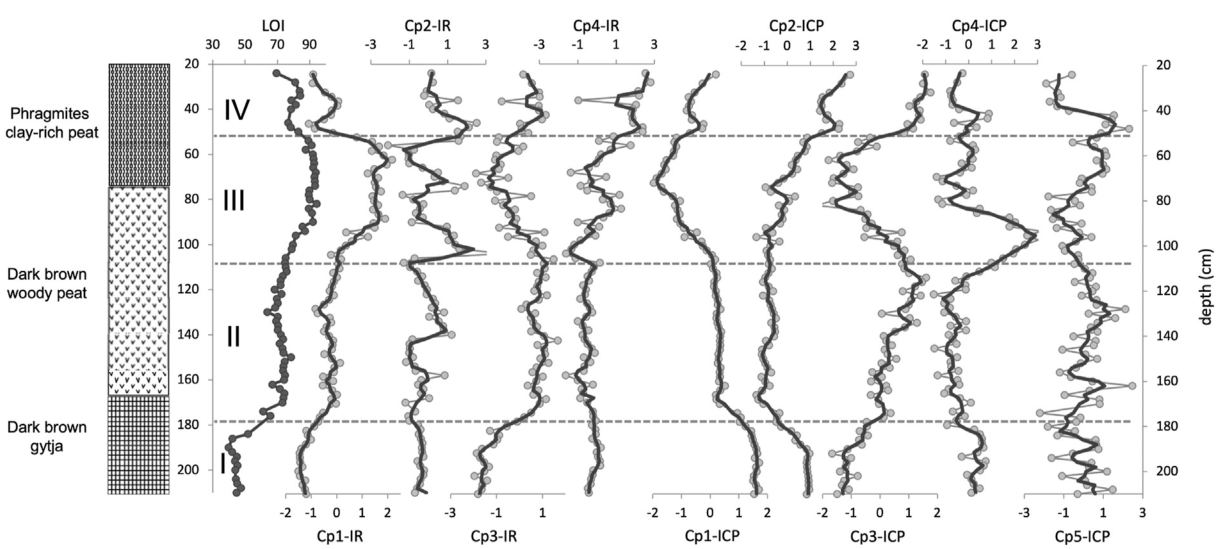


Fig. 6. Depth records of LOI and the extracted principal components (Cp1-IR to Cp4-I, components of the vibrational spectroscopy dataset; Cp1-ICP to Cp5-ICP, components of the elemental composition dataset). A sketch of the macroscopic stratigraphy is also included.

probably reflects changes in within lake bioproductivity. The Cp3 record reflects low values below 182 cm (before AD100), rapidly increasing until 176 cm (*c.* AD250), followed by a more gradual increase until 170 cm (*c.* AD385) and then stabilize at higher values until 102 cm (*c.* AD720). A rapid decrease follows to 80 cm (*c.* AD950), with values comparable to those of the bottom section until 52 cm (*c.* AD1470). Then they recover in the upper 52 cm.

Cp4-IR has moderate loadings of lipids' absorbances (2850 and 2919 cm^{-1}) and represents a secondary variation in the lipids content of the organic matter, which is not explained by variations in the total organic matter content (Cp1-IR). The depth record shows low, fairly homogeneous, scores until 108 cm (*c.* AD675), and increasing values in the top 52 cm (above *c.* AD1470) (with an exception at 36 cm), peaking at the top of the core (modern).

4.2.4. Elemental composition (ICP-MS) (Cp-ICP)

Five principal components account for a 90% of the variance of the elemental composition: Cp1-ICP 48%, Cp2-ICP 20%, Cp3-ICP 12%, Cp4-ICP 7%, and Cp5-ICP 3%. Cp1-ICP shows positive loadings for U, Al, Cr, Y, Zn, Ni, P, Ti and Mn (with a low loading for Zr), and negative loadings for S, As, Pb, Mg, Ca, Sr and Na (with a low loading for K). The loadings of the extracted components are presented in supplementary material (SM_Table 2), although the principal component graphs are also presented in Fig. 6. Elements with positive loadings seem to reflect the main composition of the mineral matter of the sediments, while negative loadings are shown by biophilic elements (S, Ca, Mg, Na, K, Sr) or metals that bind to organic matter (Pb, As). This component is highly anti-correlated with both Cp1-IR ($r = -0.89$) and LOI ($r = -0.98$), which supports the interpretation of the component. The depth record of scores shows the opposite trend to Cp1-IR.

Cp2-ICP shows large positive loadings for K and Rb (SM_Table 2), moderate to low positive loadings for As, Pb, P and Ti, and moderate to low negative loadings for S, Zn, Cd, Ca, Cu and Mn. It seems to reflect changes in the mineralogical composition of the sediments as K and Rb are elements typically hosted in K-feldspar and mica, while elements with negative loadings are more common in mafic minerals (i.e. amphibole, plagioclase). This component likely reflects changes in the source of mineral matter to the loch. The record of scores shows elevated values below 190 cm (*c.* 510BC to 110BC), which decrease rapidly until 168 cm (*c.* AD400) and remain negative and quite stable until 74 cm (*c.* AD1100). Then, values increase linearly until 48 cm (*c.* AD1500) and remain high in the upper 48 cm.

Cp3-ICP is dominated by the variations in Se and Cd and, to a lower extent, in Ti, Y and Cu (SM_Table 2). Moderate to low negative loadings are also shown by Fe, Mn, Ni, P, Ni, Mg and Zr. This component is highly correlated to Cp3-IR ($r = 0.80$), suggesting that lake bioproductivity (i.e microorganisms producing biogenic silica) were involved in the export of Se and Cd (and some other elements) to the sediments. The negative loading of P may reflect the fact that diatoms prefer clear, oligotrophic waters, thus large increases in nutrients (i.e. P) affect them negatively (Leiva-Dueñas et al., 2020). On the other hand, the increase in Fe, Mn and Zr during periods of lower lake bioproductivity may indicate higher oxygen availability (facilitating Fe and Mn precipitation) in the lake bottom and higher terrestrial fluxes (Zr). The Cp3-ICP record of scores shows a steady increase from the bottom of the core to 114 cm (*c.* 510BC until *c.* AD640), decreasing values until 96 cm (*c.* AD800), negative and homogenous until 52 cm (c. AD1470), followed by a rapid recover until 48 cm (*c.* AD1500) and positive and stable thereafter.

Cp4-ICP shows a large positive loading for Cu, moderate positive loadings for Fe, Zr and Se and low negative loadings for Cd and Ni (SM_Table 2). Copper variance is fractionated into three components (SM_Table 2), with mineral matter source changes (Cp2-ICP) and biological export (Cp2-ICP) accounting for almost a third of the variance. Thus Cp4-ICP should account for Cu in excess not related to within lake and mineral sources. The record of scores of this component shows a single peak between 118 and 86 cm (*c.* AD620 and AD880), although peaking at 96–98 cm (*c.* AD760–800), against a background of low variation and is likely to represent a local metal pollution event.

Cp5-ICP only accounts for the variation in Zr – which is not allocated to other components - (SM_Table 2) and may likely represent detrital fluxes. The record is highly variable, with no clear pattern.

4.3. Pollen and NPP analysis

The pollen and NPP results are presented below and in Fig. 7 and SM_3. English translations for the Latin names can be found in supplementary material section 3. The results have been divided into zones 1–5.

Zone 1: (210-185 cm, *c.* 510BC–25BC) represents a lake environment and is dominated by woodland and tall shrub taxa (70–80%): *Alnus, Betula, Quercus*, *Corylus avellana* type, and some *Salix, Ulmus*, *Fraxinus*, *Fagus*, *Ilex*, Rosaceae undiff., and *Prunus*, as well as pollen and NPP taxa typical of a lake environment: particularly diatoms and *Botryococcus* as well as the presence of *Mougeotia*, *Spirogyra*, *Zygnema, Callitriche, Potamogeton, Myriophyllum* & Nymphaeaceae. Herb representation is dominated by Poaceae, Cyperaceae, Ranunculaceae and *Filipendula*, likely representing natural wetland vegetation around the loch. Anthropogenic indicators are poorly represented in this zone. This includes only 2 grains of >38 μm Poaceae (cereal type) at 208 cm (*c.* 490BC), and the occasional presence of coprophilous fungi *Sporormiella*, *Tripterospora* and *Sordaria* which might be associated with wild deer or livestock.

Zone 2a: (185-142 cm, 25BC–AD550) represents declining lake levels, the beginning of human-land use, but with a later period of arable discontinuity. The algae *Botryococcus* falls to below 2%, whilst diatoms show a more gradual fluctuating decrease from ~95% at 182 cm to 70-35%. There are slight increases in Nymphaceae, potentially linked to shallower water levels. There is also a gradual increase in both the percentage and concentrations of Poaceae, Cyperaceae, *Sphagnum* particularly at 166 cm and *Salix* which may represent the formation of a sedge-grass-willow carr on newly exposed sediments, although some of the Poaceae may equally represent dry grassland. The marsh taxon *Filipendula* also shows a continued presence. The most significant change in zone 2a is a rise in disturbance, pastoral and arable indicators (e.g. *Podospora, Sporormiella, Sordaria* and *Tripterospora*, Apiaceae, *Artemisia* and Chenopodiaceae, Asteraceae, Caryophyllaceae, Lactuceae, *Plantago lanceolata, Potentilla*, Ranunculaceae, *Rumex* and the presence of *Polygonum*). Cereal type pollen (Poaceae >38 μm) are present at: 184-182 cm (4 grains *c.* 25BC) and 176 cm (3 grains *c.* AD275). Wet and dry woodland pollen taxa show similar percentages to zone 1 but show a decline in the concentration record.

After 176 cm (*c.* AD275) cereal type pollen disappear until 140 cm, with the exception of a sporadic occurrence at 154 cm (*c.* AD490). There are also some decreases in herbs e.g., *Potentilla, Rumex, Plantago lanceolata*, although other herbs increase: Lactuceae, Rubiaceae, Chenopodiaceae. Coprophilous fungi (*Podospora, Sporormiella* and *Sordaria, Tripterospora*) also increase initially but then decrease above 174 cm (see Fig. 10).

At 164 cm charcoal appears for the first time (from *c.* AD450) and coincides with a peak in corroded unidentified pollen, and small increases in Chenopodiaceae, *Rumex*, *Plantago lanceolata*, *Potentilla* and *Gelasinospora*.

Zone 2b: (142-105 cm; *c.*AD550–640). This zone is represented by a strong anthropogenic signal. Poaceae >38 μm pollen (Cereal types) reappear and are more consistent in both concentration and percentage representation suggesting nearby arable land; the highest representation is 2–3 counts between 136 and 114 cm. These results are supported by the reappearance of *Polygonum* and the only appearance of Lactuceae in this zone. Herbs & NPPs often associated with disturbance & pastures**:** Asteraceae, *Plantago lanceolata*, Apiaceae, *Rumex*, Rubiaceae, Ranunculaceae, *Saxifraga* & Lamiaceae are more frequent. There is a continued presence of *Artemisia*, Brassicaceae, Caryophyllaceae and Chenopodiaceae whilst coprophilous fungi continue to increase. Charcoal is consistently present in this sub-zone. A small increase in charcoal between 122 and 114 cm coincides with a small peak in corroded pollen. *Gelasinospora* also increases at 118 cm (*c.*AD620). Between 114 cm and 106 cm (*c.*AD640 - AD700) there is a distinct decline in charcoal, arable (cereal types), pastoral (*Plantago lanceolota*), coprophilous fungi and disturbance indicators (*Rumex*), clearly represented in Fig. 10. Lamiaceae, Apiaceae and Asteraceae disappear. Aquatic diatoms and algae continue to decline (except the unidentified algae group). Fluctuations in the aquatic group could potentially represent freshwater input/levels. Woodland taxa increase slightly in both percentage and concentration representation: *Alnus*, *Betula*, *Ulmus*, *Fraxinus*, *Corylus avellana* type, *Quercus* and *Fagus*. *Pinus* fluctuates. Other heathland and open shrub vegetation also increase or are more consistently present including wild fruit taxa: *Prunus* (likely blackthorn), *Empetrum* (Crowberry) & *Vaccinium* (Blueberry), and other shrubs and dwarf shrubs: *Hedera*, Rosaceae undiff. and *Calluna vulgaris*.

Zone 3: (105-60 cm; AD700–1320) represents the driest phase on the former loch and human land-use. This is evidenced by the

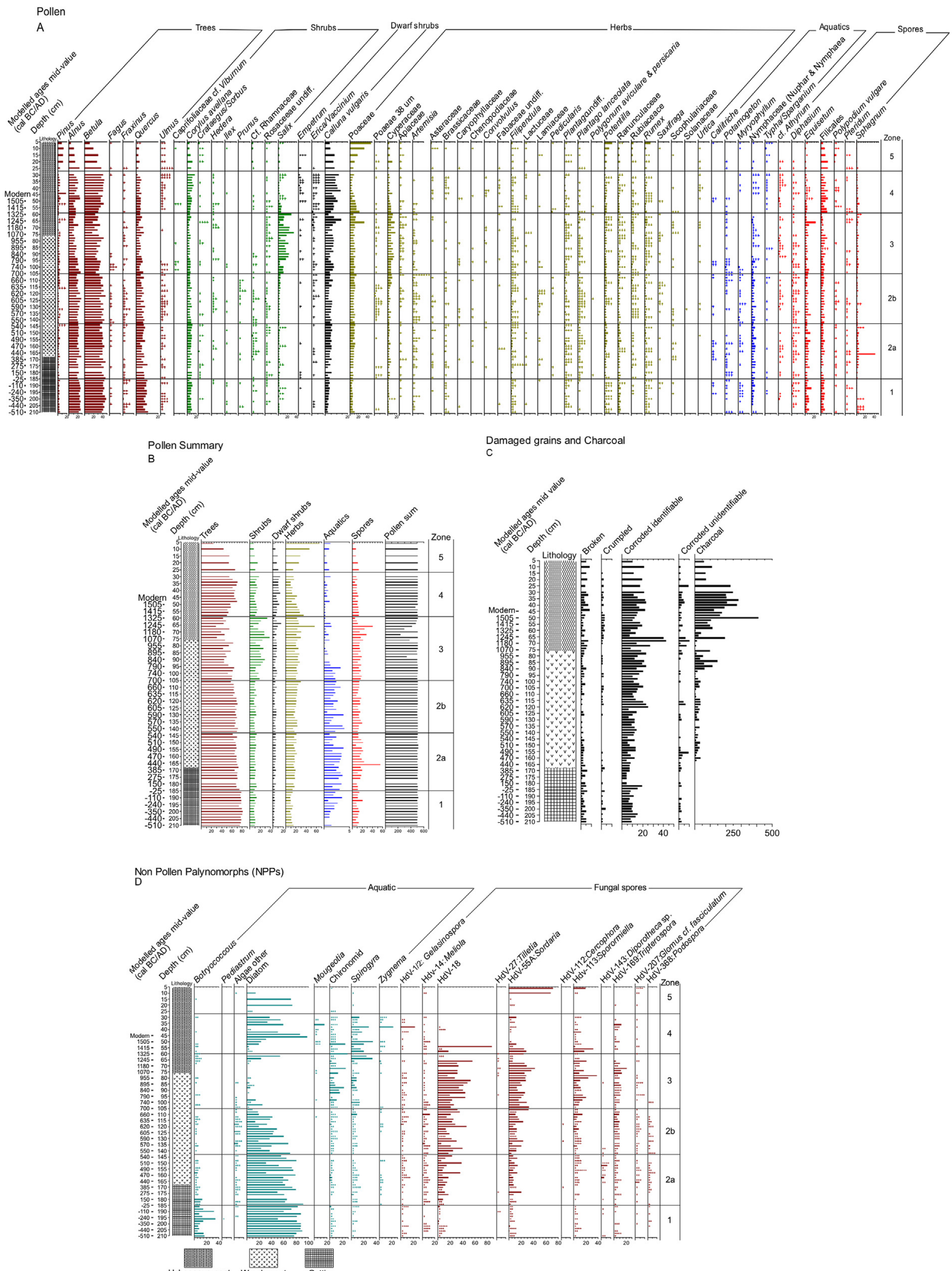


Fig. 7. Palynological results: A) Pollen, B) Pollen Summary C) Damaged grains and charcoal D) NPP summary, ++: rare types.

disappearance of the aquatic *Myriophyllum* pollen above 95 cm, a decline in all aquatic plant pollen and NPPs and by a pronounced decrease in diatoms: 55-0% albeit with fluctuations (a brief increase occurs at 102 cm and at 66-60 cm. There is also a rise in corroded pollen grains. Pollen from dwarf shrubs continue to increase: *Empetrum*, *Erica/Vaccinium* & *Calluna vulgaris*. The rise in *Calluna vulgaris* is likely associated with slightly drier heathland conditions. Increased terrestrialization on the former loch may also have allowed the encroachment of carr taxa since there is a gradual increase in HdV-19 and a substantial rise in Cyperaceae, Poaceae (representing wet and dry grassland) and *Salix* although *Salix* fluctuates. Wet woodland taxon *Alnus* decreases slightly. Other mixed woodland taxa also decline slightly in both the pollen percentage and concentration records: *Betula*, *Fagus* and *Ulmus* decline between 95 cm and 56 cm, and *Pinus* declines above 86 cm. Anthropogenic indicators remain relatively consistent: Poaceae >38 μm grains (cereal-type), although at lower representation, remain relatively consistent between 105 and 56 cm (*c.* AD700−1400). Apiaceae, *Artemisia*, *Plantago lanceolata*, *Rumex*, Ranunculaceae and *Potentilla* continue to be present while Lactuceae, *Convolvulus*, Chenopodiaceae and Caryophyllaceae are more sporadically represented. At 66 cm there is also a pronounced increase in Poaceae, small increases in *Plantago lanceolata*, Asteraceae, Apiaceae and *Rumex*, and an increase in corroded pollen grains. This zone also represents the strongest increase in coprophilous fungi for the entire record (15−95%) and includes *Sporormiella*, *Sordaria* and *Tripterospora*, which coincide with the strongest increase in LOI: >90%. Charcoal increases between 90 cm and 75 cm (AD800 until AD1070), and again at 66 cm (*c.*AD1230).

Zone 4: (60-27 cm; AD1320−>1500) is represented by a gradual return to wetter conditions albeit with fluctuations and human land-use. The zone begins with an initial dry phase between 60 and 54 cm (*c.*AD1320−1400) represented by sporadically low diatom & algae representation. *Salix* is lessprominent, as percentages are significantly reduced compared to zone 3, particularly above 56 cm. Above 56 cm increasing wetness is evidenced by fluctuating increases in diatoms coinciding with a decline in LOI to 72%, and the reappearance & consistent presence of Nymphaeaceae, Typha/*Sparganium* & *Myriophyllum*. As the proportion of diatoms increase, fungal spores decrease, including all NPPs associated with herbivore dung, and HdV-18. The decline in HdV-18, a fungus commonly found on *Eriophorum vaginatum*, coincides with a general decline in Cyperaceae and Poaceae pollen. During the same period tree and shrub taxa increase including *Alnus, Corylus avellana* type, *Betula* pollen*Ulmus* reappears and there is a slight increase in Filicales spores. *Calluna vulgaris* also continues to increase coinciding with a slight increase in the fungal parasite *Meliola*. Zone 4 shows a strong anthropogenic signal at the beginning of this zone with evidence of disturbance, arable and pastoral farming in the pollen and NNP records. Between 60 and 54 cm coprophilous fungi *Sporormiella* and *Sordaria* briefly increase, although these show a substantial decline above 56 cm. There is a substantial rise in micro-charcoal above 60 cm (*c.*AD1320): from below 10 counts to ~500 counts and a sharp rise in *Gelasinospora* to 25% at 36 cm. The charcoal values coincide with a rise in *Mougeotia*, *Spirogyra* and *Zygnema*. Nutrient inwash from nearby burning and erosional events may therefore have been responsible for these algal blooms. Poaceae briefly increases and also coincides with the rise in microcharcoal. Other herbaceous taxa show a more constant presence including Apiaceae, *Artemisia*, *Plantago* undif., *Potentilla* and *Rumex*. At 60 cm (*c.*AD1325) a pronounced rise in *Plantago lanceolata* (in S1) coincides with the appearance of the arable weed *Polygonum*. Poaceae >38 μm (cereal type) pollen grains also continue to show a presence until 50 cm (*c.* AD1505) before disappearing. Other herbaceous pollen grains, including Asteraceae, Brassicaceae, Lactuceae, *Convolvulus*, Fabaceae & Ranunculaceae, appear more consistently above 54 cm.

Zone 5: (27-5 cm; AD>1500−Modern) This zone represents wetter conditions and a decline in land-use although there is still some evidence of low intensity human activity/disturbance. An increase in aquatics particularly diatoms (high between 20 and 14 cm) but also plants *Potamogeton*, *Myriophyllum*, Nymphaeaceae & *Typha/Sparganium* types occurs. Agricultural indicators are lower & more sporadic but some Poaceae >38 μm (cereal type) pollen remain present. The main taxa represented in zone 5 include: *Pinus,* Poaceae and Cyperaceae. *Filipendula* also increases slightly and there is a small rise in *Salix* but a decline in other wet woodland taxa *Alnus* & *Betula.*

5. Discussion

The discussion has been structured to take each crannog period and local environmental history into consideration first. This is then followed by an exploration of the wider context of these changes.

A first approximation to the evolutionary stages of the Loch of Leys has been obtained using the projection of the samples in the space delimited by the main changes in sediment type (organic matter versus mineral matter; Cp1-IR) and inferred lake bioproductivity (Cp3-IR). Four major phases have been identified (Fig. 8): phase I, *c.* 510BC to *c.* AD100, represents a lake stage with clay-rich sediments and relatively lower organic matter content (Fig. 9) (LOI 39−52%). From *c.* AD100−250 the loch rapidly transitioned into a wetland stage (phase II) accompanied by higher lake bioproductivity and an increase in organic matter accumulation (LOI 61−78%) that lasted until *c.* AD650. A rapid increase in organic matter and an abrupt decrease in lake bioproductivity marks the onset of a drier peatland/fen stage (phase III) that lasted until *c.* AD1500, when the loch returned to a semi-aquatic stage (phase IV). These phases coincide with those defined based on changes in colour parameters of the sediments (Fig. 5).

Other changes in the evolution of the loch are described below based on their chronology. Fig. 9 summarises the proxies of these inferred changes described above.

5.1. Pre crannog construction: < 25 BC

Between *c.* 510 and 25BC the Loch of Leys was an open mesotrophic water body. This is evident in the characteristic spectroscopic signals of inorganic matter, organic matter and biogenic

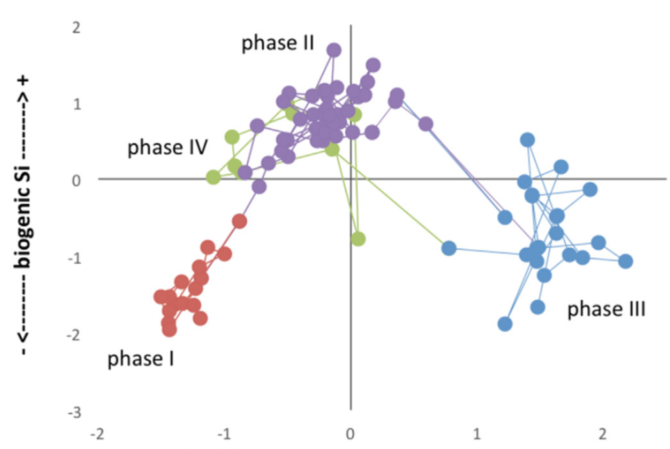


Fig. 8. Main evolution phases of Loch of Leys identified from the PCA analyses.

silica (Cp1-IR and Cp3-IR; Figs. 6 and 9), but also in the positive loadings for mineral matter proxies from the geochemical record of Cp1-ICP (Fig. 6); all proxies indicate highly homogenous sedimentation of light-coloured mineral matter. These results appear to be supported by the strong diatom representation (Fig. 7); however, diatoms may record a wide range of nutrient status, depending on species, and can also be found in standing water so some caution is needed. Around the edges of the loch a birch-alder-willow carr/wet woodland prevailed (Fig. 7 & SM_3). On drier ground, deciduous woodland dominated and this likely includes woodland components from the nearby hills (e.g. including oak, hazel, elm, ash and beech).

There is no evidence yet for the construction of the crannog prior to *c.*25 BC and evidence for other human activity in the palaeoecological record is equally limited to two grains of cereal type pollen at *c.*490 BC. The size of *Hordeum* pollen can overlap with *Glyceria fluitans*, a native upland grass indicative of natural reed swamp and fen communities (Rodwell, 1995; Albert and Innes, 2019). Together with low herbaceous (except Poaceae) representation and sporadic coprophilous fungal spores (Fig. 7) this may indicate natural rather than anthropogenic environment; if people were living locally, then their impacts on the environment were minimal.

5.2. Crannog occupation phase 1: c. 25 BC — AD 210 (Roman Iron Age)

The earliest phase of crannog occupation/use recorded in the archaeological record has been dated to between *c.*AD20 and AD210 (Stratigos and Noble, 2018). The continued presence of gyttja in the stratigraphic record suggests the loch was still present at the time of crannog construction. Further evidence of lacustrine sediments was identified during the excavations of the crannog and from the gouge augured sediment profiles; from these findings, combined with evidence from the desk based stratigraphic survey it was estimated that the loch depth may have been as much as 3 m at the time of the crannog's construction (Stratigos, 2017). Sedimentary analyses from the vibrational spectroscopy and elemental analyses (Figs. 6 and 9) suggest the loch likely prevailed until *c.*AD100, although bioproductivity began to increase from *c.*25BC, well before the first radiocarbon dates from the crannog. Between *c.*25BC and *c.*AD100 slight shifts are recorded in the colour of the sediments (lowering of luminosity and hue) probably due to a gradual enrichment in organic matter content driven by the increase in lake bioproductivity (Fig.SM_2). The LOI results also display a sharp rise in organic content from 40% to 66% between *c.*5BC and AD300. These changes could potentially be associated with natural terrestrialization processes. However, the changes coincide with a small rise in cereal type pollen grains between *c.*25BC to *c.*AD275, by a brief appearance of *Polygonum* and by small increases in *Rumex*, *Potentilla* and Asteraceae (Behre, 1981; Brown et al., 2007) (See Fig.SM_3). A change in mineral composition (MM source change, Fig. 9) and subtle increases in sedimentary evidence for increased bioproductivity could be linked to the increase in arable land and soil erosion. A farming community may have been situated around the edges of the loch during this period although given the chronological uncertainties, the crannog could equally have been occupied slightly earlier.

By *c.*AD100 the crannog would have been occupied and it is during this period that the loch rapidly transitioned into a wetland (phase II), marked by an acceleration in lake bioproductivity demonstrated by accumulation of organic matter and darkening of the sediment (i.e., lower luminosity), consolidating the trend in the decrease of mineral matter composition. Dark brown woody peat had replaced the gyttja in the sediment stratigraphy by AD350. These changes coincide with a rise in more distinctive anthropogenic indicators in the pollen and NPP records in addition to the continued presence of cereal types. This is evidenced by a rise in both coprophilous fungi (Perrotti and van Asperen, 2019) and herbaceous pollen often associated with disturbance and pastures (Brown et al., 2007) (Fig. 7 & SM_3). The results are comparable to other wetland sites across Scotland, Ireland and continental Europe

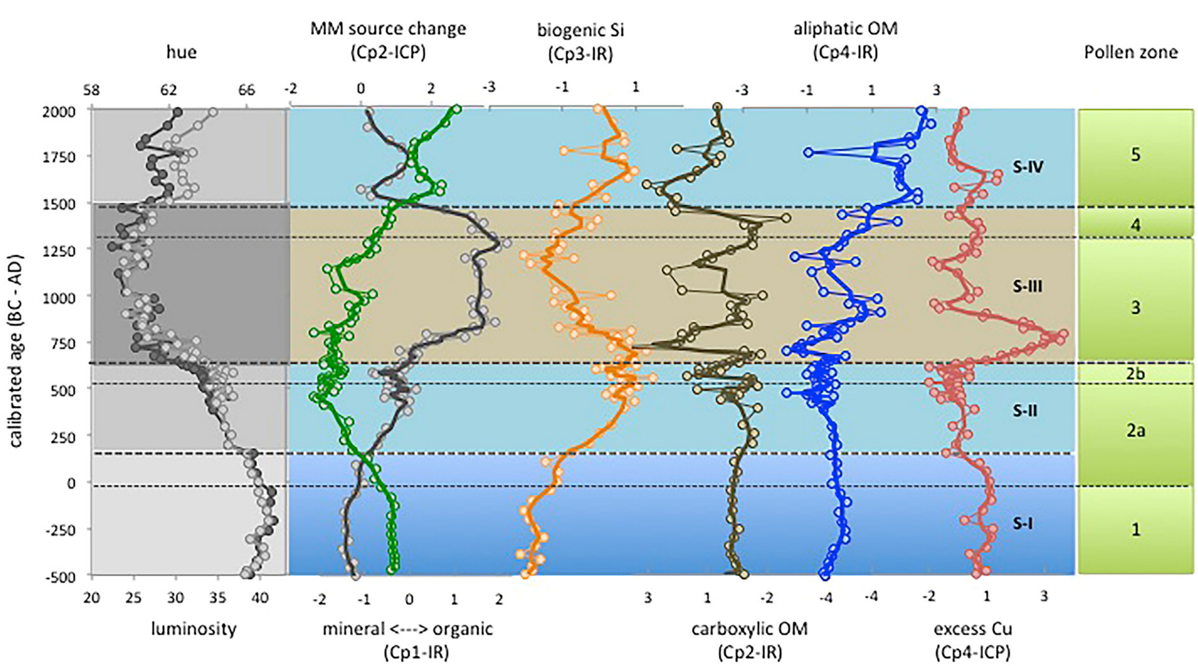


Fig. 9. Summary of the main lithological proxies and include hue (dark line) & luminosity (light line), Cp1-IR (black/1st line) & Cp2-ICP (green/2nd line), Cp3-IR (orange), Cp2-IR (dark brown), Cp4-IR (blue); these have been used to determine the main lake stages: S–I to S-IV. Cp4-ICP (red) represents excess Cu and is a potential metal working signal. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

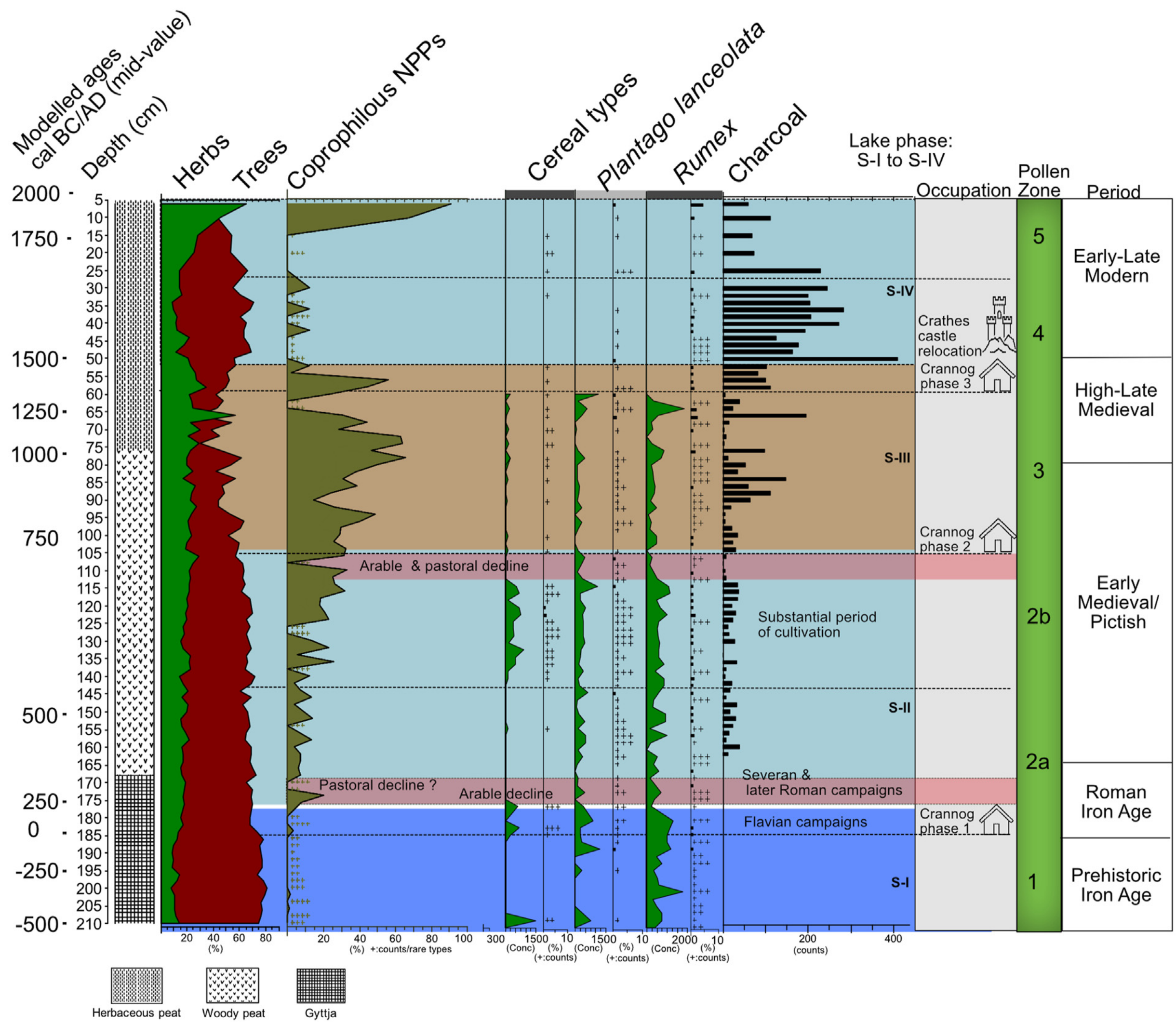


Fig. 10. Environmental and archaeological synthesis diagram from the Loch of Leys. The synthesis compares the lake changes S–I to S-IV identified from the combined lithological results with the vegetational history associated with land use (NPPs & pollen), crannog excavation history and regional influences (e.g Roman, Pictish etc …).

where eutrophication/increased organic inwash have been recorded and linked to wetland/loch occupation and activity (e.g. Brown et al., 2021; Craig, 2018; Fonville, 2015; De Marinis et al. 2005).

A substantial decline in both wet and drier woodland, more strongly represented in the pollen concentration record (Fig.SM_3), might be attributed to the first occupation phase of the crannog. Woodland would have been exploited for construction and clearance may have taken place for agriculture. Wood may have been sourced from the immediate vicinity of the crannog and from the nearby hills. *Alnus* and *Quercus* are the two commonest species used in crannog construction around Scotland (Crone, 2014), and *Betula* was noted by Burnett (1851) along with *Quercus* as among the timber species that were laid horizontally to create the Loch of Leys crannog.

An increase in wet and dry heathland together with Poaceae (grass), Cyperaceae (sedge) and *Filipendula* (meadowsweet) (Fig. 7 & SM_3) likely reflects the terrestrialization process to some extent with successional and peatland taxa probably colonising the newly exposed sediments. Most notably the increase in Poaceae, Cyperaceae, and *Sphagnum* may represent the formation of a fen and or reed swamp. A slight increase in Nymphaeaceae (water lilies) (Fig. 7) may also reflect lower loch levels since most water lilies prefer to grow in shallow depths between 1.5 and 2 m (Padgett, 2007). Small amounts of *Salix* along with *Alnus* likely also represent the presence of carr woodland nearby.

5.2.1. Wider context of landscape use

The local landscape around the Loch of Leys may have contained several Iron Age settlements spanning the prehistoric and Roman Iron Age. However, it is difficult to contextualize the settlement history of the Loch of Leys within the wider locality or within the broader region of north-eastern Scotland since most prehistoric settlements have been destroyed or remain undated. Just over 1 km to the south of the Loch of Leys the remains of a field system containing at least two hut circles (Figs. 2) and 18 cairns (Ralston, 1977; RCAHMS: Royal Commission on the Ancient and Historical Monuments of Scotland, 1984) were destroyed to build a housing estate, and 1.5 km to the east of the Loch of Leys crannog there is at least 1 hut circle (Fig. 2) which has never been excavated (RCAHMS: Royal Commission on the Ancient and Historical Monuments of Scotland, 1984). Despite the lack of local archaeological evidence, it is unlikely that the Loch of Leys was an isolated case of occupation and land use during the prehistoric and Roman Iron Age. On a national level there are several crannog sites (Fig. 1) that have been radiocarbon dates indicating construction/occupation in this period including at Tombreck and Morenish on Loch Tay in central Scotland (Dixon et al., 2007); Loch of Clans I (Stratigos, 2017) and Redcastle (Hale, 2000) further north near to Inverness; and at Buiston (Crone, 2000), Erskine Bridge (Jacobsson et al., 2018) and Cameron Bay in south-west Scotland (Crone, 2012). Regionally, between the River Dee and River Don in Aberdeenshire, there are as many as six other crannog sites recorded at Corby Loch, Loch Builg, Loch Davan, the Houff, and Prison and Castle islands on Loch Kinord. Out of these only the Houff and the Loch Kinord crannogs have been sampled for radiocarbon dating but these do not appear to have been occupied during the Roman Iron Age (Stratigos and Noble, 2018). Nevertheless, there is evidence of both prehistoric and Roman Iron Age occupation around the edges of Loch Kinord, situated 26 km to the west of Loch of Leys (Fig. 11). Three potentially contemporary prehistoric settlements comprised of multiple structures are found at Old and New Kinord, and at Culblean Hill (Abercromby, 1904; Ogston, 1931; Romankiewicz et al., 2020). The age of the New Kinord and Culblean settlements remain unresolved but are likely to be Iron Age in date. The Old Kinord settlement has been recently investigated and shows evidence for occupation between 200 and 55BC although it appears to have been abandoned sometime between AD25–145 (Romankiewicz et al., 2020).

The radiocarbon evidence from both the Loch of Leys crannog and Old Kinord settlements indicate that they both could have been occupied during the first major Roman campaigns into northeast Scotland. Very significant Roman activity is known from the temporary marching camps 13 km to the east of Loch of Leys at Normandykes (camp size: 43 ha/0.43 km^2) and 15 km south-east at Raedykes (camp size: 38 ha/0.38 km^2) (Fig. 11); however, chronological limitations mean the extent of Roman occupation at the camps is unclear. Agricultural decline is reported by Whittington and Edwards (1993) at Loch Davan (adjacent to Loch Kinord), which they associate with the impacts of warfare (e.g. the battle of Mons Graupius of AD83/84) and the ravaging of communities during the Flavian period; however, the story is likely more complex. Low resolution and ^{14}C limitations from the Loch Davan record means the precise dates for agricultural decline are uncertain and could possibly be from later campaigns or might be unrelated to Roman influence. Hunter (2007) argues that many Roman finds found on sites in Scotland beyond the frontier of the Empire seem to be associated with luxury and feasting: and these predominantly span the Flavian and Antonine periods from AD75 to AD160. A large army would likely have required at least some local support to supply fresh meat and particularly grain, but equally any attempts to invade a territory would likely also have required some form of diplomacy (Campbell, 2001; Westphalen, 2020). Recent excavations at Milltimber, just to the east of the Normandykes fort have certainly demonstrated that there was a demand for cereals. At least ninety bread ovens were discovered dating to AD 40–170 (95% probability) and most likely belong to the Agricola campaigns of the 80s (Dingwall and Shepherd, 2018; Hunter, 2018). Most integrated palaeoecological, historical, and archaeological investigations for the first millennium AD, tend to be focused on the region between the Antonine and Hadrianic Walls where Roman influence in northern Britain was strongest. This includes detailed works by Dumayne-Peaty (Dumayne, 1994; Dumayne and Barber, 1994; Dumayne-Peaty, 1998a,b; 1999) but also contributions by McCarthy (1995), Dark and Dark (1996), Tipping (1997) and Tipping and Tisdall (2005). The lack of both palaeoenvironmental and archaeological sites further north means it is very difficult to define Roman-local interactions. The Loch of Leys and its landscape context therefore adds important evidence to how we understand the complex interactions between the often-short lived presence of the Roman military campaigns and local communities in Scotland.

Both the local Iron Age settlements at Kinord and Loch of Leys, as well as the Roman fort at Normandykes are very close to the river Dee (on or within 2 km). Navigation of the waterways (despite the lack of historical/archaeological evidence) perhaps enabled easier access into these regions and vice versa. There are no confirmed Roman artefacts from the Loch of Leys crannog. However, both the Loch of Leys and Loch Kinord settlements show evidence of arable and pastoral farming during this period (Edwards, 1983). It could be argued that this might represent minimal/no Roman-local contact; however, a Roman 1st century glass perfume bottle (Fig. 12) was also recovered from Loch Kinord in the 19th century (Stratigos,

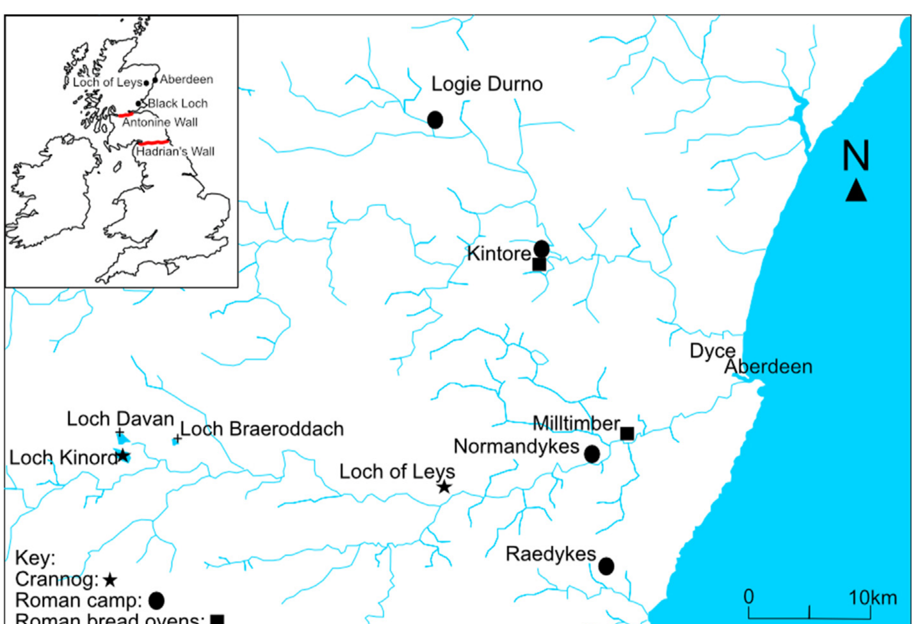


Fig. 11. Position of Roman marching camps in relation to the Loch of Leys and Loch Kinord crannogs. Map adapted from Dingwall and Shepherd (2018).

2017) and if contemporary settlements were present at Kinord, this might represent the kind of exchange relationships Hunter (2007) describes, with at least some of the local Iron Age communities along the River Dee able to access Roman goods. Currently there are over 24 Roman material culture findspots in Aberdeenshire (Curtis and Hunter, 2006), which suggest that despite lying so far to the north of long-term Roman occupation there was at least some Roman interaction with local communities.

Despite the lack of Roman finds at the Loch of Leys coins of unknown age were taken by workmen during the excavation of the crannog in 1850 (Burnett, 1851) and just 5 km north-east Roman coins were identified and recovered from the Red Moss of Crathes (Walker, 1892). These represent coins from different periods including Galba, Vespasian, Titus, Trajan, Hadrian, Pius, Faustina and Severus spanning the 2nd century AD until the mid-third century AD (Aberdeenshire Council, 2021).

5.3. Crannog abandonment: c. AD 210–500 (Roman Iron Age – Post Roman)

By the beginning of the 2nd and 3rd centuries AD the Loch of Leys crannog displays a prolonged archaeological hiatus of 400–500 years with no apparent construction or occupation (Stratigos, 2017). Cereal type pollen grains disappear from the palaeoenvironmental record after *c.* AD275, and do not reappear until *c.* AD500 and this coincides with a decline in *Potentilla*, *Plantago lanceolata* and *Rumex* and a later decline in coprophilous fungi (Fig. 10). This might be linked to the hiatus in the archaeological record, but some caution is needed since other herbaceous taxa and coprophilous fungi show and initial increase (e.g. Lactuceae, Rubiaceae, Chenopodiaceae, *Podospora*, *Sporormiella* and *Sordaria*) (Figs. 7 and 10 & SM_3), thus a shift (albeit possibly short-lived) in the agricultural economy to one that was more pasture-based could be an alternative explanation. There are no notable changes in geochemical-lithological signals to suggest a reduction in human-induced erosion, although corroded pollen grains do decline.

Fig. 12. Photo of 1st century AD Roman glass perfume bottle from Loch Kinord. Photo by Michael Stratigos.

5.3.1. Wider context of landscape use

A similar archaeological hiatus is witnessed at Loch Kinord (Stratigos, 2017) and at Kintore 20 km to the north of the Loch of Leys, with the cessation of unenclosed settlement sequences from the 3rd century until the 7th century AD (Cook and Dunbar, 2008). The archaeological hiatuses recorded here and at the Loch of Leys appear to match a general trend across Scotland, which sees radiocarbon dates from crannogs and many other native settlements conspicuously absent in the 3rd-5th centuries AD (clearly represented in Fig. 1b in Brown et al., 2021; Crone, 2012; Hunter, 2007; Cook and Dunbar, 2008) with no significant archaeological evidence of island or lake shore settlements until the 6th-7th centuries AD. There also appears to be a decline in Roman material goods found at native sites, including glassware and brooches (Hunter, 2007).

Palaeoenvironmental investigations from other lochs and settlements (despite chronological uncertainties) have identified both decreasing arable and pastoral activity spanning the same period, including at nearby Loch Davan and Loch Braeroddach (26 km & 22.5 km west of Loch of Leys and 120 km further south at Black Loch in Fife (Fig. 11), which has been suggested might be associated with abandonment linked to the Roman army's impact on the landscape and agricultural economy between the 2nd and 4th centuries AD in NE Scotland (Edwards and Whittington, 2000; Whittington and Edwards, 1993). By the later 2nd century AD, the Roman army would have been predominantly based behind the Hadrian's wall (c. 320 km to the south). The various campaigns into north-eastern Scotland after AD160 appear to have been mainly aimed at quelling unrest rather than invasion and these may have been in the form of direct military interventions (Fraser, 2009 pp: 22–29; Hanson, 2006 pp: 136–138). The destruction of farming communities caused by Roman campaigns, social/political restructuring, or the migration of people out of the region due to conflict may well have contributed to the apparent decline in agricultural activity recorded in the pollen diagrams from north-eastern Scotland. There is some documented intervention of the Roman army north of the Antonine walls, particularly during the Severus campaigns of AD208–210, but also at times during the 4th century AD (Hanson, 2006 p.139). It is quite likely that the nearby Roman marching camps were re-used during these periods (Alexander et al., 2000; Cook and Dunbar, 2008; Cook, 2011a). Repeated references to the impacts of hostile-to-Roman groups on Hadrian's Wall and incursions beyond the wall, most notably during the Barbarian Conspiracy of AD367, suggest continuing resistance of local groups to Roman presence from communities in the far north (Fraser, 2009 pp: 54–63; Hunter, 2014; Wilson, 2003); unrest is perhaps reflected at the Loch of Leys both by the hiatus in the archaeological record but also in the pollen record by the disappearance of arable farming indicators and some pastoral indicators.

5.4. Wetland activity: c. AD 450–700 (early medieval period)

The period spanning *c.* AD450–700 shows no archaeological evidence for crannog occupation at Loch of Leys. This may, however, be due to the small-scale nature of the excavations and does not necessarily reflect an absence of land-use around the loch. The value of the interpretation of the multi-proxy datasets is therefore important as not only can these help to detect human land-use, but they also help to define the environmental changes taking place in the wetland. From *c.* AD450 evidence for fires not only appears for the first time in the Loch of Leys charcoal record (Fig. 7), but charcoal is then consistently present. Natural fires could have occurred, but these may equally represent a more permanent or increased human presence in the locality. Fire may have been adopted as a way of managing the surrounding vegetation, perhaps to support livestock or to encourage game, and coincides with small increases in *Gelasinospora*, a carbonicolous fungi (Fig. 7) often linked to fire (Van Geel, 1976). Small increases in herbaceous plants (Fig. 7 & SM_3) (e.g. Chenopodiaceae, *Rumex*, *Plantago lanceolata* and *Potentilla*) may be associated with disturbance and pasture (Brown et al., 2007), whilst fungal spores associated with large herbivore dung also continue to increase (Fig. 7). From *c.* AD550 to *c.* AD640 evidence of arable farming reappears with a more constant representation of cereal type pollen and arable weeds (Behre, 1981; Brown et al., 2007) (Fig. 7 & SM_3). The sedimentary proxies spanning this period highlight moderate fluxes of inorganic nutrients associated with enhanced soil erosion. Human induced soil erosion could well be responsible for the peak in loch bioproductivity (Cp3-IR, Fig. 9).

Increased terrestrialization of the loch is represented between *c.* AD450–700. This is strongly evidenced by different proxy datasets including a continued decline in aquatic NPPs (Fig. 7) and mineral matter fluxes (Cp1-ICP; Fig. 6), and a continued increase in organic matter accumulation (Cp1-IR; Figs. 6 and 9) and LOI (Fig. 6). Increased terrestrialization likely explains a slight rise in tree taxa, shrubs and dwarf shrubs which most likely represent an expansion of heathland and open woodland in areas of the previous loch and around the edges of the wetland environment (Fig. 7 & SM_3). During this period wild fruits and nuts such as *Prunus* (likely blackthorn as blackthorn/sloe is common around the former loch today), *Empetrum* (Crowberry), *Vaccinium* (blueberry) and *Corylus avellana* type (hazelnut) were also available (Fig. 7 & SM_3). The terrestrialization process was impacted by fluctuating wetness; the various proxy indicators for organic-inorganic matter, wetland bioproductivity, mineral matter composition (Fig. 9) tend to be more irregular, probably reflecting short-lived wet-dry episodes on the fen. It is possible that some of the fluctuations recorded in the mineral composition (e.g. Cp2-ICP; Fig. 9) and organic matter (i.e, fluctuations in carboxylic OM, Cp2-IR; Fig. 9) are associated with human-induced erosional episodes associated with clearance and agriculture.

A brief decline in human land-use is represented towards the end of the 7th century AD evidenced by a decline in arable and pastoral indicators (e.g. cereal type pollen, coprophilous fungi, *Rumex*, *Plantago lanceolata* pollen and charcoal (Fig. 10).

5.4.1. Wider context of landscape use

Despite the absence of archaeological evidence, the palaeoenvironmental results suggest people were actively present in the area during the mid-5th to 7th centuries AD. Local legend suggests the Pictish saint St. Ternan was buried on the crannog in the 5th century AD (Stuart, 1866: 128). There is no evidence to confirm this, but 2 km south (Fig. 2; at 57° 03′ 06″ N 2° 29′ 06″ W; canmore id: 36 178) are two incised cross-marked stones suggesting some form of early Christian settlement or establishment nearby (Simpson, 1943). In a wider context, archaeological excavations have revealed a change in settlement organisation from the 4th to the 7th century AD in Scotland with the construction of numerous hillforts and enclosures (Alcock and Alcock, 1990, 1992; Cook, 2011a, 2013; Noble et al. 2013, 2019; Noble and Evans, 2019). Fortification and re-fortification processes were probably related to instability and social structure deterioration or to protect against disturbance, sieges and warfare across the late Roman and early medieval periods (Cook, 2011a; Noble et al., 2013; Noble and Evans, 2019). Nevertheless, some areas of Scotland appear to show little evidence of crisis during the post Roman era and may alternatively have been an opportunity for newly emerging elites and the construction of new forms of power centres (Hunter, 2014). There is equally no evidence of crisis at the Loch of Leys from the mid-5th century AD. Many sites in England, Wales and Scotland either show continuity of land use or intensified activity during this period (Dark and Dark, 1997). In north-eastern Scotland this applies not only to the Loch of Leys, but also to the Craw Stane fortified complex at Rhynie, where a prosperous agricultural economy prevailed during and beyond the 4th-6th centuries AD (Jones et al., 2021). In non-Romanized areas Dark and Dark (1997) have proposed this to be related to a lack of integration into the imperial economy, with Roman withdrawal having little negative impact on communities. However, beyond the Roman frontier other factors likely played a more significant role. For example, at the Loch of Leys, the appearance of burning events and reappearance of agriculture may be a direct result of the devastating impacts caused by the Roman campaigns and unrest of the 3rd-5th centuries AD and subsequent population recovery and reorganisation thereafter, although a brief population decline/decline in land-use may have occurred towards the end of the 7th century AD. To understand these events better, more integrated interdisciplinary research is needed at other locations to explore regional patterns of change.

5.5. Crannog occupation phase 2: c. AD 700–1300 (early medieval period – middle ages)

A second phase of crannog occupation/use is recorded in the archaeological record between *c.* AD890 and *c.* AD1010 (Stratigos and Noble, 2018). Fires in the surrounding area also increased in frequency between *c.* AD800 and *c.* AD1070 (identified by increased charcoal Fig. 7) and although natural fires cannot be ruled out the timings coincide with the crannog occupation and construction phase, suggesting they were more likely deliberate, perhaps used to maintain the area around the crannog settlement or/and domestic fires on the crannog itself. There is a slight decrease in *Salix* during this period (Fig. 7 & SM_3), as well as small decreases in tree pollen, including wet woodland, and the disappearance of *Fagus* and *Ulmus,* which might represent small-scale clearance. A rise in Cu (Cp4-ICP) (Figs. 6 and 9) is evident from *c.* AD640 to *c.* AD905 and peaking at *c.* AD760–800. Peaks in copper concentration and enrichment can coincide with drier climates (Küttner et al., 2014), although the Cu represented in Cp4-ICP does not appear to be associated with biological export or mineral matter source changes. The rise in excess Cu might signify an anthropogenic source, such as local copper working. If so, then fuel would be needed to maintain the furnaces which might also account for the rise in charcoal and decline in woody taxa. During the early medieval period metalworking would have been an essential component for newly emerging power centres, not only to produce weapons and tools but also to produce items of prestige which could amplify power and status (such as brooches and hand-pins). Crannogs are known to be key craft production sites across Scotland and Ireland in this period (Crone and Campbell, 2005; O'Sullivan, 2009). In Aberdeenshire, there is evidence for both non-ferrous and ferrous metalworking in the first millennium AD (8th-9th centuries at Dyce (Woodley, 2018); 7th-9th centuries at Kintore (Heald, 2008 p.209-210); 5th-7th centuries at Maiden castle (Cook, 2011b); 4th-6th centuries at Rhynie (Noble et al., 2019). The evidence for metalworking at the Loch of Leys sits with some strong evidence for arable and pastoral farming around the site, again pointing to a period of intense activity at the crannog and around it. Both the pollen and NPP records (Fig. 7 & SM_3) show evidence of arable and pastoral farming between *c.* AD700 and AD1400. Evidence for arable and pastoral activities includes the reappearance and relatively consistent presence of cereal type pollen grains and herbs associated with disturbance and pasture. There is also a high representation of coprophilous fungi. A substantial increase in *Salix*, Cyperaceae and Poaceae (Fig. 7 & SM_2) suggests larger areas of the former loch may have been exposed during this period, allowing fen and woodland carr taxa to colonise and this is further supported by a rise in degraded pollen grains (Fig. 7) likely caused by *in-situ* exposure to oxygen (e.g. Havinga, 1964; Keil et al. 1994; Moore et al., 1991), but potentially also erosion (e.g. Wilmshurst and McGlone, 2005). The re-occupation on the crannog and increased anthropogenic activity in the locality may have contributed towards a gradual change in water chemistry such as is reflected by a rapid decrease in biogenic Si (Cp3-IR, Figs. 6 and 9), although this is difficult to ascertain, as terrestrialization and build-up of peat would equally have impacted the primary productivity.

What is clear from the palaeoenvironmental records is that reoccupation of the crannog took place during major environmental changes linked to a significant drop in the water table and peat accumulation between *c*. AD650 and *c*. AD1300. These changes are highlighted by several of the proxy datasets including a rapid decrease in Cp2-IR (wetland bioproductivity; Fig. 9) accompanied by a rapid increase in Cp1-IR (organic matter accumulation; Fig. 9) from *c*. AD650 to *c*. AD820, this is followed by a rise in LOI (organic matter content) to 94% between *c*. AD800 and *c*. AD1250 (Fig. 7) which coincides with the lowest aquatic representation in the NPP record, particularly diatoms (Fig. 7). There is a strong correlation between the LOI, NPP, geochemical (Cp1-ICP & Cp3-ICP), colour (L* and hue) and FTIR (Cp1-IR & Cp3-IR) records (Figs. 6 and 7). The increase in HdV-19, found in a range of peatland to fen environments (Van Geel, 1978; Prager et al., 2012), chironomids and *Spirogyra* (Fig. 7), likely reflects the transition from a mesotrophic to a eutrophic fen. These changes coincide with the Medieval Warm period (MWP); however, whilst there are some good palaeoclimatic investigations for north-western Scotland, such as stalagmite records, suggesting drier winters between AD600 and AD900 (Baker et al., 2015; Proctor et al., 2000) and oxygen isotope research on shells suggesting greater seasonality during the Medieval Warm period with warmer summers and cooler winters (Mobilia, 2009), trying to compare local environmental events with regional climate change in Scotland is difficult due to a lack of well-defined regional datasets. The findings from this investigation have however produced a good record of local environmental change. The combined proxy evidence clearly demonstrates a change in fen wetness to much drier conditions, which would have provided a favourable environment for agriculture and settlement in the immediate vicinity of the core location.

Around the mid-13th century AD, a major short-lived fire is identified in the charcoal record (at 65 cm; Fig. 10) and likely caused a substantial reduction in willow cover, expansion of grassland and some herbaceous taxa (*Plantago lanceolata*, Asteraceae, Apiaceae and *Rumex*), as well as a substantial rise in corroded pollen grains (Fig. 7). Corroded pollen grains will increase during erosional pulses (Wilmshurst and McGlone, 2005). A major fire and soil exposure could also have exposed the pollen grain to chemical oxidation (Havinga, 1964; Keil et al. 1994). There is no evidence available to determine where the fire started, thus it remains unclear whether the fire may have begun on the crannog or somewhere in the locality. These changes might in some way be associated with the Wauchope family who in AD1247 were granted possession of the lands of Tulimacboythne, including the Loch of Leys (Burnett, 1901; Bailey et al., 2000). Today only the ruins of a medieval castle of Leys remain on the crannog, although its exact construction date is unknown. There is no documentary evidence of the Wauchope family residing on the crannog, although tradition suggests the castle was once a fortalice, from which the Wauchopes were driven from after the first Scottish war of independence. The castle then became the seat of the Burnett's until the middle of the 16th century (Munro, 1882).

5.6. Crannog occupation phase 3: c. AD 1300–1500 (middle ages)

A stronger, consistent anthropogenic signal is recoded in the palaeoecological record spanning *c*. AD1320–1500. Evidence includes a pronounced increase in fires (Fig. 7), a substantial reduction in willow (*Salix*) and expansion of grassland (Poaceae). There is also a combination of disturbance, pastoral and arable indicators and coprophilous fungi such as *Sporormiella* and *Sordaria* types (Fig. 7). By AD1323 it is well known from historical texts that the Burnard (Burnett) family were in possession of the crannog and surrounding estate (Burnett, 1901; Bailey et al., 2000).

The initial increase in anthropogenic indicators coincides with a dry period on the former loch lasting just under ~100 years; both diatoms and algae are significantly low in the NPP record (Fig. 7). This is then followed by increasing wetness and likely corresponds to the Little Ice Age (LIA). This was a period of fluctuating cold inversions between the AD1300s and the 1800s (Folland et al. 1990), but as with the MWP the environmental impacts of the LIA have been difficult to determine due to the paucity of robust, chronologically well resolved palaeo climatic records for this region of Scotland, particularly before the 1500s. Regional and temporal variability of wetness between the AD1300s-1500s is shown in peat records in Scotland (e.g. Barber, 1981; Mauquoy and Barber, 1999; Langdon and Barber, 2005). The Loch of Leys record also provides compelling evidence for an increase in wetness from the NPP, colour, geochemical and FTIR records. Evidence includes a rapid decrease in the *in-situ* accumulation of organic matter and a concomitant increase in mineral matter (Cp1-IR, Figs. 6 and 9) with a source signal typical of the basal lake sediments (Cp2-ICP, Figs. 6 and 9). Other proxy evidence includes a decrease in LOI to 74%, a progressive increase in lake bioproductivity represented by Cp3-IR (Figs. 6 and 9), an increase in diatoms (NPP results; Fig. 7) and a gradual increase in IR signal of biogenic silica, resulting from the increased bioproductivity, represented in both the geochemical and FTIR results (Fig. 6). Overall, these results combined demonstrate a gradual, sustained increase in wetness with a rapid transition from peatland back to wetland. This is also clearly represented in the stratigraphy by a change to a *Phragmites* rich clayey peat.

5.7. Crannog abandonment: c. AD 1500–1850 (Post medieval)

Increasing wetness caused the reversion of the fen/bog back into a semi-aquatic reed swamp environment and facilitated the re-expansion of wet woodland around the former loch's margins. After *c*. AD1500 bioproductivity in the loch returned to values similar to those of the most productive phases seen in the previous wetland (Cp3-IR, Figs. 6 and 9).While the composition of the mineral matter resembles that of the basal lake sediments, the molecular composition of the organic matter largely differs by being more aliphatic (Fig. 9), and the sediment also shows an increase in luminosity and, to a lesser extent, in hue (Figs SM_2 & 9). Together these results point to larger contributions of terrestrial allochthonous sources. A rise in semi-aquatic to emergent plants (Fig. 7) such as Nymphaeaceae, *Myriophyllum* and *Typha/Sparganium* further indicates that by the 1500s the site had transitioned back into a semi aquatic, reed swamp environment. Today, even after partial drainage, access to the crannog site is inaccessible during the wetter winter months.

In addition to wetter conditions at the Loch of Leys, temperatures would also likely have been much cooler by the 1500s. A prominent cold phase associated with the Little Ice Age has been identified in the Cairngorm tree ring record between the 1500s and early 1800s, with the coldest decade recorded in the 1690s (Rydval et al., 2017). Such wet and cool conditions at the Loch of Leys, in addition to a change in the family fortunes (Burnett, 1901: p. 22), may have been a contributing factor for the decision by the Burnard (Burnett) family to eventually relocate to Crathes castle.

During the 1700s and in 1850 there were two major schemes to drain the loch. The first attempt occurred in the 1730s according to the *New Statistical Account* (New Statistical Account, 1845: p. 328). The second attempt was made by Burnett in 1850, shortly before he excavated the crannog (Burnett, 1851; Munro, 1882). These attempts are possibly evident in the stratigraphy and geochemical record by brief shifts in organic content (represented in the LOI (Fig. 6), geochemical (Figs. 6 and 9) and FTIR (Figs. 6 and 9) records, and abrupt changes in a* and b* (Fig.SM_2), by a rise in vegetation associated with the expansion of a grass-sedge-willow fen type environment (Fig. 7) as well as fluctuations in diatoms, algae and fungal spores (Fig. 7)). The presence of marsh/fen taxa, aquatic plants and diatoms as well as small increases in willow and sedge in the pollen record likely reflect the continued wetness after the attempts at drainage. There was, however, likely some success in drainage as according to Munro (1882) during the 1850s the land had been converted into corn land, whilst there is also some evidence of cereal type pollen between zones 4 and 5 as well as herbs and fungal spores often associated with disturbance, arable or pastoral activities (Fig. 7).

6. Conclusion

This paper represents the first high-resolution multi-proxy palaeoenvironmental investigation of an infilled loch in north-eastern Scotland and highlights how combined interdisciplinary and novel techniques, such as colour, elemental and FTIR-analysis can help to define the responses of wetland habitats to environmental and cultural change. Limited excavation of a nearby crannog provides chronological context for its inhabitation, whilst the integration of the palaeoenvironmental records provide a greater understanding of continuity and land use change across a time period in Scotland that has little information. This research has wider context and value as it explores in the earlier phases of crannog use the responses of native communities to Roman occupation and abandonment beyond the Roman frontier, which is significant not only to Scotland but also to other parts of Europe that had similar frontiers and conflict zones during the Roman period. The first occupation of the Loch of Leys crannog can be placed in the 1st and 2nd centuries AD, during a period of receding lake levels and gradual terrestrialization. The occupation coincided with the first major Roman campaigns into north-east Scotland, but there is no evidence to suggest local communities were impacted negatively during these initial campaigns. Not only was the crannog occupied during this period but arable and pastoral farming continued until the 3rd century AD. Roman diplomacy may have occurred in at least some localities, which seems likely when the broader archaeological record is considered (i.e. number and types of Roman 1st-2nd C. artefacts found at non-Roman sites). A different story, however, emerges from the 3rd century AD, potentially linked to the Severan and later Roman campaigns. A potential hiatus is represented in the Loch of Leys archaeological record and cereal pollen disappears until *c.* AD550 which coincide with a general trend in crannog and settlement abandonment or paucity of occupation across Scotland during the 3rd-5th centuries AD. It is well known that there was increasing unrest north of the Roman frontier in Britain from the end of the 2nd century AD onwards. What is clear from the combined archaeological and palaeoenvironmental records is events between the late 2nd to 5th centuries AD had a more profound impact on farming communities in north-eastern Scotland compared to events during the 1st to 2nd centuries AD or even events after Roman withdrawal from Britain in the early 5th century AD.

The appearance of frequent and consistent fires and reappearance of cereal type and arable weed pollen from *c.* AD450 suggest that people were more actively present and managing the local landscape during this period, despite the absence of archaeological evidence for crannog occupation or construction. Between *c.* AD890 and *c.* AD1010 a second phase of crannog activity is recorded in the archaeological record, coinciding with a significant drop in the water table (*c.* AD650–1470). Favourable environmental conditions may have prompted increased agriculture and settlement, and potentially also a change in water chemistry and eutrophication. A substantial rise in copper identified by the elemental analysis may represent the first appearance of a metalworking economy in the locality and if so, contributes towards the growing number of metalworking sites (non-ferrous and ferrous) identified between the 4th-9th centuries AD in north-east Scotland. A third and final phase of crannog occupation is recorded from *c.* AD1323, during which the Burnard (Burnett) family resided on the crannog. The combined palaeoecological findings suggest that the initial occupation in *c.* AD1323 was during a drier period with more intensive land-use (fires, disturbance, arable and pastoral farming); however, by the *c.* AD1400-1500s conditions had gradually become much wetter, resulting in the transition of the peatland back into a semi aquatic reed swamp, and by the 16th century the crannog had been abandoned. Overall, despite the scarcity of research conducted on crannogs in Scotland, this paper illustrates how integrated multi-proxy research when combined with limited excavation can be a very successful way to unravel the complexities of wetland settlement chronologies and their impact on their wider environments.

Credit author statements

Samantha Elsie Jones: Conceptualization, Methodology (Pollen, LOI, NPP & all dataset amalgamation), Formal analysis, Investigation, Data curation, Writing-original draft, Writing-review and editing, Visualization, Supervision, Project administration. **Olalla López-Costas**: Conceptualization; Methodology (Colour analysis & Vibrational spectroscopy using FTIR/ATR), Formal analysis, Investigation, Data curation, Writing (Editing & Review) Visualization. **Antonio Martínez Cortizas:** Conceptualization; Methodology (Elemental composition analysis (geochemistry)), Formal analysis, Investigation, Data curation, Writing (Editing & Review), Visualization. **Tim Mighall:** Conceptualization; Project Administration; and Writing (Editing & Review). **Michael Stratigos:** Conceptualization; Methodology (Archaeological excavations of the Loch of Leys and Loch Kinord crannogs & sediment core extraction for the palaeoenvironmental analysis); Funding Acquisition, Project Administration, and Writing (Editing & Review). **Gordon Noble:** Funding Acquisition, Project Administration and Writing (Editing & Review).

Final Note: all co-authors have spent considerable if not equal time on editing and reviewing, which has significantly contributed towards the high standard of this article.

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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Appendix A. Supplementary data

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