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1 **The environmental context of the Neolithic monuments on the Brodgar Isthmus, Mainland,**
2 **Orkney**

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4

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15
16 **Key words**

17
18 **Loch of Stenness, sea level change, bathymetry, seismic profiling, microfossils, Neolithic**
19 **World Heritage site, palaeolandscapes**

20
21
22 **Abstract**
23

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

41
42 **Introduction**
43

44 The contextualisation of archaeological sites in the landscape requires an understanding of
45 the relationship between landscape, site structure and site function/use. In practice,
46 generating the ground truth control to provide this context can be difficult, timing consuming
47 and costly. This is particularly the case where sites sit in a landscape that straddles the

48 transition zone from terrestrial to wetland/marine and where landscape flooding by the sea
49 may have had a considerable impact on the changing relationship between site and
50 environment through time.

51

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

63

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

72

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

86

87 Understanding the relationship between the changing context of these sites and the local
88 geography is critical for many reasons. At a time when significant changes in economy,
89 behaviour and monumentality were taking place across the Mesolithic to Neolithic transition
90 in Orkney (Wickham-Jones 2015; Richards and Jones, 2016) it appears that shifts in the
91 boundaries between wetland and dryland and between freshwater and estuarine/marine
92 conditions were also occurring (Bates *et al.* 2012). Within the Brodgar Isthmus these
93 relationships are currently inadequately documented. This is in part a function of the bias
94 towards excavation of monumental archaeology, because of its spectacular nature, as well as

95 the inherent difficulty of linking terrestrial archaeological data to stratified
96 palaeoenvironmental evidence from the sedimentary units we can trace across the
97 landscape. Consequently we have chosen to investigate sequences from within the Loch of
98 Stenness in order to provide that contextual information. This work is part of a wider
99 interdisciplinary project undertaken by the Rising Tides project (Bates *et al.* 2012) that is
100 examining the impact of relative sea level change on Prehistoric Orkney. This paper provides
101 information on the nature of environmental change across the Mesolithic to Neolithic
102 transition in the immediate vicinity of the World Heritage sites. Furthermore, it provides
103 environmental data that can be tested against archaeological information documenting
104 human activity at the sites.

105

106 **Geographical setting and landscape history of the study area**

107

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

121

122 The landscape history of mainland Orkney has been examined at a number of sites (Figure 1B)
123 and perhaps the most complete record derives from Crudale Meadow (Moar, 1969; Bunting,
124 1994; Whittington *et al.*, 2015). This site, an infilled lake basin (formerly called Yesnaby by
125 Moar (1969)) contains a sequence of calcareous marls overlain by peats that span more than
126 15,000 years through the Devensian Lateglacial and into the Holocene. The sequences
127 present are similar in appearance to those investigated by the Rising Tides project in the Bay
128 of Firth (Bates *et al.*, 2012) and at the Loch of Brockan (Bates *et al.*, 2010) as well as the
129 sediments overlying till in the Bay of Skail (De la Vega-Leinert *et al.*, 2000).

130

131 The vegetation history indicates that birch-hazel woodland was well established in Mainland
132 Orkney by 9.4 ka cal. B.P. (Bunting, 1994; De la Vega-Leinert *et al.*, 2007). This woodland
133 appears to have had a grass and herb understory, which persisted until c. 7.8 ka cal. B.P.
134 (Tisdall *et al.*, 2013). Woodland cover continued with oak until around 5.9 ka cal. B.P.
135 (Bunting, 1994; de la Vega-Leinert *et al.*, 2007). Farrell *et al.* (2012) argue that woodland loss
136 (both primary and secondary) occurred at different times in different places in Orkney. Thus
137 at Bay of Skail De la Vega-Leinert *et al.* (2000) indicate woodland loss in the Neolithic by c.
138 5.5 ka cal. B.P. where a calcareous pond existed in a hollow on the till surface. This pond was
139 beginning to be overwhelmed by sand blown on-shore by c. 5.2 ka cal. B.P. and by c. 4.5 ka
140 cal. B.P. charcoal and *Plantago lanceolate* pollen indicated Neolithic agricultural activity in the
141 vicinity was taking place. At Scapa Bay this loss of woodland took place at the beginning of

142 the Neolithic (De la Vega-Leinert et al., 2007; Farrell, 2009) while at Mill Bay, Stronsay, Tisdall
143 *et al.* (2013) have documented evidence for hazel scrub and grassland vegetation being
144 replaced by heathland after 4 ka cal. B.P. All of these observations suggest that landscape
145 change, and in particular woodland clearance, was widespread in Orkney throughout the
146 Neolithic.

147
148 Against this patchwork mosaic of vegetation change the other major factor controlling
149 landscapes in Orkney is that of rising sea levels. Work on Holocene sea-level change in
150 Orkney, for example in the Bay of Firth, indicates that relative sea-levels have been rising since
151 the early Holocene to reach their present position some 4000 years ago (Dawson and
152 Wickham-Jones 2007; Wickham-Jones *et al* forthcoming). Final inundation occurred
153 considerably later than the arrival of the first Mesolithic population of Orkney c. 9 ka cal. B.P.,
154 and nearly two millennia after the development of farming in the islands c. 6 ka cal. B.P.
155 (Downes *et al*, 2005).

156

157

158 **Archaeological background**

159 The archaeological evidence for Neolithic Orkney (Figure 1A) is dominated by the large stone
160 structures that occur throughout Orkney and have been the focus of attention since the
161 discovery of Skara Brae in 1850. In addition to the settlement remains of individual
162 farmsteads (e.g. Knap of Howar, Smerquoy) and larger villages (e.g. Links of Notland, Pool,
163 Skara Brae) there are also stone tombs that relate to both the Early (e.g. Unstan, Midhowe)
164 and Late (e.g. Maeshowe, Cuween) Neolithic. The repertoire is completed with standing stone
165 circles (Stones of Stenness and Ring of Brodgar) and the newly discovered ceremonial site of
166 Ness of Brodgar (Figure 2). In recent years the discovery of the remains of timber buildings
167 has added to the rich pool of knowledge of Orkney in the Early Neolithic (Lee and Thomas,
168 2012; Richards and Jones, forthcoming). Within the study area, the material archaeology is
169 dominated by the ceremonial complex that runs along the Brodgar Peninsula (Figure 2), from
170 the henge and tomb at Bookan, past the Ring of Brodgar, Ness of Brodgar, and the Standing
171 Stones of Stenness to the great tomb at Maeshowe (Figure 2, Downes *et al.*, 2005). With the
172 exception of Barnhouse, settlement remains are lacking, but it has to be noted that
173 archaeological excavation has focused on the area to the east of the Loch of Stenness, yet the
174 other shores offer considerable potential which has yet to be explored in detail (Richards,
175 2005, 8-16). The earliest dates for activity in the study area come from the excavated
176 settlement at Barnhouse and relate to the late sixth millennium cal B.P. (late fourth
177 millennium BC) (Griffiths and Richards, 2013).

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

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

198
199 In general, the evidence for the Neolithic around the Loch of Stenness is biased in favor of
200 ceremonial activity. While sites along the Brodgar peninsula suggest that it was indeed the
201 ceremonial heart of Neolithic Orkney (Richards, 2013; Downes *et al.*, 2005), surface finds from
202 the other shores of the loch suggest that daily life elsewhere in the area included small
203 farming communities of the type now recognized across Orkney (Richards, 2005, 8-13).

204

205

206 **Field investigation**

207

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

213

214 **Seismic investigation**

215

216 Sonar data was collected across the loch using a small, customised survey boat. The boat was
217 fitted with RTK dGPS to ensure positioning to at least 5cm accuracy. For mapping the loch
218 floor a 468kHz SEA Swathplus bathymetric sidescan was used together with a TSS DMS05
219 motion reference unit. The combined survey system provides up to 30 pings per second
220 producing a potential footprint of less than 10cm at a standard survey speed of approximately
221 4kts. The use of the RTK dGPS allowed real-time tidal corrections and the motion reference
222 unit compensated for heave, pitch and roll from wave and swell. Bathymetry data (Figure 3)
223 was collected along a number of line transects that focused on the rugged loch perimeter
224 where 100% coverage was achieved. At the centre of the loch the swath coverage was
225 supplemented by depth information provided by the sub-bottom profiling. Sub-bottom
226 profiling information on the history of sediment infilling was collected using a Tritech SeaKing
227 parametric sub-bottom profiler. This was also deployed along line transects around the
228 perimeter of the loch and across the loch interior with seismic signatures converted to depth
229 profiles using a seismic velocity of 1500ms⁻¹ following standard procedures (Bates *et al.*,
230 2007).

231

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

254
255 The sub-bottom profile seismic data was of high quality throughout the loch and showed a
256 sequence of layered sediments marked by sharp discontinuities to a depth of at least -10m
257 OD. Two example profiles are shown in Figures 4 and 5 with their locations shown on Figure
258 3. At the loch centre, the sedimentary layers were obscured by the presence of gas likely
259 derived from the decomposition of organic material near the base of the sequence (Figure
260 4). The seismic interpretation of the sediment sequence suggests a complex history of
261 gradual loch filling punctuated by periods of erosion that can be summarised into a number
262 of key stages based on the seismic character (Table 1) and interpreted through the coring
263 sequence.

264
265 Sequence 1 at the base of the seismic section is distinguished by a reflector that is generally
266 jagged or rough in appearance. The unit is opaque with generally no internal reflectors. Near
267 the margins of the loch the unit extends to the loch floor and can be traced onshore as a
268 continuous rock platform, thus the unit represents the seismic basement of local bedrock.
269 Towards the centre of the loch the depth to sequence increases to a maximum of at least -
270 10m OD. A number of mounds or outcrops of the unit are identified where the overlying
271 layers of sediment have not covered the rock. These outcrops manifest as skerries which can
272 be seen in the east of the loch on aerial photographs.

273
274 Sequence 2 infills on top of the bedrock surface that thickens towards the loch centre. It
275 appears to drape the bedrock surface and has only occasional discontinuous internal
276 reflections that are parallel to its surface. In the western arm of the loch towards Voy very
277 small pockets of this material were noted where depth to the layer reduces to less than 5m
278 and thus it was accessible for coring.

279

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

287

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

302

303

304 **Palaeoenvironmental investigation**

305

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

326 examined from the cores. Full details of the methods employed are presented in
327 Supplementary information 3 and results in Supplementary Information 4 to 9.

328
329 Five lithological units were identified in the cores:

330
331 *Unit A.* This is present at the base of 2014-5 (2.18m to base) (Figure 6) and consists of dense
332 silt with poorly sorted gravel clasts. The appearance of the sediment suggest this unit was
333 deposited with minimal sorting and is possibly the upper part of late Pleistocene till deposits
334 known to be present in the area. Sieving of a single sample from this unit failed to produce
335 any organic material.

336
337 *Unit B.* This unit is also present in 2014-5 (1.10 – 2.18m) (Figure 6) and consists of grey silts
338 with sands. The sediments may be bedded in places. Organic and carbonate content are low
339 throughout this unit and with iron staining in the lower part only (below 1.57m depth). No
340 palaeoenvironmental remains were present in the lower part of this sediment unit (1.90-
341 2.18m) (Supplementary information 4). The remainder of the unit (1.10-1.90m) contained
342 charophyte oogonia, cladocera and insects throughout. This suggests freshwater lacustrine
343 or shallow water body conditions in which the watertable may have fluctuated.

344
345 *Unit C.* This unit consisted of pale grey brown silt and sand and is present in 2014-1 (0.81-
346 2.10m) (Figure 7), 2014-3 (0.47-1.65m), 2014-4 (0.48-1.60m), 2014-5 (0.18-1.10m) (Figure 6)
347 and 2014-8 (0.33-2.62m) (Figure 8). The initial phase of freshwater deposits are dated in
348 2014-8 to 10691-10435 cal. B.P. (8742-8486 cal. BC) (Figure 8). In 2014-5 (Figure 6) the
349 minerogenic sediment declines and there is a marked increase in carbonate content within
350 this unit. Freshwater molluscs are present as well as charophyte oogonia, cladocera,
351 ostracods, and latterly, foraminifera (Supplementary information 4-8). For the most part this
352 unit is characterised by the presence of distinctive freshwater ostracods – and by very similar
353 assemblages throughout. Four species are ubiquitous and occur in great numbers (*Candona*
354 *candida*, *Pseudocandona rostrata*, *Cyclocypris ovum* and *Limnocythere inopinata*). In some of
355 the cores these species are joined by up to four other less common freshwater species. This
356 ostracod assemblage is typical of a large permanent shallow waterbody (Meisch, 2000). *C.*
357 *candida*, in association with other species often indicates cool conditions, but it is widespread
358 through Britain at the present day, and is thus not necessarily a climatic indicator here. In
359 2014-1 Unit C is more complex and exhibits a trend towards decreasing mean grain size
360 upwards (Figure 7). Organic values attain greater than 20% by loss-on-ignition below 1.40m
361 depth and this is associated with the coarsest part of the sequence (Figure 7). Microfossils
362 show that the last occurrence of freshwater species occurs at the boundary between Unit C
363 and the overlying unit; however the initial tidal access, based on the first occurrence of the
364 brackish species *Cyprideis torosa*, can be seen to be 20cm lower at 1.02m. This species occurs
365 right up to the unit boundary at 0.81m, significantly, however, its valves are highly noded
366 which would indicate the salinity was very low (<6‰) (Athersuch, Horne and Whittaker,
367 1989). The onset of brackish conditions are dated in 2014-1 between 5939-5753 and 5862-
368 5612 cal. B.P. (3990-3663 cal. BC). In 2014-7 (Supplementary information 7) organic content
369 increases up profile and is entirely freshwater to the surface. Finally, in 2014-8 (Figure 8,
370 Supplementary information 6) organic content is low although does appear to increase
371 slightly towards the top of the unit. The upper part of this unit coincides with the initial tidal
372 access (evidenced by both the first occurrence of noded *Cyprideis torosa* and the brackish

373 foraminifer *Haynesina germanica*). However, the last occurrence of freshwater ostracods is
374 not until c. 0.28-0.30m. This is dated between 6310-6209 cal. B.P. (4361-4260 cal. BC).

375
376 *Unit D.* This consists of massive grey silts and sands and is present in 2014-3 (0.12-0.47m),
377 core 2014-4 (0.28-0.48m) and 2014-6 (0.42-1.64m). In 2014-6 the unit is organic and
378 carbonate rich towards the base but this declines upwards. Microfossils (Supplementary
379 information 8) indicate brackish conditions throughout, typified by noded *Cyprideis torosa*
380 (indicating low salinity of <6‰), but up-core the valves of this species become smooth,
381 suggesting rising salinity and with it at the same depth (c. 1.00m), the first foraminifer
382 (*Elphidium williamsoni*). Freshwater ostracods are still present throughout this unit, albeit
383 latterly patchy, disappearing entirely at 0.42m, the unit's upper boundary. This unit is
384 restricted to a channel-like feature, probably eroded into the underlying material.

385
386 *Unit E.* This unit is present in the top of most cores (2014-1, 0-0.81m (Supplementary
387 information 5), 2014-3, 0-0.12m, 2014-4, 0-0.28m, 2014-5, 0-0.18 (Supplementary
388 information 4), 2014-6, 0-0.42m, 2014-7, 0-0.85m (Supplementary information 7) and 2014-
389 8, 0-0.33m(Supplementary information 6)) and consists of fine grey sands and silt. The
390 microfossils indicate a wholly brackish environment. In cores 2014-1/3/ 5/6 this includes
391 foraminifera and ostracods of tidal flats. *Cyprideis torosa*, where present, is smooth and
392 indicates a salinity of >6‰. The ostracods, and especially the foraminifera are of low diversity,
393 sometimes only represented by *Miliammina fusca* (an agglutinating species that has a shell of
394 mineral grains bound together with organic cement rendering it virtually indestructible) but
395 in large numbers, suggesting the sediments are decalcified.

396

397

398 **An integrated environmental history of the Loch of Stenness**

399

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

407

408 Much of the lake basin is infilled with sediments defined in the seismic stratigraphy as
409 Sequence 3 (a/b) and this has been linked to Units B and C. Unit B contains little in the way
410 of palaeoenvironmental material and is probably a correlative of Sequence 3a. The sediments
411 indicate sequence accumulation in a fresh, shallow water body, perhaps one impacted by
412 fluctuating water tables through time as the indicated in the seismic interpretation.
413 Minerogenic sedimentation dominated at this time coincident with deglaciation from a
414 barren landscape and the release of clastic material into the environment. Sequence 3b (Unit
415 C) by contrast consists of carbonate rich sediments with the seismic layering suggesting
416 slower sedimentation indicating deposition from controlled run-off again in a freshwater loch
417 environment. Detailed study of these sediments has not been undertaken but the microfossil
418 samples are typical of species living in a large permanent shallow water body while the
419 presence of *C. candida* may indicate cool conditions. Dates from the top of these deposits in

420 cores 2014-1 and 2014-8 suggest accumulation that may have commenced in the late
421 Pleistocene continued into the early/mid-Holocene with final accretion taking place just after
422 6ka B.P. By comparison with Crudale Meadow (Whittington *et al.*, 2015) accumulation is likely
423 to have begun by 15ka B.P.

424

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

438

439 The upper parts of Unit C indicate the onset of brackish conditions in the basin. Thus in cores
440 2014-1 and 2014-8 the upper part of Unit C (top 20cm) contains evidence for brackish water
441 microfossils within a lithological unit little different to that below. This transition is marked
442 by the first occurrence of the brackish species *Cyprideis torosa* and has been dated in 2014-1
443 to the early Neolithic period (Figure 11). The precise nature, and the mechanism responsible, for
444 generating this pattern of data is difficult to assess at present and a number of possible scenarios can
445 be considered to explain the observations:

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

453

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

462

463 True brackish conditions are associated with lithological Unit D and seismic Sequence 4 and
464 5. Brackish conditions (exemplified by noded *Cyprideis torosa*) become increasingly more
465 saline up-core (denoted by the replacement of noded *Cyprideis torosa* by the smooth variety)
466 and the first foraminifer (*Elphidium williamsoni*) to appear. Freshwater ostracods are still
467 present throughout this unit suggesting continued input from these sources. The distribution

468 of these units (5) is shown in Figure 5 and this unit appears to form a channel like feature cut
469 into the underlying sediments. Thus these units are those associated with initial flooding of
470 the basin by brackish water and the creation of the tidal channel into the loch.

471
472 The final event in the loch history is that associated with seismic Sequence 6 and lithological
473 Unit E which represent the modern and recent loch basal conditions associated with the low
474 energy brackish conditions within the loch today.

475
476
477

478 **Implications for the setting of the Neolithic monuments and activity in the vicinity of the** 479 **Brodgar Isthmus**

480
481 The combined geophysical and palaeoenvironmental evidence for landscape reconstructions
482 for the Loch of Stenness in the Mesolithic and early Neolithic have interesting implications for
483 the development of the landscape just prior to Neolithic monument construction along the
484 Brodgar Isthmus. The data suggest that the landscape hollow occupied by the Loch of
485 Stenness has been infilling with sediment from the Lateglacial. Prior to this the Orcadian
486 landscape was blanketed by late Pleistocene till that represents the base of the sediment
487 sequence in the loch (Figure 10a). Near the Brig o'Waithe this till cover probably provided the
488 barrier that allowed higher loch water levels than present in a similar manner to the barrier
489 that would have existed to the sea side of Skara Brae. Sediment accumulation in an ever
490 decreasing accommodation space would have shallowed the water levels of the loch and
491 focused channelling along a central valley axis eventually resulting in a decrease in area of the
492 loch as it infilled (Figure 10b-c). Changes in sedimentation pattern were a result of changing
493 landscape around the loch. Between approximately 7000 ka cal. B.P. and 6000ka cal. B.P. the
494 confining barrier was reduced in relative height either by gradual erosion (by both stream
495 action and perhaps the encroaching sea) or a sudden erosive event resulting from a change
496 in external, climate conditions (Figure 10d). Subsequent to erosion the lowered loch level
497 meant that sedimentation was only taking place along the central eroded valley channel. The
498 implied erosion event and its coincidence to climate shifts that have been reported elsewhere
499 in the literature is noted. For example, a Holocene cooling event with the implication of
500 increased run-off has been reported by Wanner *et al.* (2011) between 6.5 and 5.9ka cal B.P.
501 Incision within fluvial systems in the Highlands of Scotland has been reported by Macklin *et*
502 *al.* (2013) between 6.4 and 6.0ka cal B.P. by and finally a period of increased storminess in the
503 North Atlantic was noted at 5.5ka cal B.P. by Sorrel *et al.* (2012).

504
505 The lowering of loch levels in the late Mesolithic or early Neolithic would have reduced the
506 Loch of Stenness in size, exposing low-lying land that would have increased the width of the
507 Brodgar Isthmus by at least 50% on the Stenness side (Figure 11). This could have been further
508 increased in size if a similar reduction in the water level was experienced in the Loch of Harray.
509 An additional feature of this landscape, identified through the geophysical survey, comprises
510 the rocky sides of the loch. These were mapped around the complete perimeter and
511 extended from -1m to full water depth at -5m OD along the eastern shore (Figure 11). Here
512 the >4km long exposure would have represented a considerable and highly accessible
513 resource of nearby construction material for activities on the isthmus in the early Neolithic.

514

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

528
529 Terrestrial vegetation changes across the late Mesolithic to Neolithic boundary have been
530 demonstrated in the pollen records from the Stenness landscape (Farrell *et al* 2012). These
531 changes have been interpreted as primary and secondary woodland clearance occurring in
532 response to a number of factors which might include human activity. We can now see that
533 these changes are taking place at a time coincident to the changes in loch conditions (Figure
534 12). The scale of these changes in the environment is emphasised by consideration of the
535 input of sediment to the loch system. The seismic stratigraphy has enabled us to calculate the
536 volume of sediment filling the loch system to bedrock for those units associated with the
537 freshwater loch (seismic Sequences 2-3) and those associated with the initial transgression of
538 sea water into the loch (Sequences 4 and 5). The calculations we used assumes that initial
539 freshwater accumulation of sediment in the loch began c.15,000 years ago and ceased c.6,000
540 years ago. Our calculations suggest a shift in rates of sedimentation from 0.25mm/yr. during
541 the freshwater phase of loch history to 1.3mm/yr. during the period of transgression within
542 the loch (Supplementary Information 10).

543
544 The dramatic increase in sedimentation rates in Units 4 and 5 took place during the early
545 Neolithic and is likely to result from a combination of factors. While the impact of individual
546 weather events cannot be ruled out and the impact of the low amplitude tidal cycles
547 associated with transgression would certainly have brought additional sediment into the loch
548 other factors are also likely to have been important. The vegetation history and the primary
549 and secondary woodland clearance is likely to have had a long-term impact on the stability of
550 soils and the importance of soil erosion and the introduction of sediment into the loch
551 through run-off will also have played a significant role. However, in the context of soil
552 deterioration French noted that at least at Barnhouse soil micromorphological evidence from
553 the excavations here suggested that the podsolization and soil deterioration seen elsewhere
554 in the Neolithic in Orkney as a result of anthropogenic activity had not begun at this site
555 (French, 2005).

556

557

558 **Conclusions**

559

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

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

570
571 These changes would have been obvious to those who made their lives here over a period of
572 at least a thousand years. Although research elsewhere highlights the way in which
573 environmental change was a fact of life in the Early Holocene around the Loch of Stenness it
574 was particularly dramatic and occurred in a location that has been established as of particular
575 ceremonial significance. Nevertheless, the actual sites that made up the area that we now call
576 ‘the Heart of Neolithic Orkney’, remained on dry land and in use. Much has been made of the
577 shift from marine resources to terrestrial resources at the onset of the Neolithic (Thomas,
578 2013); rising relative sea-levels around the archipelago of Orkney might have threatened the
579 new dominance of the land, but they did not overturn it. Here in Stenness we can see a
580 ‘return’ to marine conditions at the heart of the new economy when other indicators suggest
581 decreasing marine influence on life. We can only surmise the ways in which the local
582 community made sense of such changes in the heart of Neolithic Orkney and the role played
583 by the changing world context in the significance of the Neolithic sites here.

584
585 While Orkney offers a relatively shallow water and easily accessible environment, the
586 exigencies of data collection, analysis and integration are presented as a case study of value
587 to the wider archaeological community. Truly interdisciplinary studies require careful merging
588 of datasets that may be traditionally treated in very different ways. It is also clear that
589 investigation of the palaeoenvironment, including the submerged landscape, and associated
590 change, is an absolute prerequisite for a proper understanding of human behavior. Given the
591 emerging global significance of submerged landscapes and continental shelf archaeology in
592 relation to the spread of hominins around the world and developing technological and
593 cultural complexity, the expansion of archaeological techniques to include off-site studies
594 such as that outlined here is a high priority. Furthermore, in many locations the value and
595 relevance of such studies extends from the earliest Holocene into more recent prehistory.

596 **Acknowledgments**

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754 **List of Figures**

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

760

761 **Figure 2.** Loch of Stenness and Harray including distribution of sites discussed in the text.
762 Mesolithic Sites m1: Urigar, m2: Barnhouse, m3: Odin's Field, m4: Seatter 1, m5: Deepdale,
763 m6: Crua Breck, m7: Bookan, m8: Skara Brae, m9: Arion, m10: Quoynamoan, m11: Mayfield.
764 Neolithic sites n1: Stones of Stenness, n2: Ring of Bodgar, n3: Unstan, n4: Maeshowe, n5:
765 Ness of Brodgar.

766

767 **Figure 3.** Loch of Stenness bathymetry and location of seismic profile lines and boreholes.

768

769 **Figure 4.** Seismic line 1 and interpretation showing the position of boreholes drilled in
770 project.

771

772 **Figure 5.** Seismic line 2 and interpretation showing the position of boreholes drilled in
773 project.

774

775 **Figure 6.** Core St-5 lithology, sedimentary properties, identified units and inferred
776 palaeoenvironmental conditions.

777

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

780

781 **Figure 8.** Core St-8 lithology, sedimentary properties, identified units and inferred
782 palaeoenvironmental conditions.

783

784 **Figure 9.** Core stratigraphy and correlations between key boreholes including inferred
785 environments of deposition and age estimates.

786

787 **Figure 10a-f.** Model of sediment accumulation and erosion interpreted from geophysics and
788 core logs. Dates and date ranges for specific events: SS1 – 20,000ka cal BP; SS2 – 15-20ka
789 cal BP; SS3a – ?10-13ka cal BP; SS3b – 6-?10ka cal BP; SS4 – ?4-6ka cal BP; SS5 – ?2-6ka cal
790 BP; SS6 – 0-2ka cal BP.

791

792 **Figure 11.** Suggested reconstruction of Loch of Stenness in early Neolithic during marine
793 transgression into Loch.

794

795 **Figure 12.** Summarised archaeological and palaeoenvironmental data for the Loch of
796 Stenness area. ¹ Holocene cooling event between 6.5 and 5.9ka cal BP (Wanner et al., 2001).
797 ² Onset of incision even in Scottish Highlands between 6.4 and 6.0ka cal. BP (Macklin et al.,
798 2013). ³ Bond event 4 at 5.9ka cal BP (Bond et al., 1997). ⁴ Period of increased storminess in
799 North Atlantic at 5.5 and 5.8ka cal BP (Sorrel et al., 2012).

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List of Tables

Table 1. Seismic stratigraphy unit descriptions and interpretations.

Supplementary Information

Supp 1. Core sedimentology summary descriptions

Supp 2. Radio Carbon results

Supp 3. Sample preparation description

Supp 4. Organic and microfossil assessment data from core 2014-5

Supp 5. Organic and microfossil assessment data from core 2014-1

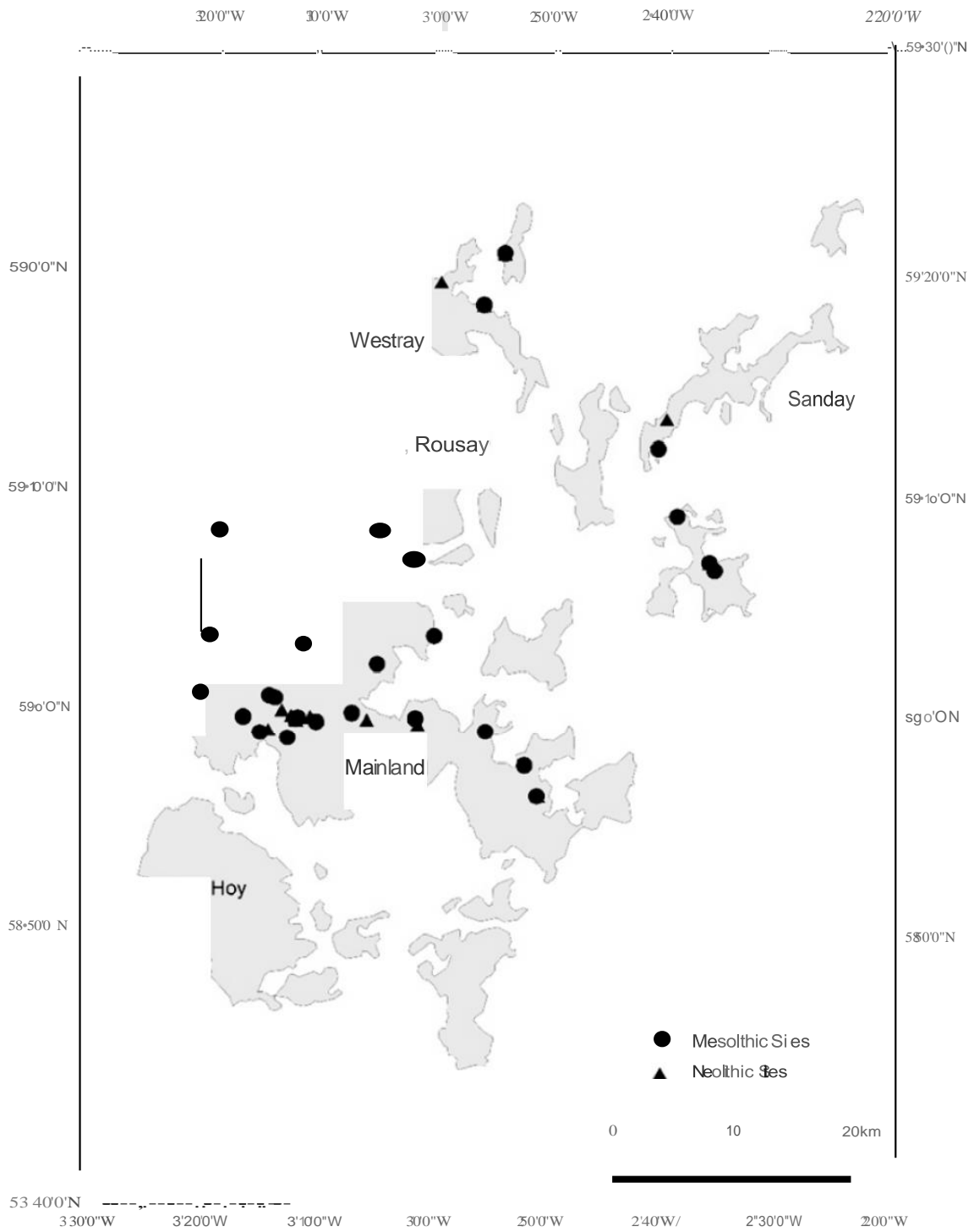
Supp 6. Organic and microfossil assessment data from core 2014-8

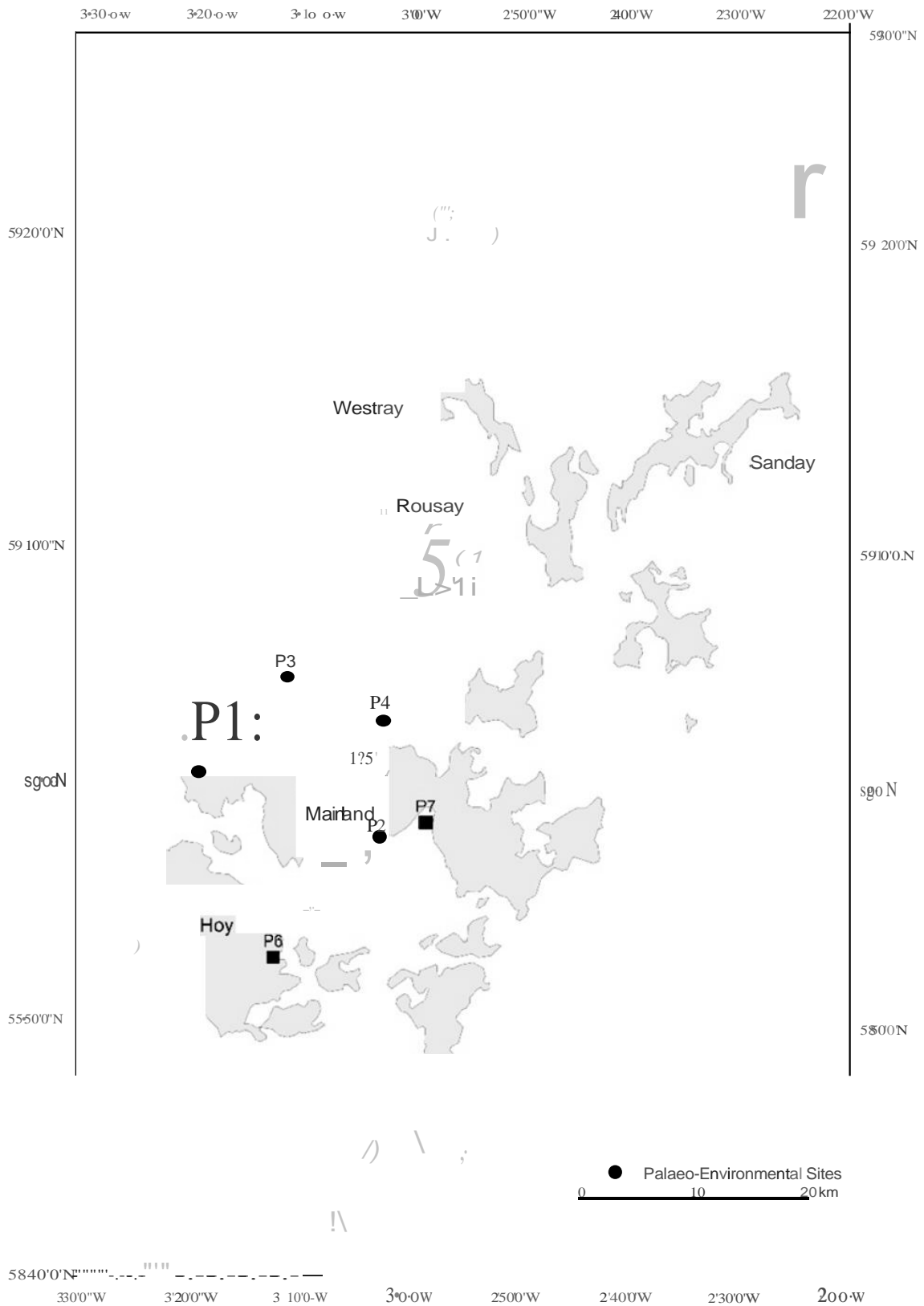
Supp 7. Organic and microfossil assessment data from core 2014-7

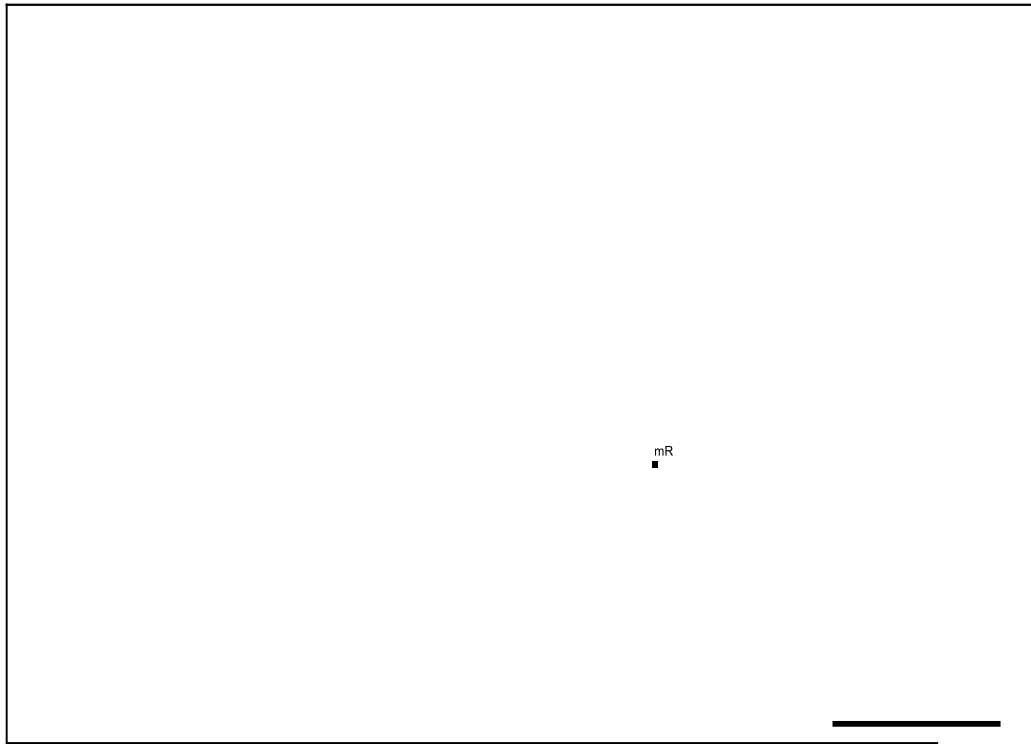
Supp 8. Organic and microfossil assessment data from core 2014-6

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

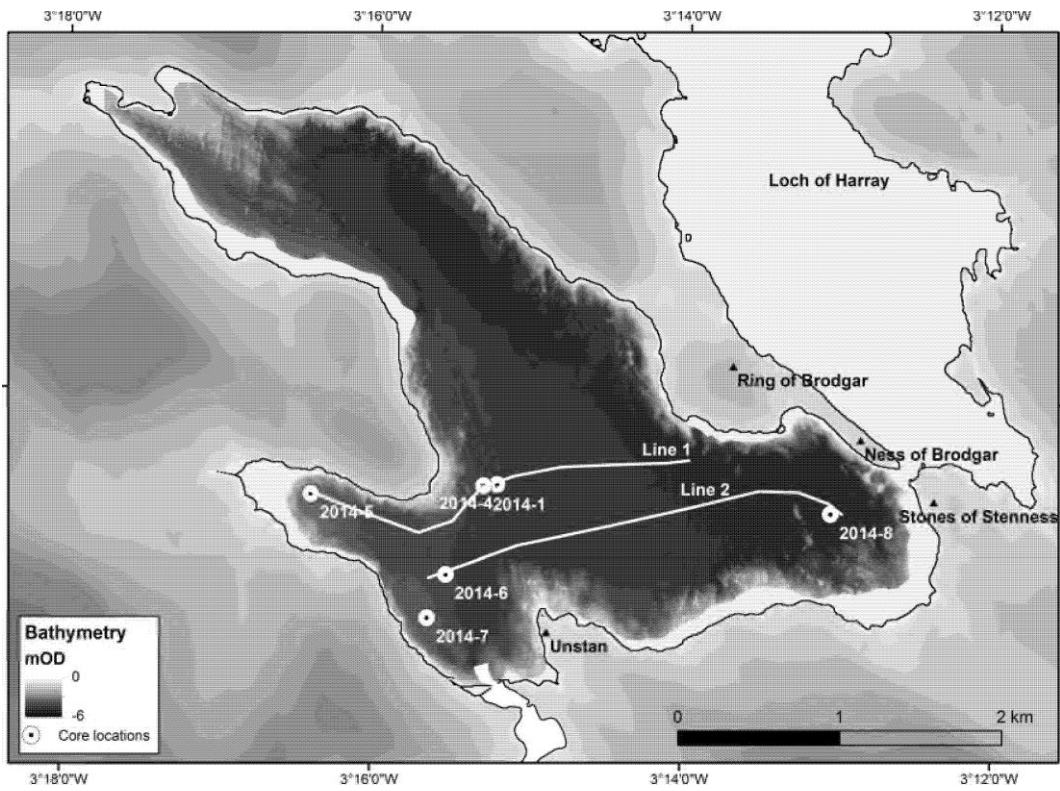
Supp 10. Calculated sedimentation rates for the freshwater and brackish lake sequences in Loch of Stenness.



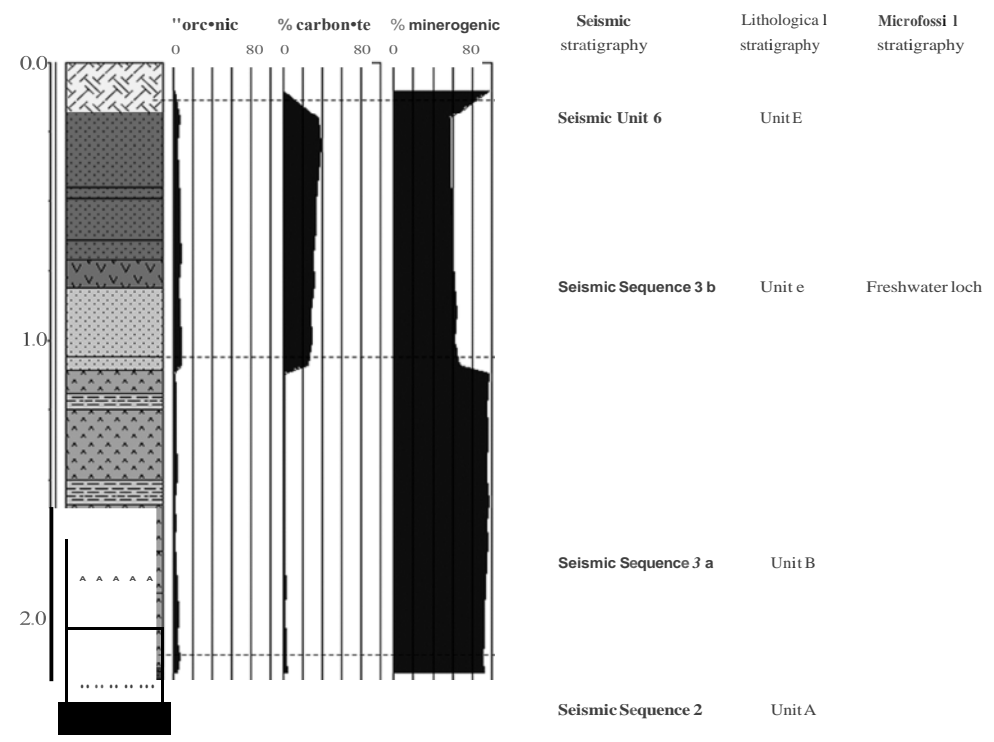
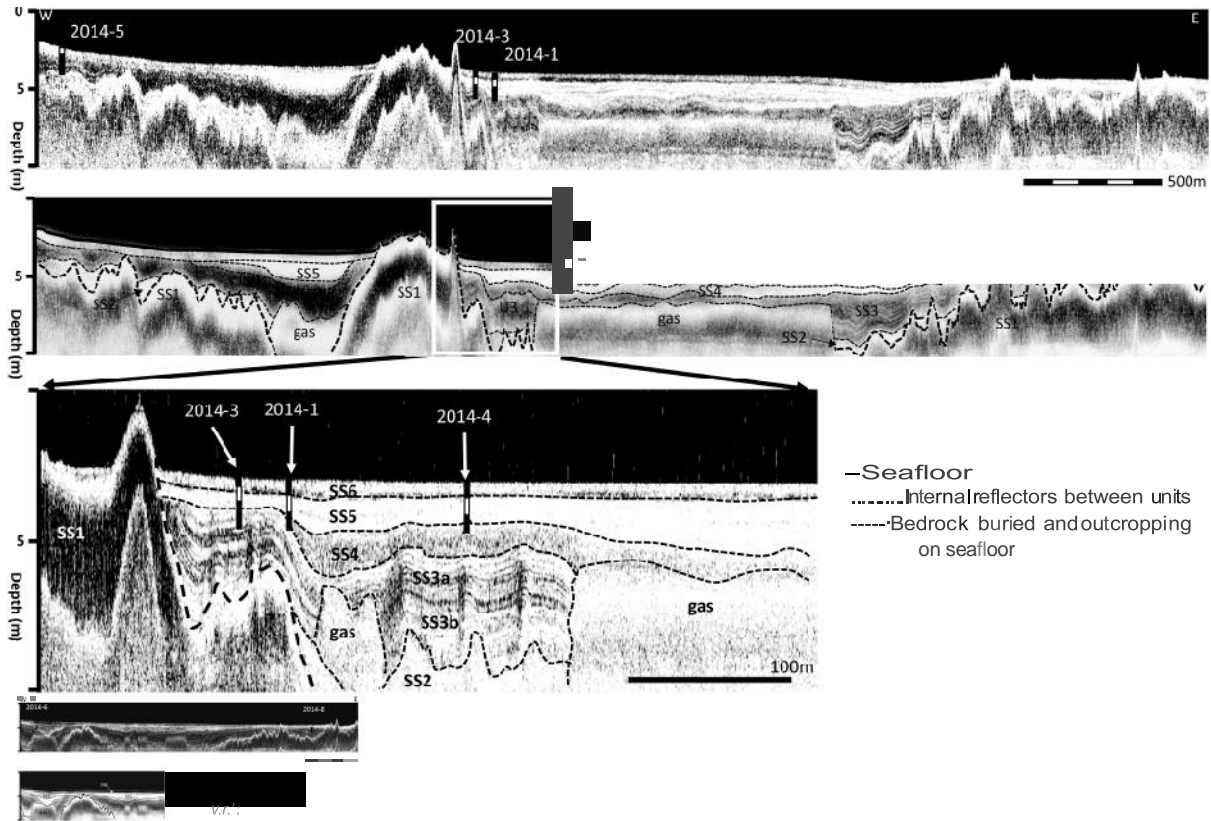


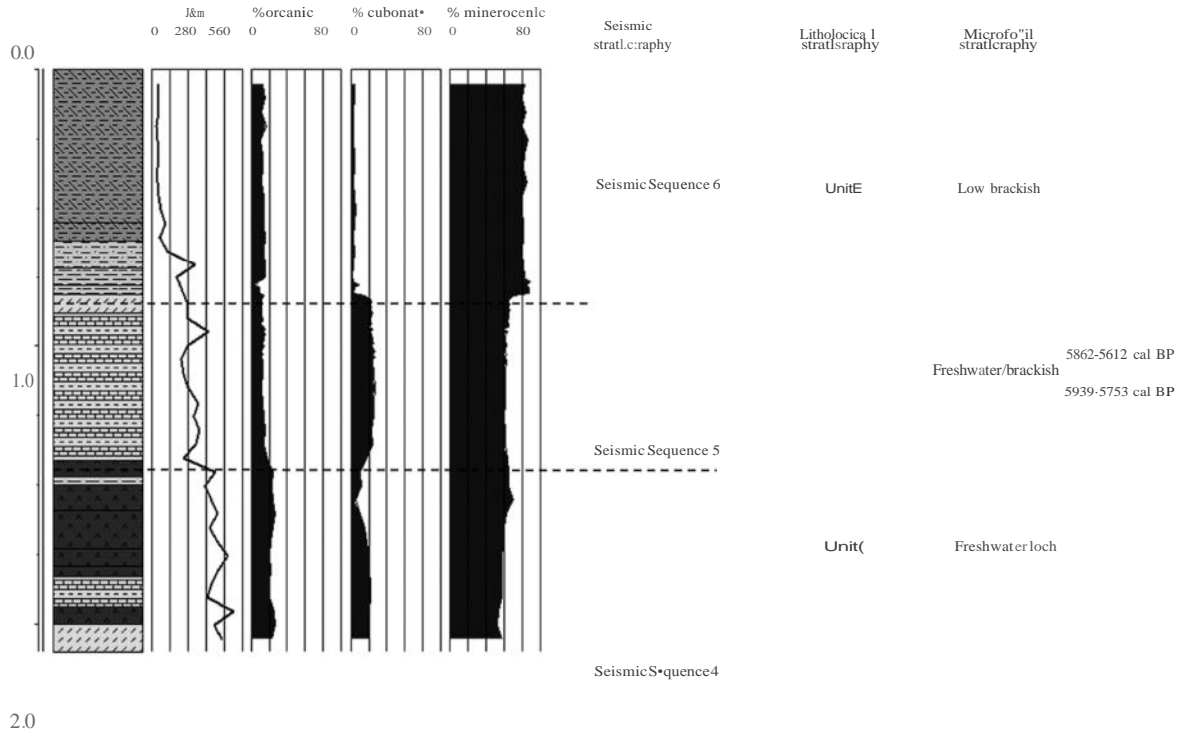


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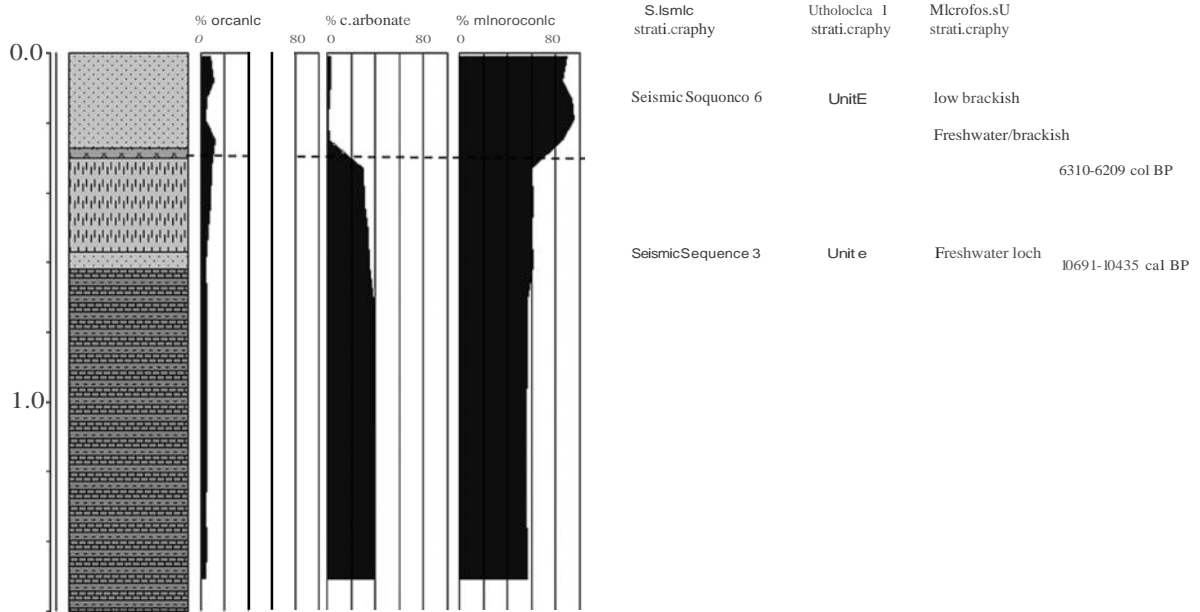


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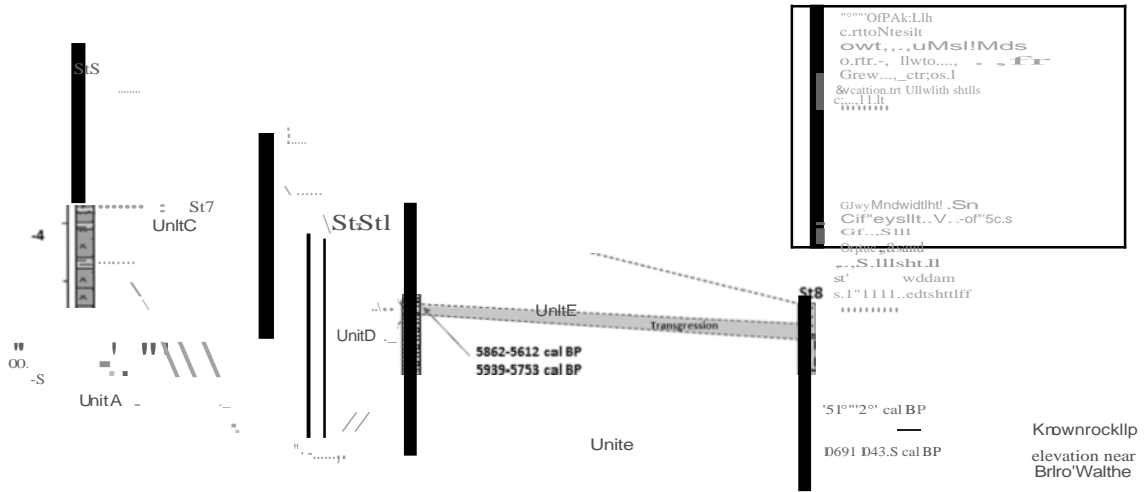




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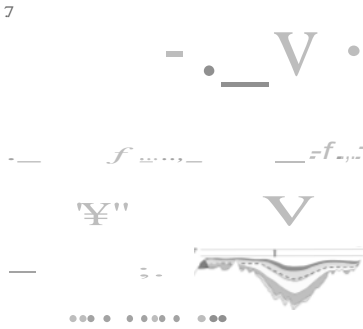


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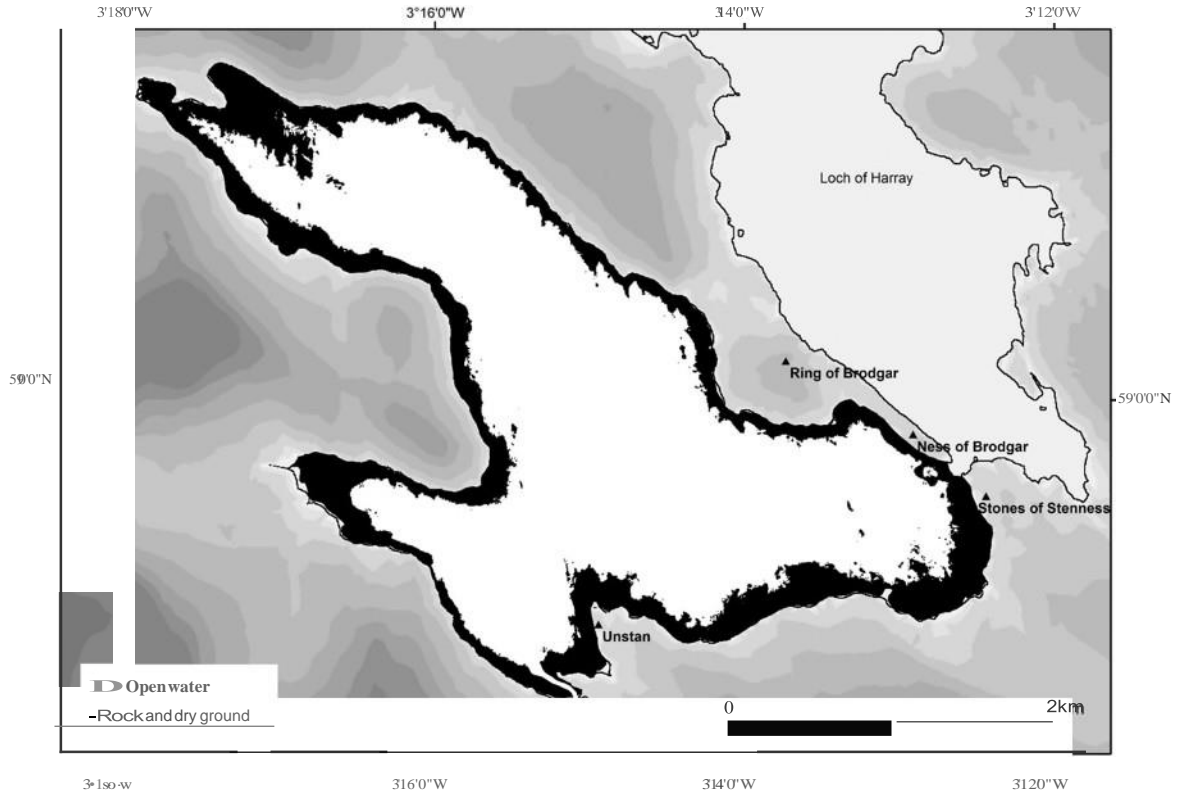


Unh: E:bnckJsh coutal loch
 Unit D: bnckish tidal chInnel wllh fruhwuer lnpUI:
 Unit C: fres.hw water lake
 Unit B: fruhwat r .akawith fluctuInw t11ev11
 Unit A: lte P11 ist0<:en ltm

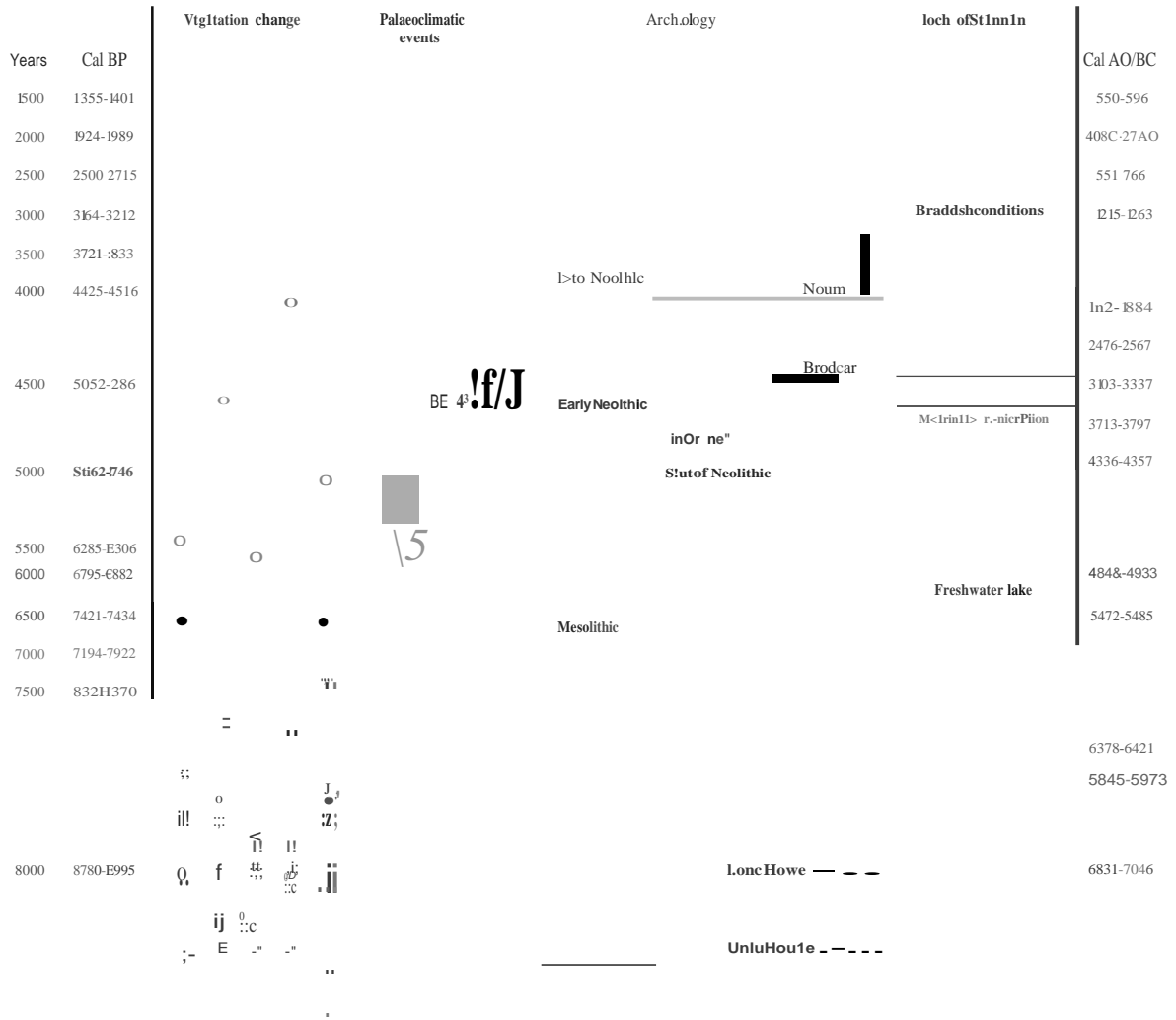
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Seismic Sequence	Sesmic facies description	Lithological Unit	Palaeoenvironmental evidence	Age ascriptions	Integrated interpretation (seismic/lithological/biological)
SS6	No dominant internal reflectors, generally a single +/-/+ (positive/negative/positive) polarity waveform. The sequence is uniform in thickness, c. 0.5m thick	E	Microfossils indicate a wholly brackish environment including foraminifera and ostracods of tidal flats	Recent to modern	Modern sea floor environments, low brackish tidal marine
SS5	Generally negative amplitude. Sequence sometimes divides into one or two parts that are high amplitude and occasionally banded. Thickness varies but it generally thins/tapers towards the loch edges and is thicker towards the loch centre at up to 2m thickness.	D	Microfossils indicate brackish conditions throughout but freshwater ostracods still present		Low brackish tidal channel with freshwater influx
SS4	Diffuse low amplitude return, devoid of seismic character. Laterally intermittent and appears to thicken towards loch centre.	D	Microfossils indicate brackish conditions throughout with freshwater ostracods still present		Low brackish tidal channel with freshwater influx
SS3b	Wavy parallel internal reflectors alternating between positive high and positive low amplitude, closely spaced. Often dipping layers especially	C	First occurrence of the brackish species <i>Cyprideis torosa</i> , at top of sequence. Freshwater molluscs, charophyte oogonia,	5939-5753 and 5862-5612 cal. B.P. (3990-3663 cal. BC)	Freshwater lacustrine, well developed lake basin with marginal reedswamps and open water mid basin. Beginning of transgression at top of unit.

SS3a	towards the edge of the loch, more horizontal towards the middle.	B	cladocera, ostracods dominate throughout. Charophyte oogonia, cladocera and insects throughout.	10691-10435 cal. B.P. (8742-8486 cal. BC)	Freshwater lacustrine or shallow water body conditions in which the watertable may have fluctuated.
SS2	High amplitude occasional discontinuous internal reflectors , near basal unit, only present in some areas but there is a strong signal in Seatter, Voy and near the loch entrance. When present the unit is up to 0.75m thick but generally 0.5m thick.	A	-	>15,000 cal. B.P.	Till
SS1	Opaque with no internal reflectors for most of loch however occasional bedding mapped when shallow (<2m water depth)	-	-	Last glacial maximum	Mixed till and bedrock perhaps combined in solifluction layer in places