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Bates, C.R.[1], Bates, M. R.[2], Dawson, S.[3], Huws, D.[4], Whittaker, J.E.[5], and Wickham-Jones, C.R.[6]

1 Department of Earth and Environmental Sciences, University of St Andrews, St Andrews, Fife, Scotland. KY16 9AL
2 School of Archaeology, History and Anthropology, University of Wales Trinity Saint David, Lampeter, Ceredigion, Wales. SA48 7ED
3 Geography, School of Social Sciences, University of Dundee, Perth Rd, Dundee, Scotland. DD1 4HN
4 School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, Wales. LL59 5AB
5 Department of Earth Sciences, Natural History Museum, Cromwell Road, London. SW7 5BD
6 Archaeology Department, University of Aberdeen, St Mary's Building, Elphinstone Road, Aberdeen, Scotland. AB24 3UF

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Abstract

The World Heritage Sites of Orkney, Scotland contain iconic examples of Neolithic monumentality that have provided significant information about this period of British prehistory. However, currently, a complete understanding of the sites remains to be achieved. This is, in part, because the monuments lack an adequate context within the broader palaeolandscape. Recent investigations (seismic geophysical survey, microfossil analysis and 14C dating) in and around the Brodgar Isthmus, both onshore and offshore, are used to reconstruct the landscapes at a time when sea-level, climate and vegetation were different to that experienced today. Results show that in the early Neolithic the isthmus between the Ring of Brodgar and Stones of Stenness was broader with a smaller loch to the west. Furthermore this landscape contained sandstone outcrops that would have provided a potential source of stone for monument construction. Microfossil analysis and radiocarbon dates demonstrate that the Loch of Stenness was transformed from freshwater to brackish during the early Neolithic, perhaps immediately preceding construction of the major monuments. Finally, the analysis of our data suggests that sediment influx to the loch shows a tenfold increase coincident with widespread vegetation change that straddles the Mesolithic/Neolithic transition at c. 8 ka cal. B.P. These results provide, for the first time, a landscape context for the Neolithic sites on the isthmus.

Introduction

The contextualisation of archaeological sites in the landscape requires an understanding of the relationship between landscape, site structure and site function/use. In practice, generating the ground truth control to provide this context can be difficult, timing consuming and costly. This is particularly the case where sites sit in a landscape that straddles the transition zone from terrestrial to wetland/marine and where landscape flooding by the sea may have had a considerable impact on the changing relationship between site and environment through time.

Ironically, it is these precise landscapes that have recently been identified as of particular interest with regard to the intensification of human settlement and societal development in the early millennia of the Holocene. Bailey and Milner (2002), examine the role of coastal environments in the social evolution of hunter-gatherers from 6000 BP onwards, across the Mesolithic/Neolithic transition, while Wickham-Jones (2013) highlights the potential of the fluid marine-skerry landscapes of southern Scandinavia as a driver in the development of coastal technologies where the role of woodland as an isolating element between coast and land is also noted. The dynamic coastal environment and its influence on technological and cultural developments from as early as 11,000 BP has been discussed in detail with regards to the Hensbecka sites of southern Sweden (Schmitt, 1994; Scmitt & Svedhage, 2016) while Evans *et al.* (2014) emphasize the significance of continental shelf locations for early society.

Increased awareness of the value of these vulnerable landscapes presents specific challenges to archaeology. Not only are they often difficult to access (e.g. Tizzard *et al*., 2015), but any archaeological remains are subject to complex taphonomic processes that are still poorly understood (Ransley and Sturt, 2013), while the zones themselves are particularly vulnerable to environmental change (Bailey, 2014). Currently, understanding of submerged landscapes, and potential associated archaeology, relies heavily on broadscale models (Sturt *et al*., 2013) with their inherent limitations for the interpretation of human behavior (Wickham-Jones *et al.,* forthcoming a & b).

Nowhere, perhaps, are these issues more pertinent than in Orkney (Figure 1) where the mechanics of relative sea-level rise, coupled with climatic change (Farrell, 2009), resulted in a dynamic environment that persisted into more recent millennia. It is thus necessary to understand the changing environment of Holocene Orkney in order to understand fully more recent periods such as the Neolithic. While specific remains have yet to be verified underwater, the great monuments of Neolithic Orkney (Ring of Brodgar, Stones of Stenness and Maeshowe), lie along the Brodgar Isthmus which today separates the brackish waters of the Loch of Stenness to the west from the fresh waters of the Loch of Harray to the east (Figure 2). This paper presents the results of multidisciplinary research into the palaeoenvironmental setting and landscape context of the Neolithic sites that make up the suite of monuments along the Brodgar Isthmus. It provides a more detailed understanding of these sites and in particular the landscape changes which those who used the sites may have experienced.

Understanding the relationship between the changing context of these sites and the local geography is critical for many reasons. At a time when significant changes in economy, behaviour and monumentality were taking place across the Mesolithic to Neolithic transition in Orkney (Wickham-Jones 2015; Richards and Jones, 2016) it appears that shifts in the boundaries between wetland and dryland and between freshwater and estuarine/marine conditions were also occurring (Bates *et al*. 2012). Within the Brodgar Isthmus these relationships are currently inadequately documented. This is in part a function of the bias towards excavation of monumental archaeology, because of its spectacular nature, as well as the inherent difficulty of linking terrestrial archaeological data to stratified palaeoenvironmental evidence from the sedimentary units we can trace across the landscape. Consequently we have chosen to investigate sequences from within the Loch of Stenness in order to provide that contextual information. This work is part of a wider interdisciplinary project undertaken by the Rising Tides project (Bates *et al.* 2012) that is examining the impact of relative sea level change on Prehistoric Orkney. This paper provides information on the nature of environmental change across the Mesolithic to Neolithic transition in the immediate vicinity of the World Heritage sites. Furthermore, it provides environmental data that can be tested against archaeological information documenting human activity at the sites.

Geographical setting and landscape history of the study area

The archipelago of Orkney (Figure 1) consists of a small group of islands situated 10 km north of the Scottish mainland. The low-lying islands are well known for their preservation of stone built houses, tombs and monuments of Neolithic date (6 – 4 ka cal. B.P.). The islands are exposed to the Atlantic Ocean to the west and the North Sea to the east but despite their geographic position the soils of Orkney are fertile and the mild climate has resulted in a long tradition of agriculture. Since last glacial maximum at 20 ka cal. B.P., the islands have experienced relative sea-level rise reaching present day levels approximately 4 ka cal. B.P. The human population is known to have re-colonised the islands c. 9 ka cal. B.P. with farming introduced at c. 6 ka cal. B.P. The Loch of Stenness (Figure 2) lies west of the Brodgar Isthmus and consists of a c. 4km long basin orientated northwest to south east entering the sea at the Brig o'Waithe. The loch is connected to the east with the Loch of Harray at the Bridge of Brodgar. Today the Loch of Stenness is a brackish lagoon in contrast to the freshwater conditions of the Loch of Harray.

The landscape history of mainland Orkney has been examined at a number of sites (Figure 1B) and perhaps the most complete record derives from Crudale Meadow (Moar, 1969; Bunting, 1994; Whittington *et al*., 2015). This site, an infilled lake basin (formerly called Yesnaby by Moar (1969)) contains a sequence of calcareous marls overlain by peats that span more than 15,000 years through the Devensian Lateglacial and into the Holocene. The sequences present are similar in appearance to those investigated by the Rising Tides project in the Bay of Firth (Bates *et al*., 2012) and at the Loch of Brockan (Bates *et al.*, 2010) as well as the sediments overlying till in the Bay of Skaill (De la Vega-Leinert *et al*., 2000).

The vegetation history indicates that birch-hazel woodland was well established in Mainland Orkney by 9.4 ka cal. B.P. (Bunting, 1994; De la Vega-Leinert *et al*., 2007). This woodland appears to have had a grass and herb understory, which persisted until c. 7.8 ka cal. B.P. (Tisdall *et al*., 2013). Woodland cover continued with oak until around 5.9 ka cal. B.P. (Bunting, 1994; de la Vega-Leinert *et al*., 2007). Farrell *et al*. (2012) argue that woodland loss (both primary and secondary) occurred at different times in different places in Orkney. Thus at Bay of Skaill De la Vega-Leinert *et al*. (2000) indicate woodland loss in the Neolithic by c. 5.5 ka cal. B.P. where a calcareous pond existed in a hollow on the till surface. This pond was beginning to be overwhelmed by sand blown on-shore by c. 5.2 ka cal. B.P. and by c. 4.5 ka cal. B.P. charcoal and *Plantago lanceolate* pollen indicated Neolithic agricultural activity in the vicinity was taking place. At Scapa Bay this loss of woodland took place at the beginning of the Neolithic (De la Vega-Leinert et al., 2007; Farrell, 2009) while at Mill Bay, Stronsay, Tisdall *et al.* (2013) have documented evidence for hazel scrub and grassland vegetation being replaced by heathland after 4 ka cal. B.P. All of these observations suggest that landscape change, and in particular woodland clearance, was widespread in Orkney throughout the Neolithic.

Against this patchwork mosaic of vegetation change the other major factor controlling landscapes in Orkney is that of rising sea levels. Work on Holocene sea-level change in Orkney, for example in the Bay of Firth, indicates that relative sea-levels have been rising since the early Holocene to reach their present position some 4000 years ago (Dawson and Wickham-Jones 2007; Wickham-Jones *et al* forthcoming). Final inundation occurred considerably later than the arrival of the first Mesolithic population of Orkney c. 9 ka cal. B.P., and nearly two millennia after the development of farming in the islands c. 6 ka cal. B.P. (Downes *et al,* 2005).

Archaeological background

The archaeological evidence for Neolithic Orkney (Figure 1A) is dominated by the large stone structures that occur throughout Orkney and have been the focus of attention since the discovery of Skara Brae in 1850. In addition to the settlement remains of individual farmsteads (e.g. Knap of Howar, Smerquoy) and larger villages (e.g. Links of Notland, Pool, Skara Brae) there are also stone tombs that relate to both the Early (e.g. Unstan, Midhowe) and Late (e.g. Maeshowe, Cuween) Neolithic. The repertoire is completed with standing stone circles (Stones of Stenness and Ring of Brodgar) and the newly discovered ceremonial site of Ness of Brodgar (Figure 2). In recent years the discovery of the remains of timber buildings has added to the rich pool of knowledge of Orkney in the Early Neolithic (Lee and Thomas, 2012; Richards and Jones, forthcoming). Within the study area, the material archaeology is dominated by the ceremonial complex that runs along the Brodgar Peninsula (Figure 2), from the henge and tomb at Bookan, past the Ring of Brodgar, Ness of Brodgar, and the Standing Stones of Stenness to the great tomb at Maeshowe (Figure 2, Downes *et al*., 2005). With the exception of Barnhouse, settlement remains are lacking, but it has to be noted that archaeological excavation has focused on the area to the east of the Loch of Stenness, yet the other shores offer considerable potential which has yet to be explored in detail (Richards, 2005, 8-16). The earliest dates for activity in the study area come from the excavated settlement at Barnhouse and relate to the late sixth millennium cal B.P. (late fourth millennium BC) (Griffiths and Richards, 2013).

By contrast with the rich record of Neolithic occupation the Mesolithic is less well known (Figure 1A). Mesolithic find spots (Wickham-Jones *et al*., forthcoming) indicate that the archipelago was inhabited prior to the advent of farming, but only two sites have been excavated and dated (Links House, Lee and Woodward, 2009; and Long Howe, Wickham-Jones and Downes, 2007) both of which produced early ninth millennium cal. B.P. dates. In some cases Mesolithic finds were recovered during the excavation of later, Neolithic, sites (e.g. Barnhouse, Middleton, 2005, 293) highlighting the likelihood that earlier activity may be masked under later sites.

While evidence for Mesolithic activity in the study area lacks detail, people were undoubtedly present. By the time of the first house building at Barnhouse the material culture displays all the signals of a well-established Neolithic community, suggesting that transition period material is still to be recognized. In the following centuries there is evidence for activity at the nearby Stones of Stenness in the early fifth millennium cal. B.P. (early third millennium BC, Griffiths and Richards, 2013) and at Ness of Brodgar where the earliest dates to date also relate to the late sixth millennium cal. B.P. (late fourth millennium BC, Towers *et al*., 2015). Apart from one date at the start of the fifth millennium cal. B.P. (around the turn of the fourth to third millennium BC), the dates from Maeshowe suggest activity there between the early fifth and first half of the fourth millennia cal. B.P. (first half of the third to early in the second millennia BC, Griffiths and Richards, 2013). The small Neolithic tomb of Unstan, on the south shores of the loch, remains undated.

In general, the evidence for the Neolithic around the Loch of Stenness is biased in favor of ceremonial activity. While sites along the Brodgar peninsula suggestthat it was indeed the ceremonial heart of Neolithic Orkney (Richards, 2013; Downes *et al*., 2005), surface finds from the other shores of the loch suggest that daily life elsewhere in the area included small farming communities of the type now recognized across Orkney (Richards, 2005, 8-13).

Field investigation

Fieldwork has involved two phases of work. Geophysical survey of the loch base and fill was undertaken to identify loch bed features and areas of interest. This was followed by targeted coring across the loch to provide samples for palaeoenvironmental investigation and dating. Similar geophysical work was trialled in the Loch of Harray but proved impossible due to the build-up of gas from the decomposition of organic materials.

Seismic investigation

Sonar data was collected across the loch using a small, customised survey boat. The boat was fitted with RTK dGPS to ensure positioning to at least 5cm accuracy. For mapping the loch floor a 468kHz SEA Swathplus bathymetric sidescan was used together with a TSS DMS05 motion reference unit. The combined survey system provides up to 30 pings per second producing a potential footprint of less than 10cm at a standard survey speed of approximately 4kts. The use of the RTK dGPS allowed real-time tidal corrections and the motion reference unit compensated for heave, pitch and roll from wave and swell. Bathymetry data (Figure 3) was collected along a number of line transects that focused on the rugged loch perimeter where 100% coverage was achieved. At the centre of the loch the swath coverage was supplemented by depth information provided by the sub-bottom profiling. Sub-bottom profiling information on the history of sediment infilling was collected using a Tritech SeaKing parametric sub-bottom profiler. This was also deployed along line transects around the perimeter of the loch and across the loch interior with seismic signatures converted to depth profiles using a seismic velocity of $1500ms^{-1}$ following standard procedures (Bates *et al.,* 2007).

The bathymetric chart of the loch (Figure 3) shows a rugged outline to the loch with a relatively flat loch floor at between -4m and -5m OD with very gentle dip to the east. Acoustic backscatter data was interpreted to show that the majority of the loch floor is covered by fine-grained sediment (sandy silt) with occasional pebbles and boulders. Around the loch perimeter the steeper margins are marked by natural rock outcrop consisting of Devonian flagstones. This rugged margin is ubiquitous around the loch at between -1m and -3m OD with the most continuous and steep sections of rock exposed along the eastern Brodgar isthmus shoreline. A few upstanding rock skerries extend into the loch, in particular to the west of the Stones of Stenness where two outcrops of rock are oriented in an approximately north-south direction; around the Unstan peninsula an extensive rock platform extends to the north; and in the north end of the loch near Voy lines of skerries extend south from the shallow bays. The rock skerries and rocky margin to the loch are clearly defined from the bathymetry and also with the sidescan backscatter data. The very fine level of detail provided by the sonar allows for the structure of bedrock (that is the geological dip and strike of the flagstones) to be clearly mapped with a north-south strike. In general this confirms the observations made onshore that bedding is approximately horizontal with outcrops marked by the asymmetric profile of gently dipping rock units truncated by broken faces perpendicular to the bedding surface. In the South at the Brig o'Waithe (Figure 2) the loch exits to the Bay of Ireland and the loch floor shallows to approximately -1mOD. Here the loch floor is marked by large boulders and a coarsening of the sediment grain size reflecting the force of water interchange over the tidal cycle. Rockhead beneath the Brig o'Waithe is obscured by the large boulders present in the base of the channel.

The sub-bottom profile seismic data was of high quality throughout the loch and showed a sequence of layered sediments marked by sharp discontinuities to a depth of at least -10m OD. Two example profiles are shown in Figures 4 and 5 with their locations shown on Figure 3. At the loch centre, the sedimentary layers were obscured by the presence of gas likely derived from the decomposition of organic material near the base of the sequence (Figure 4). The seismic interpretation of the sediment sequence suggests a complex history of gradual loch filling punctuated by periods of erosion that can be summarised into a number of key stages based on the seismic character (Table 1) and interpreted through the coring sequence.

Sequence 1 at the base of the seismic section is distinguished by a reflector that is generally jagged or rough in appearance. The unit is opaque with generally no internal reflectors. Near the margins of the loch the unit extends to the loch floor and can be traced onshore as a continuous rock platform, thus the unit represents the seismic basement of local bedrock. Towards the centre of the loch the depth to sequence increases to a maximum of at least -10m OD. A number of mounds or outcrops of the unit are identified where the overlying layers of sediment have not covered the rock. These outcrops manifest as skerries which can be seen in the east of the loch on aerial photographs.

Sequence 2 infills on top of the bedrock surface that thickens towards the loch centre. It appears to drape the bedrock surface and has only occasional discontinuous internal reflections that are parallel to its surface. In the western arm of the loch towards Voy very small pockets of this material were noted where depth to the layer reduces to less than 5m and thus it was accessible for coring.

Sequence 3 is divided into two parts that both show well defined internal character (Figure 4). The lower part (3a) contains continuous, widely spaced internal reflectors that parallel the base of the unit, the upper sequence (3b) shows similar character but with finely spaced internal reflectors. No discordance is noted between the upper and lower part. The internal reflectors of the lower part generally thicken to the loch centre whereas the upper reflectors remain parallel throughout. The lower reflectors also onlap to the sequences 1 and 2 below suggesting infill of material into an expanding accommodation space.

Sequence 3 is truncated by a reflector which shows a very sharp boundary at the loch margin but more diffuse boundary in loch centre. At the margin this reflector (an unconformity surface) shows clear erosion of the sequence top at a depth of approximately -3.8m OD at the loch edges to -6m OD at loch centre. Above this reflector, Sequence 4 infills the centre of the loch. Sequence 4 shows a marked contrast to the Sequence 3 in that it has almost no internal structure apart from near the southern extent of the loch close to the outlet. Along east-west cross-sections the base forms a valley-like channel structure that is accentuated near the outlet (Figure 5). The top of Sequence 4 and valley structure is mirrored by the overlying Sequence 5. This sequence is highly distinctive as it contains strong negative amplitude internal reflectors that cut deeply into Sequence 4 at the base of the valley feature. The internal reflectors onlap the valley sides at the base of the unit but become conformable pinching out towards the loch centre. Finally, the top sequence, Sequence 6 is marked by its lack of any internal character. The unit drapes the whole loch sediment sequence with a uniform thickness throughout.

Palaeoenvironmental investigation

Six cores recovered by vibracoring from the bed of the Loch of Stenness provide detail for both ground truthing the geophysics and constructing the palaeoenvironmental record (Figure 3). Fieldwork was conducted using a small rib and a VibeCore-D (Specialty Devices Inc.) deployed from a purpose built raft. The location of the cores had been determined through the study of the bathymetric and sub-bottom seismic data in order to ground truth the geophysics and to return samples to the laboratory for analysis. Positioning of the boreholes was undertaken using Hypack, dGPS (error of < 20cm) and echosounder. The locations of the cores are shown in Figure 3 and located on seismic lines in Figures 4 and 5. Cores were drilled until refusal of coring; in most cases the cores failed to penetrate the full depth of the soft sediment sequence, the exception being core 2014-5. Full descriptions of individual cores are presented in Supplementary information (Supplementary Information 1). Sampling of the cores was undertaken for sediment characterisation (organic/carbonate/inorganic content) and to indicate the environments of deposition through the investigation of the contained microfossil assemblages (Figures 6-9). Samples for radiocarbon AMS dating were collected from 2014-1 and 2014-8 and sent to Beta Analytic for radiocarbon analyses (Supplementary Information 2). Shells from the freshwater units consisted of *Lymnaea sp*. While only shell fragments (non-identifiable) were available for the brackish units. Both calibrated BP (cal. BP) and calibrated years BC (cal. BC) are quoted in the text. The calibration of the radiocarbon results was undertaken using OxCal version 4.2 (Oxford Radiocarbon Accelerator Unit). Microfossils (Foraminifera and Ostracods) were also examined from the cores. Full details of the methods employed are presented in Supplementary information 3 and results in Supplementary Information 4 to 9.

Five lithological units were identified in the cores:

Unit A. This is present at the base of 2014-5 (2.18m to base) (Figure 6) and consists of dense silt with poorly sorted gravel clasts. The appearance of the sediment suggest this unit was deposited with minimal sorting and is possibly the upper part of late Pleistocene till deposits known to be present in the area. Sieving of a single sample from this unit failed to produce any organic material.

Unit B. This unit is also present in 2014-5 (1.10 – 2.18m) (Figure 6) and consists of grey silts with sands. The sediments may be bedded in places. Organic and carbonate content are low throughout this unit and with iron staining in the lower part only (below 1.57m depth). No palaeoenvironmental remains were present in the lower part of this sediment unit (1.90-2.18m) (Supplementary information 4). The remainder of the unit (1.10-1.90m) contained charophyte oogonia, cladocera and insects throughout. This suggests freshwater lacustrine or shallow water body conditions in which the watertable may have fluctuated.

Unit C. This unit consisted of pale grey brown silt and sand and is present in 2014-1 (0.81-2.10m) (Figure 7), 2014-3 (0.47-1.65m), 2014-4 (0.48-1.60m), 2014-5 (0.18-1.10m) (Figure 6) and 2014-8 (0.33-2.62m) (Figure 8). The initial phase of freshwater deposits are dated in 2014-8 to 10691-10435 cal. B.P. (8742-8486 cal. BC) (Figure 8). In 2014-5 (Figure 6) the minerogenic sediment declines and there is a marked increase in carbonate content within this unit. Freshwater molluscs are present as well as charophyte oogonia, cladocera, ostracods, and latterly, foraminifera (Supplementary information 4-8). For the most part this unit is characterised by the presence of distinctive freshwater ostracods – and by very similar assemblages throughout. Four species are ubiquitous and occur in great numbers (*Candona candida, Pseudocandona rostrata, Cyclocypris ovum* and *Limnocythere inopinata*). In some of the cores these species are joined by up to four other less common freshwater species. This ostracod assemblage is typical of a large permanent shallow waterbody (Meisch, 2000). *C. candida*, in association with other species often indicates cool conditions, but it is widespread through Britain at the present day, and is thus not necessarily a climatic indicator here. In 2014-1 Unit C is more complex and exhibits a trend towards decreasing mean grain size upwards (Figure 7). Organic values attain greater than 20% by loss-on-ignition below 1.40m depth and this is associated with the coarsest part of the sequence (Figure 7). Microfossils show that the last occurrence of freshwater species occurs at the boundary between Unit C and the overlying unit; however the initial tidal access, based on the first occurrence of the brackish species *Cyprideis torosa*, can be seen to be 20cm lower at 1.02m. This species occurs right up to the unit boundary at 0.81m, significantly, however, its valves are highly noded which would indicate the salinity was very low (<6‰) (Athersuch, Horne and Whittaker, 1989). The onset of brackish conditions are dated in 2014-1 between 5939-5753 and 5862-5612 cal. B.P. (3990-3663 cal. BC). In 2014-7 (Supplementary information 7) organic content increases up profile and is entirely freshwater to the surface. Finally, in 2014-8 (Figure 8, Supplementary information 6) organic content is low although does appear to increase slightly towards the top of the unit. The upper part of this unit coincides with the initial tidal access (evidenced by both the first occurrence of noded *Cyprideis torosa* and the brackish foraminifer *Haynesina germanica)*. However, the last occurrence of freshwater ostracods is not until c. 0.28-0.30m. This is dated between 6310-6209 cal. B.P. (4361-4260 cal. BC).

Unit D. This consists of massive grey silts and sands and is present in 2014-3 (0.12-0.47m), core 2014-4 (0.28-0.48m) and 2014-6 (0.42-1.64m). In 2014-6 the unit is organic and carbonate rich towards the base but this declines upwards. Microfossils (Supplementary information 8) indicate brackish conditions throughout, typified by noded *Cyprideis torosa* (indicating low salinity of <6‰), but up-core the valves of this species become smooth, suggesting rising salinity and with it at the same depth (c. 1.00m), the first foraminifer (*Elphidium williamsoni*). Freshwater ostracods are still present throughout this unit, albeit latterly patchy, disappearing entirely at 0.42m, the unit's upper boundary. This unit is restricted to a channel-like feature, probably eroded into the underlying material.

Unit E. This unit is present in the top of most cores (2014-1, 0-0.81m (Supplementary information 5), 2014-3, 0-0.12m, 2014-4, 0-0.28m, 2014-5, 0-0.18 (Supplementary information 4), 2014-6, 0-0.42m, 2014-7, 0-0.85m (Supplementary information 7) and 2014-8, 0-0.33m(Supplementary information 6)) and consists of fine grey sands and silt. The microfossils indicate a wholly brackish environment. In cores 2014-1/3/ 5/6 this includes foraminifera and ostracods of tidal flats. *Cyprideis torosa*, where present, is smooth and indicates a salinity of >6‰. The ostracods, and especially the foraminifera are of low diversity, sometimes only represented by *Miliammina fusca* (an agglutinating species that has a shell of mineral grains bound together with organic cement rendering it virtually indestructible) but in large numbers, suggesting the sediments are decalcified.

An integrated environmental history of the Loch of Stenness

The evidence from these related sources enables a history of loch development to be postulated (Table 1 and Figures 9 and 10). The presence of a major basin within the landscape would have encouraged a long period of sediment accretion since the Lateglacial period beginning with a basal till deposit that is intermittently present across the basin. This unit (SS 2) was reached in core 2014-5 and was assigned to Unit A. Although no dating evidence is available from the lowermost sediments in the basin, deglaciation of Orkney had begun before 15ka cal. B.P. so it is likely these deposits date to this time.

Much of the lake basin is infilled with sediments defined in the seismic stratigraphy as Sequence 3 (a/b) and this has been linked to Units B and C. Unit B contains little in the way of palaeoenvironmental material and is probably a correlative of Sequence 3a. The sediments indicate sequence accumulation in a fresh, shallow water body, perhaps one impacted by fluctuating water tables through time as the indicated in the seismic interpretation. Minerogenic sedimentation dominated at this time coincident with deglaciation from a barren landscape and the release of clastic material into the environment. Sequence 3b (Unit C) by contrast consists of carbonate rich sediments with the seismic layering suggesting slower sedimentation indicating deposition from controlled run-off again in a freshwater loch environment. Detailed study of these sediments has not been undertaken but the microfossil samples are typical of species living in a large permanent shallow water body while the presence of *C. candida* may indicate cool conditions. Dates from the top of these deposits in cores 2014-1 and 2014-8 suggest accumulation that may have commenced in the late Pleistocene continued into the early/mid-Holocene with final accretion taking place just after 6ka B.P. By comparison with Crudale Meadow (Whittington *et al*., 2015) accumulation is likely to have begun by 15ka B.P.

The top of Sequence 3 (Unit C) is marked by a sharp unconformity suggesting a widespread erosion event. This is particularly clear to the sides of the loch where truncation results in the almost complete loss of Sequence 3b (Figure 4). At the loch sides the unconformity is manifest as a plane surface dipping to loch centre however as this is reached the surface has the appearance of a valley trough or channel (Figure 5). Extrapolation of Sequence 3a and 3b to the loch sides implies that sedimentation prior to the erosion event took place to at least a thickness of 1.5m suggesting that lake levels were probably higher than even those of present day. In order to achieve this we suggest that a barrier of till probably once existed in the area of the Brig o'Waithe behind which higher loch levels could be attained. Higher loch levels imply a higher lip level that was subsequently eroded or broken through in an event that subsequently caused the erosion of the underlying sediment sequences (Sequence 3a and 3b). Above this erosion event, Sequence 4 infills the central valley feature with material derived from the loch sides.

The upper parts of Unit C indicate the onset of brackish conditions in the basin. Thus in cores 2014-1 and 2014-8 the upper part of Unit C (top 20cm) contains evidence for brackish water microfossils within a lithological unit little different to that below. This transition is marked by the first occurrence of the brackish species *Cyprideis torosa* and has been dated in 2014-1 to the early Neolithic period (Figure 11). The precise nature, and the mechanism responsible, for generating this pattern of data is difficult to assess at present and a number of possible scenarios can be considered to explain the observations:

- Brackish water ostracods are blown into freshwater lake from approaching marine environments.
- Occasional marine flooding into the freshwater loch occurs during exceptional storm surge events.
- The loch is being flooded at high tides by brackish water and populations of *Cyprideis torosa* survive within the freshwater loch.
- The process of transgression into the loch disturbs the near surface sediment of the loch and brackish microfossils become trapped within the older sediment.

The problems of interpretation of ostracod faunas in marine marginal enviornments has been considered by Boomer and Eisenhauer (2002). Some of this dichotomy can be assigned to the fact that so-called freshwater ostracods can tolerate low salinities and we also suspect that elements of the *Cyprideis torosa* assemblage might survive in nearly fresh loch waters (Dave Horner pers. comm.). Thus we favour the interpretation that periodic flooding of the loch by brackish waters may have occurred in this part of the sequence and this may have been exacerbated by events such as a storm surge that could have led to erosion/mixing at the boundary between units. Crucially this transition appears to be occurring at around the start of the Neolithic.

True brackish conditions are associated with lithological Unit D and seismic Sequence 4 and 5. Brackish conditions (exemplified by noded *Cyprideis torosa*) become increasingly more saline up-core (denoted by the replacement of noded *Cyprideis torosa* by the smooth variety) and the first foraminifer (*Elphidium williamsoni*) to appear. Freshwater ostracods are still present throughout this unit suggesting continued input from these sources. The distribution of these units (5) is shown in Figure 5 and this unit appears to form a channel like feature cut into the underlying sediments. Thus these units are those associated with initial flooding of the basin by brackish water and the creation of the tidal channel into the loch.

The final event in the loch history is that associated with seismic Sequence 6 and lithological Unit E which represent the modern and recent loch basal conditions associated with the low energy brackish conditions within the loch today.

Implications for the setting of the Neolithic monuments and activity in the vicinity of the Brodgar Isthmus

The combined geophysical and palaeoenvironmental evidence for landscape reconstructions for the Loch of Stenness in the Mesolithic and early Neolithic have interesting implications for the development of the landscape just prior to Neolithic monument construction along the Brodgar Isthmus. The data suggest that the landscape hollow occupied by the Loch of Stenness has been infilling with sediment from the Lateglacial. Prior to this the Orcadian landscape was blanketed by late Pleistocene till that represents the base of the sediment sequence in the loch (Figure 10a). Near the Brig o'Waithe this till cover probably provided the barrier that allowed higher loch water levels than present in a similar manner to the barrier that would have existed to the sea side of Skara Brae. Sediment accumulation in an ever decreasing accommodation space would have shallowed the water levels of the loch and focused channelling along a central valley axis eventually resulting in a decrease in area of the loch as it infilled (Figure 10b-c). Changes in sedimentation pattern were a result of changing landscape around the loch. Between approximately 7000 ka cal. B.P. and 6000ka cal. B.P. the confining barrier was reduced in relative height either by gradual erosion (by both stream action and perhaps the encroaching sea) or a sudden erosive event resulting from a change in external, climate conditions (Figure 10d). Subsequent to erosion the lowered loch level meant that sedimentation was only taking place along the central eroded valley channel. The implied erosion event and its coincidence to climate shifts that have been reported elsewhere in the literature is noted. For example, a Holocene cooling event with the implication of increased run-off has been reported by Wanner *et al*. (2011) between 6.5 and 5.9ka cal B.P. Incision within fluvial systems in the Highlands of Scotland has been reported by Macklin *et al.* (2013) between 6.4 and 6.0ka cal B.P by and finally a period of increased storminess in the North Atlantic was noted at 5.5ka cal B.P. by Sorrel et al. (2012).

The lowering of loch levels in the late Mesolithic or early Neolithic would have reduced the Loch of Stenness in size, exposing low-lying land that would have increased the width of the Brodgar Isthmus by at least 50% on the Stenness side (Figure 11). This could have been further increased in size if a similar reduction in the water level was experienced in the Loch of Harray. An additional feature of this landscape, identified through the geophysical survey, comprises the rocky sides of the loch. These were mapped around the complete perimeter and extended from -1m to full water depth at -5m OD along the eastern shore (Figure 11). Here the >4km long exposure would have represented a considerable and highly accessible resource of nearby construction material for activities on the isthmus in the early Neolithic.

Following the lowering of waterlevels the next significant event was the shift in water conditions from freshwater to brackish which started early in the Neolithic period. This is likely to have occurred initially as a result of periodic flooding enhanced by occasional storm surges bringing saline waters into the loch (Figure 10e). With time, as relative sea-level overtopped the height of the shrinking barrier at the Brig o'Waithe, the loch achieved the brackish conditions recorded today (Figure 10F). The loch would have expanded gradually as sea water migrated inland past the narrows at the Brig o'Waithe transforming the freshwater loch into a brackish embayment during the early Neolithic. As it became established, this change would lead to both positive and negative alterations in the flora and fauna of the loch, and is likely to have been significant for those living in the vicinity. The speed of this transition in the loch is presently unknown but it is likely that freshwater conditions in the northern end of the loch at Voy would have been maintained for some time after the southern end became brackish.

Terrestrial vegetation changes across the late Mesolithic to Neolithic boundary have been demonstrated in the pollen records from the Stenness landscape (Farrell *et al* 2012). These changes have been interpreted as primary and secondary woodland clearance occurring in response to a number of factors which might include human activity. We can now see that these changes are taking place at a time coincident to the changes in loch conditions (Figure 12). The scale of these changes in the environment is emphasised by consideration of the input of sediment to the loch system. The seismic stratigraphy has enabled us to calculate the volume of sediment filling the loch system to bedrock for those units associated with the freshwater loch (seismic Sequences 2-3) and those associated with the initial transgression of sea water into the loch (Sequences 4 and 5). The calculations we used assumes that initial freshwater accumulation of sediment in the loch began c.15,000 years ago and ceased c.6,000 years ago. Our calculations suggest a shift in rates of sedimentation from 0.25mm/yr. during the freshwater phase of loch history to 1.3mm/yr. during the period of transgression within the loch (Supplementary Information 10).

The dramatic increase in sedimentation rates in Units 4 and 5 took place during the early Neolithic and is likely to result from a combination of factors. While the impact of individual weather events cannot be ruled out and the impact of the low amplitude tidal cycles associated with transgression would certainly have brought additional sediment into the loch other factors are also likely to have been important. The vegetation history and the primary and secondary woodland clearance is likely to have had a long-term impact on the stability of soils and the importance of soil erosion and the introduction of sediment into the loch through run-off will also have played a significant role. However, in the context of soil deterioration French noted that at least at Barnhouse soil micromorphological evidence from the excavations here suggested that the podsolization and soil deterioration seen elsewhere in the Neolithic in Orkney as a result of anthropogenic activity had not begun at this site (French, 2005).

Conclusions

The results of an interdisciplinary approach to the study of landscape history around the Loch of Stenness in Orkney has highlighted the changing landscape for the late Mesolithic and

Neolithic inhabitants of the islands. Previous work indicated the landscape was changing due to the replacement of mixed woodland (including birch, hazel, willow, oak and pine; Farrell *et al* 2012) with pockets of farmland in the earliest Neolithic. Additionally from early on in the life of these monuments rising sea-levels, changes in salinity in the loch and increased sedimentation added to this change, increasing the size of the adjoining loch and decreasing the width of the neck of land occupied by the sites. Local sources of building material would have been flooded. Storm surges and the influx of brackish water into the loch altered the nature of the area and the species that it supported.

These changes would have been obvious to those who made their lives here over a period of at least a thousand years. Although research elsewhere highlights the way in which environmental change was a fact of life in the Early Holocene around the Loch of Stenness it was particularly dramatic and occurred in a location that has been established as of particular ceremonial significance. Nevertheless, the actual sites that made up the area that we now call 'the Heart of Neolithic Orkney', remained on dry land and in use. Much has been made of the shift from marine resources to terrestrial resources at the onset of the Neolithic (Thomas, 2013); rising relative sea-levels around the archipelago of Orkney might have threatened the new dominance of the land, but they did not overturn it. Here in Stenness we can see a 'return' to marine conditions at the heart of the new economy when other indicators suggest decreasing marine influence on life. We can only surmise the ways in which the local community made sense of such changes in the heart of Neolithic Orkney and the role played by the changing world context in the significance of the Neolithic sites here.

While Orkney offers a relatively shallow water and easily accessible environment, the exigencies of data collection, analysis and integration are presented as a case study of value to the wider archaeological community. Truly interdisciplinary studies require careful merging of datasets that may be traditionally treated in very different ways. It is also clear that investigation of the palaeoenvironment, including the submerged landscape, and associated change, is an absolute prerequisite for a proper understanding of human behavior. Given the emerging global significance of submerged landscapes and continental shelf archaeology in relation to the spread of hominins around the world and developing technological and cultural complexity, the expansion of archaeological techniques to include off-site studies such as that outlined here is a high priority. Furthermore, in many locations the value and relevance of such studies extends from the earliest Holocene into more recent prehistory.

Acknowledgments

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Figure 1. A: Locations for Neolithic/Mesolithic Orkney sites discussed in the text. **B:** Locations for palaeoenvironmental sites discussed in the text. P1: Spretta Meadow, P2: Hobbister, P3: Glimms Moss, P4: Loch of Brokan, P5: Bay of Firth, P6: Mill Bay, P7: Scapa Bay, P8: Crudale Meadow.

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Figure 7. Core St-1 lithology, sedimentary properties, identified units and inferred palaeoenvironmental conditions.

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Supp 6. Organic and microfossil assessment data from core 2014-8

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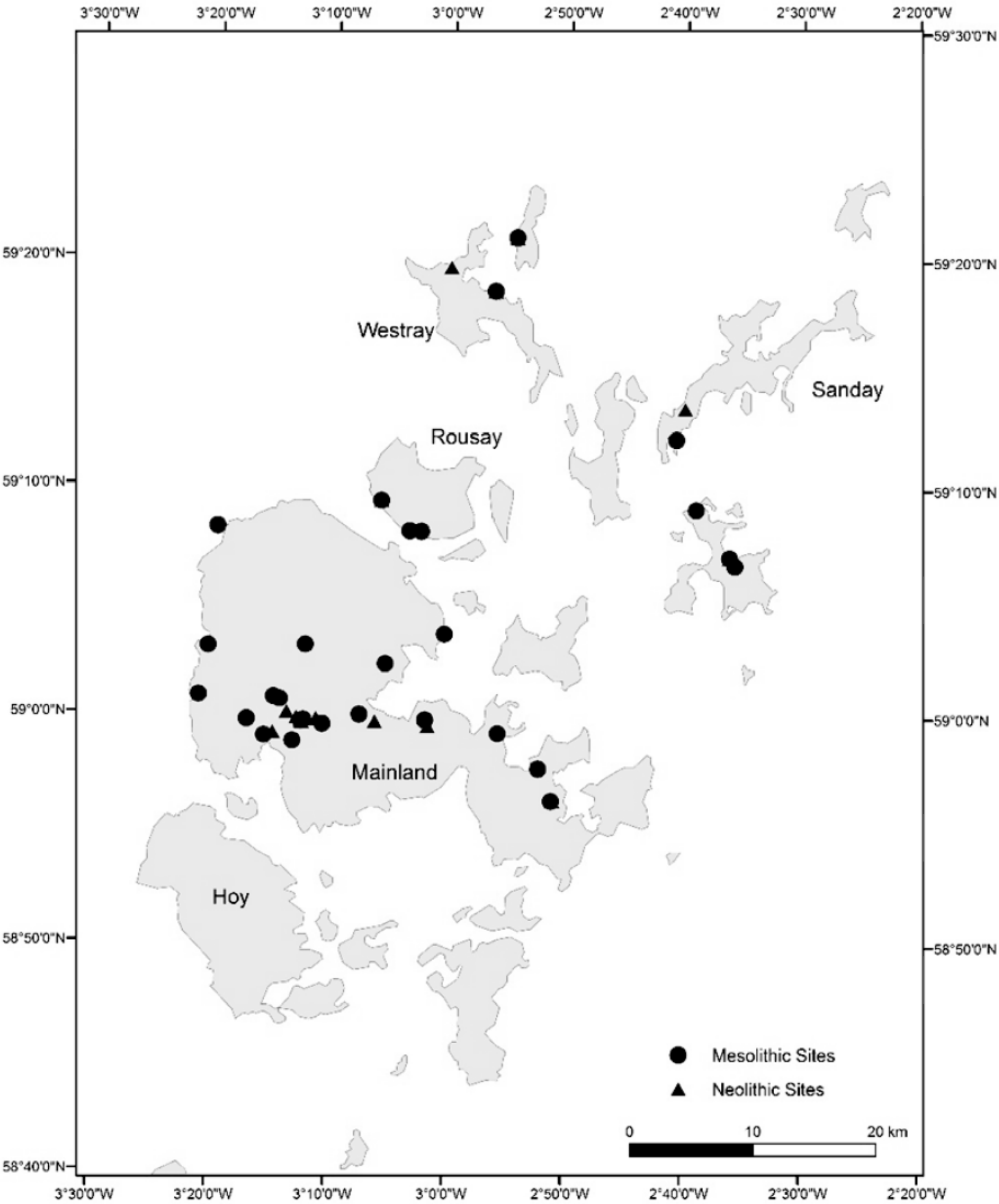
Supp 8. Organic and microfossil assessment data from core 2014-6

Supp 9. Organic and microfossil assessment data from core 2014-3

Supp 10. Calculated sedimentation rates for the freshwater and brackish lake sequences in Loch of Stenness.



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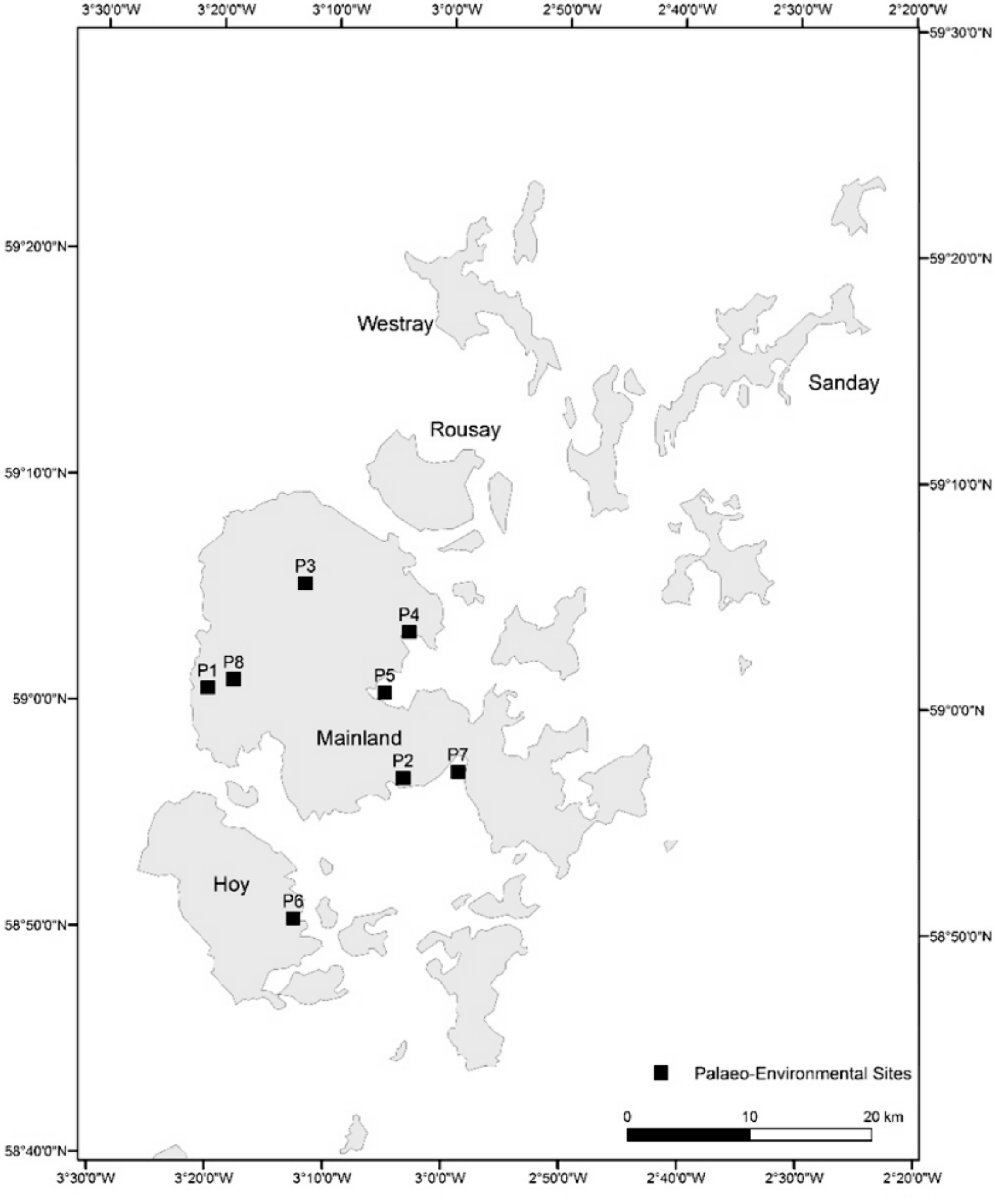
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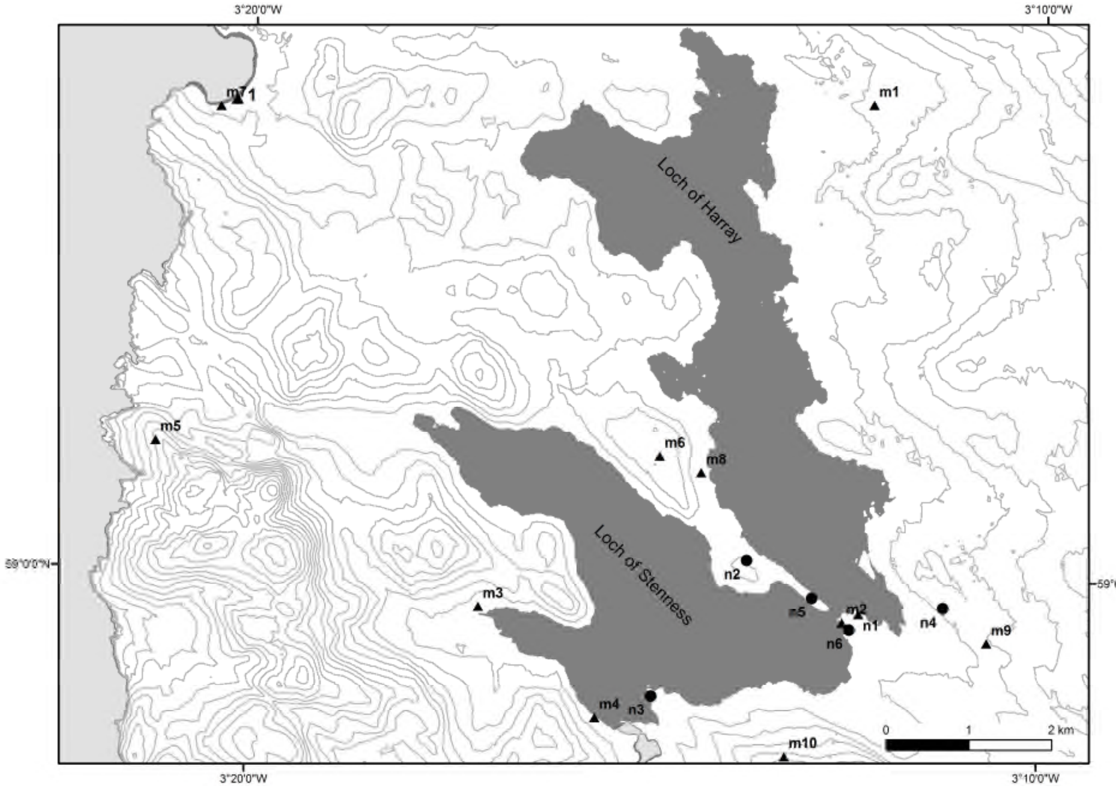
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m8
Loch of Stenness
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59°0'0"N
m3
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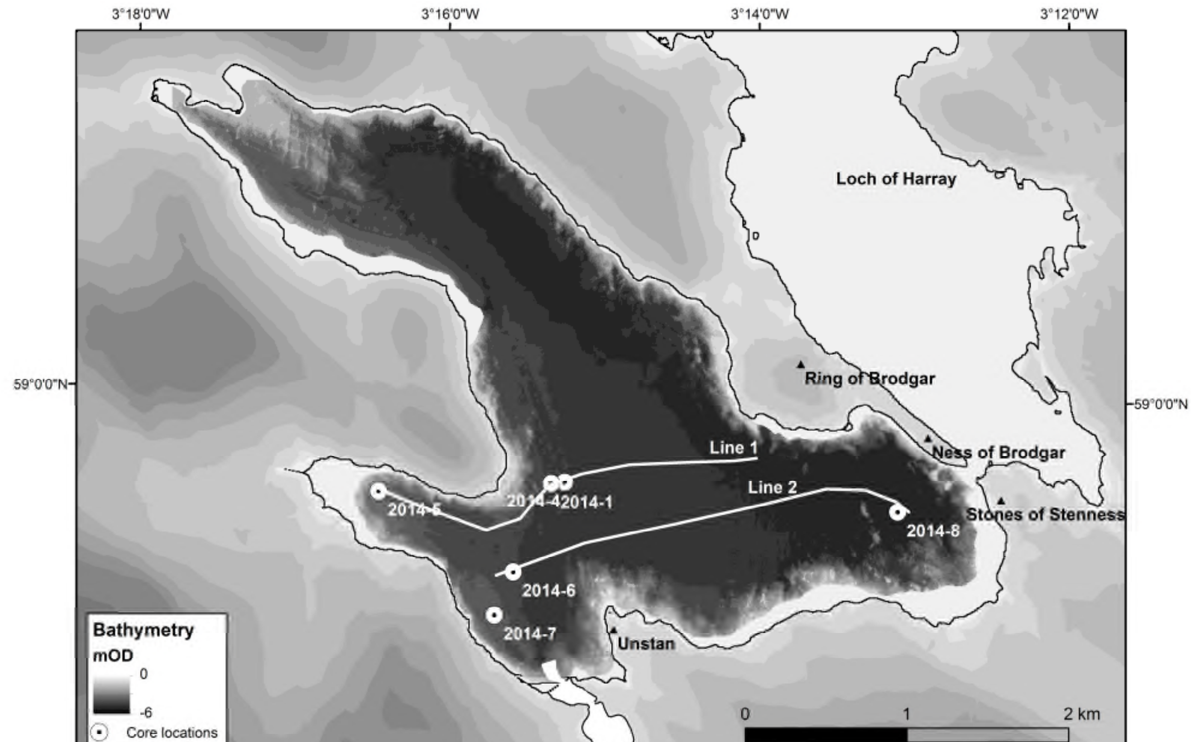
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Ring of Brodgar
59°0'0"N
Line 1
Ness of Brodgar
Line 2
2014-5
2014-4
2014-1
Stones of Stenness
2014-8
2014-6
Bathymetry
mOD
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2014-7
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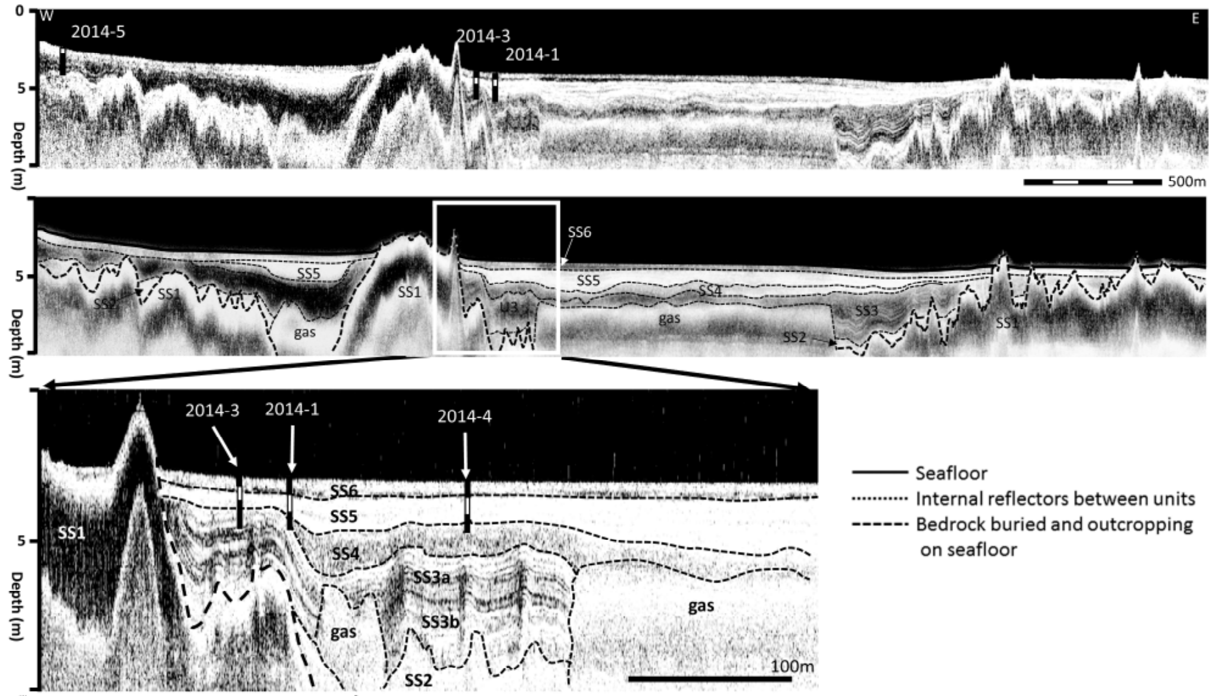
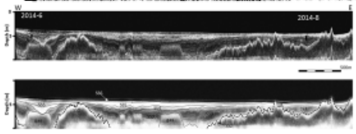
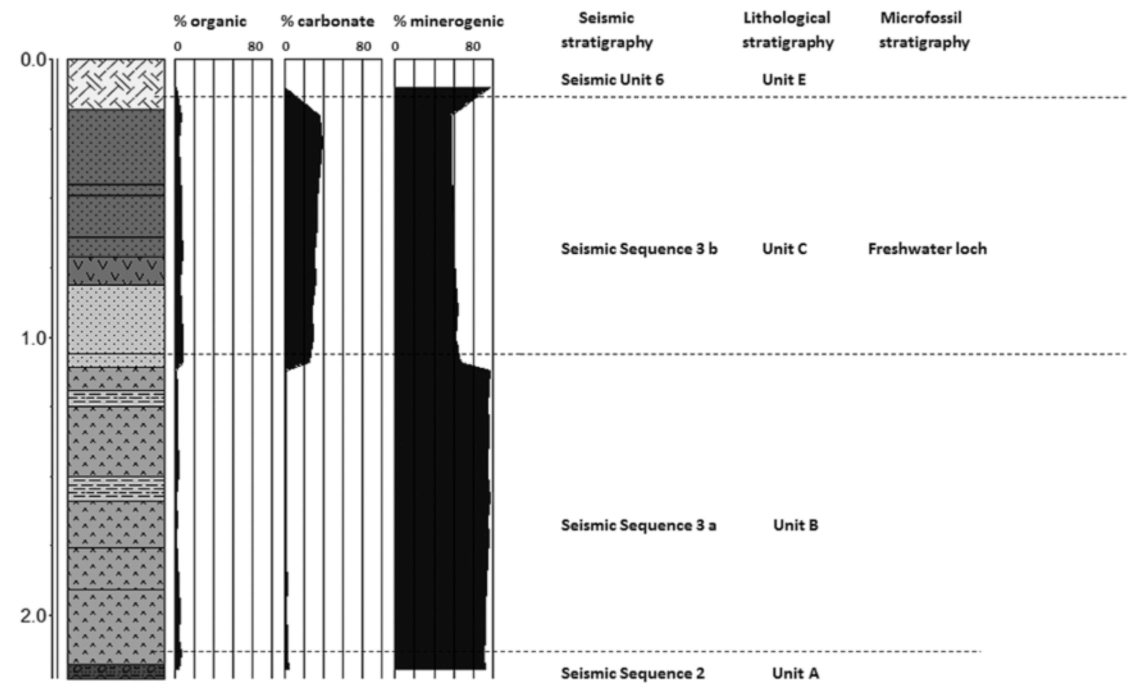


W
E
2014-5
2014-3
2014-1
0
5
Depth (m)
500m
SS6
SS5
SS4
SS3
SS2
SS1
gas
2014-4
SS3a
SS3b
100m
Seafloor
Internal reflectors between units
Bedrock buried and outcropping on seafloor





% organic
% carbonate
% minerogenic
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Seismic stratigraphy
Lithological stratigraphy
Microfossil stratigraphy
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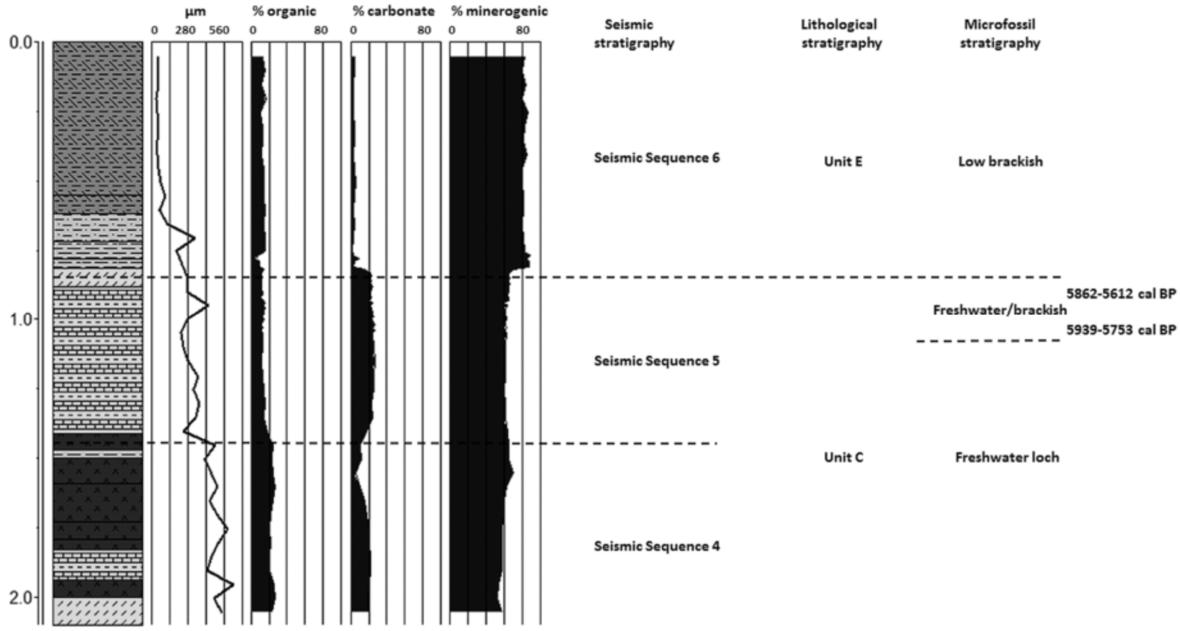
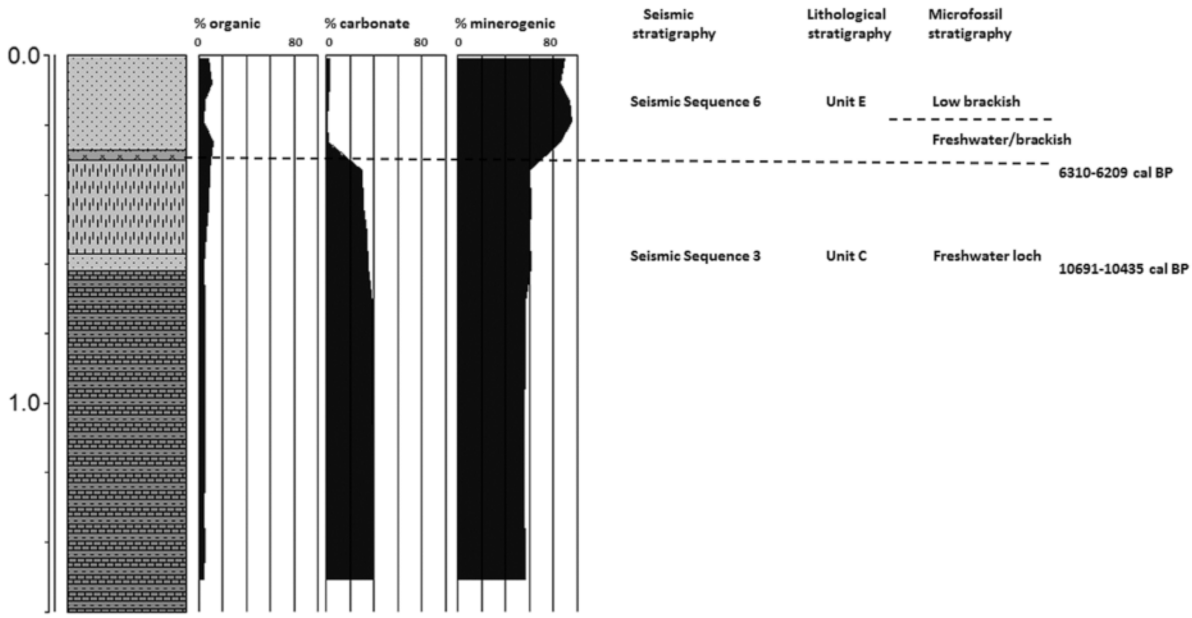
1.0
2.0
Seismic Unit 6
Unit E
Seismic Sequence 3 b
Unit C
Freshwater loch
Seismic Sequence 3 a
Unit B
Seismic Sequence 2
Unit A



µm
% organic
% carbonate
% minerogenic
0 280 560
0 80
0 80
0 80
0.0
1.0
2.0
Seismic stratigraphy
Lithological stratigraphy
Microfossil stratigraphy
Seismic Sequence 6
Unit E
Low brackish
5862-5612 cal BP
Freshwater/brackish
5939-5753 cal BP
Seismic Sequence 5
Unit C
Freshwater loch
Seismic Sequence 4

838



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Seismic stratigraphy
Lithological stratigraphy
Microfossil stratigraphy
Seismic Sequence 6
Unit E
Low brackish
Freshwater/brackish
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Seismic Sequence 3
Unit C
Freshwater loch
10691-10435 cal BP

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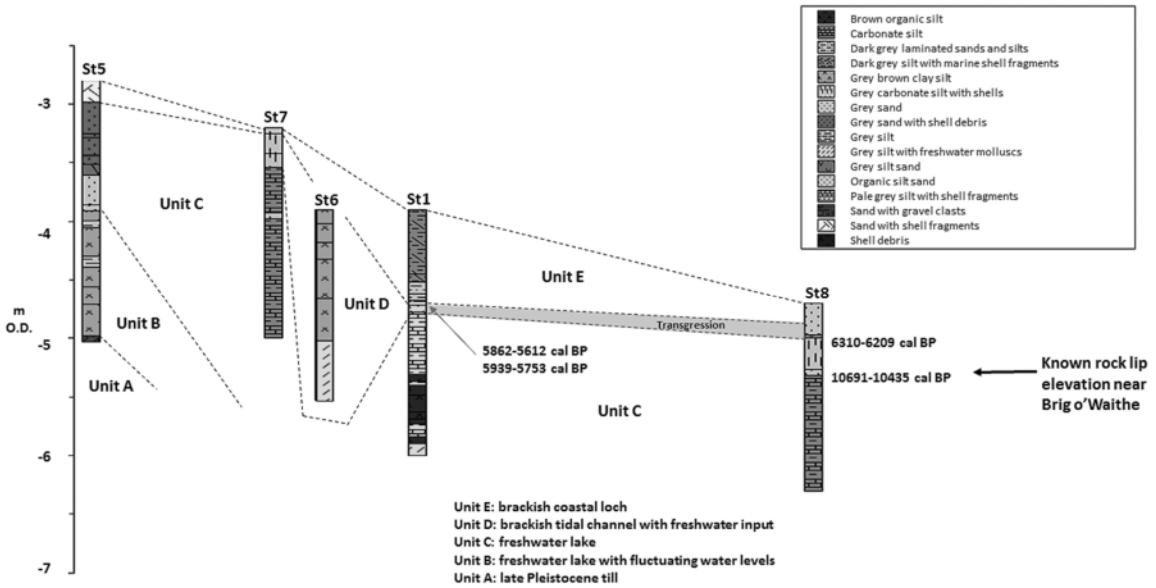
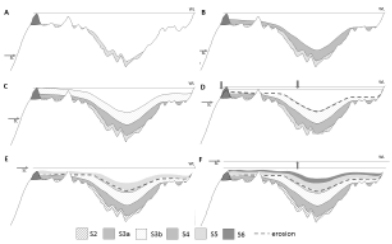
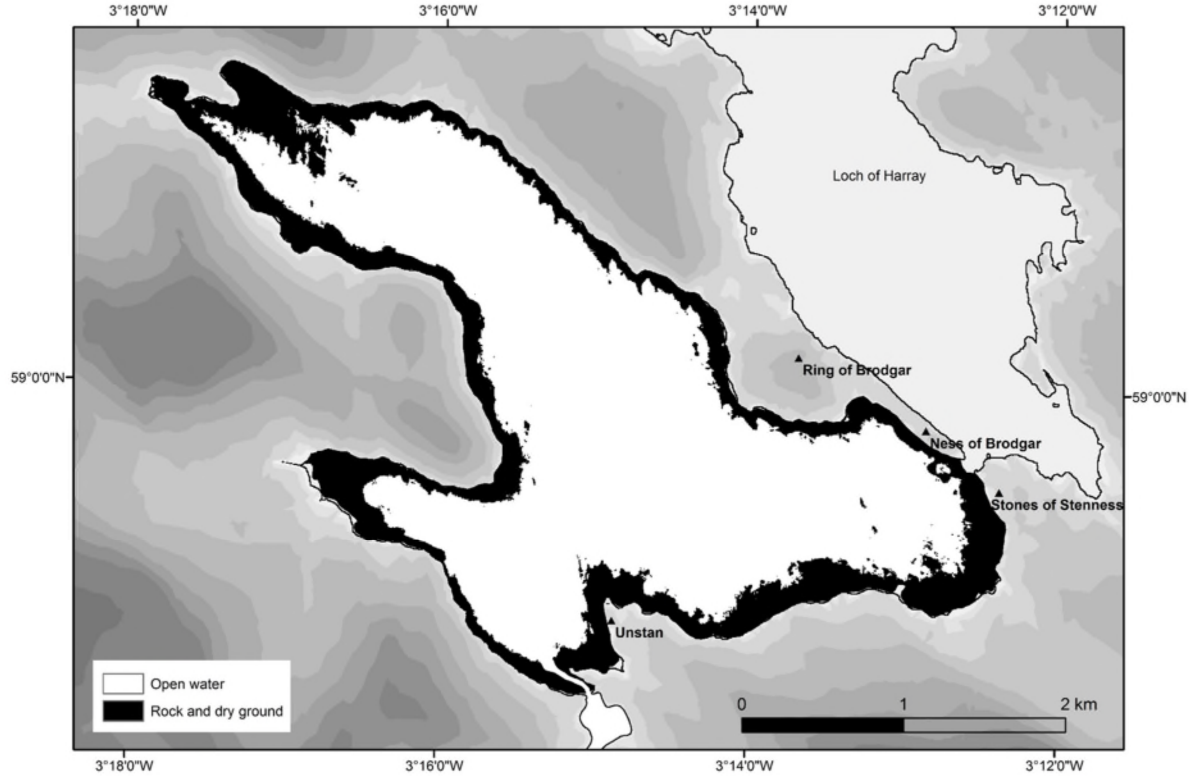
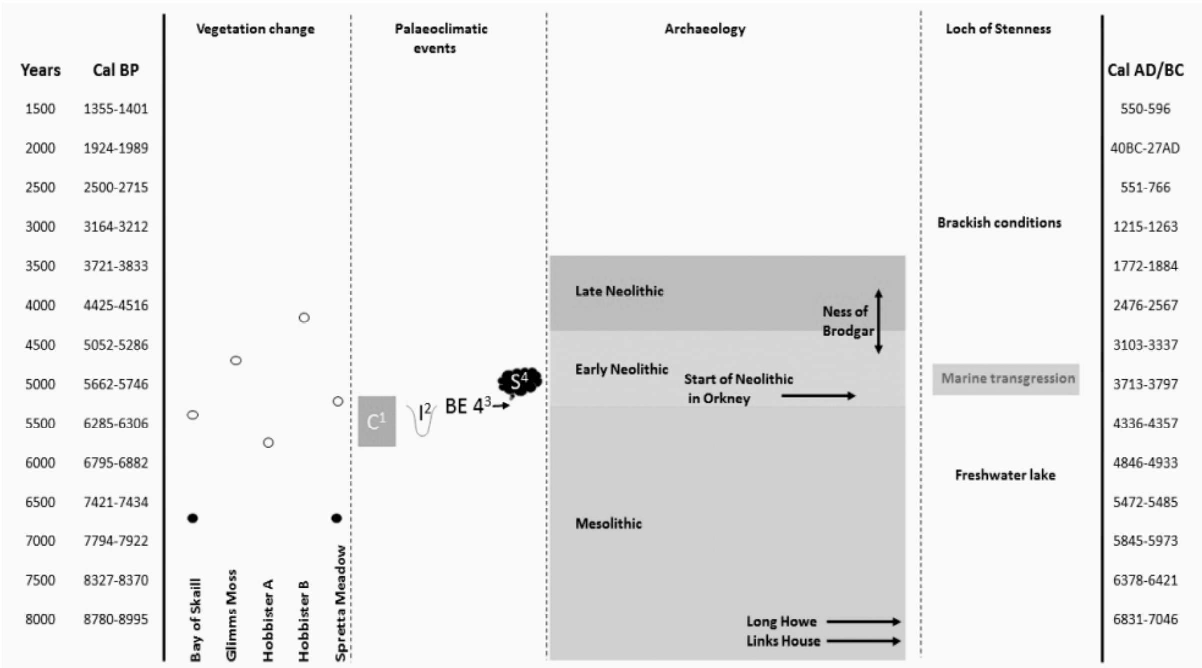

Brown organic silt
Carbonate silt
Dark grey laminated sands and silts
Dark grey silt with marine shell fragments
Grey brown clay silt
Grey carbonate silt with shells
Grey sand
Grey sand with shell debris
Grey silt
Grey silt with freshwater molluscs
Grey silt sand
Organic silt sand
Pale grey silt with shell fragments
Sand with gravel clasts
Sand with shell fragments
Shell debris
St5
St7
St6
St1
St8
m O.D.
-3
-4
-5
-6
-7
Unit C
Unit B
Unit A
Unit D
Unit E
Unit C
Transgression
5862-5612 cal BP
5939-5753 cal BP
6310-6209 cal BP
10691-10435 cal BP
Known rock lip elevation near Brig o'Waithe
Unit E: brackish coastal loch
Unit D: brackish tidal channel with freshwater input
Unit C: freshwater lake
Unit B: freshwater lake with fluctuating water levels
Unit A: late Pleistocene till

A
B
C
D
E
F
S2
S3a
S3b
S4
S5
S6
erosion


3°18'0"W
3°16'0"W
3°14'0"W
3°12'0"W
59°0'0"N
Loch of Harray
Ring of Brodgar
Ness of Brodgar
Stones of Stenness
Unstan
Open water
Rock and dry ground
0
1
2 km


Years
Cal BP
Vegetation change
Palaeoclimatic events
Archaeology
Loch of Stenness
Cal AD/BC
1500 1355-1401 550-596
2000 1924-1989 40BC-27AD
2500 2500-2715 551-766
3000 3164-3212 1215-1263
3500 3721-3833 1772-1884
4000 4425-4516 2476-2567
4500 5052-5286 3103-3337
5000 5662-5746 3713-3797
5500 6285-6306 4336-4357
6000 6795-6882 4846-4933
6500 7421-7434 5472-5485
7000 7794-7922 5845-5973
7500 8327-8370 6378-6421
8000 8780-8995 6831-7046
Bay of Skaill
Glimms Moss
Hobbister A
Hobbister B
Spretta Meadow
C1
I2
BE 43
S4
Late Neolithic
Ness of Brodgar
Early Neolithic
Start of Neolithic in Orkney
Mesolithic
Long Howe
Links House
Brackish conditions
Marine transgression
Freshwater lake