15

Magnetic moments at Ness of Brodgar

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The magnetic analysis of material from the Ness of Brodgar has formed part of the research programme at the site, with annual collection of samples, since 2012.[1] Primarily concerned with dating and with the refinement of site chronologies, magnetic analysis is also being used to address questions regarding the nature of resource exploitation and the use of space within buildings. This chapter presents the results of the research undertaken so far and highlights the areas that are likely to prove informative in future.

Questions and potentials

Key to the success of magnetic analysis has been the nature of the archaeology and the scope of excavations at the Ness of Brodgar. A multitude of hearths has been revealed and the residues within have proved excellent candidates for archaeomagnetic directional studies and for the investigation of fuel use. The extensive pottery record also provides a wide range of sherds for archaeomagnetic intensity studies. As excavations have progressed, earlier layers within hearths have been revealed with clear stratigraphic relationships, allowing investigation of the longevity of structures and changes in fuel use over time.

Also critical to our research has been the ongoing nature of excavations, allowing time to develop ideas, plan research, obtain funding and process data between field seasons. The meticulous nature of the excavations has made it possible to build on results in successive years and the commitment to scientific analysis has maximised both the sampling opportunities and the synergies offered by collaboration across a range of different methods.

Our main concern thus far has been to develop the contribution of archaeomagnetic dating to the chronology of the site and to Neolithic studies more generally. Archaeomagnetic analysis of hearths has been used alongside radiocarbon dating and the stratigraphic record to produce a Bayesian model for the site chronology.[2] Far from being a routine application of archaeomagnetic dating, the studies at the Ness of Brodgar have been ground-breaking; developing a record of the direction of the past magnetic field which can be used for dating other Neolithic sites in the UK and producing the first measurements of the intensity of the past magnetic field using British Neolithic pottery.[3]

15.1 Dr Zoe Outram taking samples by the tube method from hearth deposits in Structure 14

The study of resource exploitation has focussed on identifying fuels and heating temperatures based on magnetic analyses.[4] Promising results so far will reach their full potential in the post-excavation phase, when they can be integrated with chemical, environmental and micromorphological analysis to provide an integrated interpretation of resource use and how people interacted with their wider environment.

So far, there has been less emphasis on using magnetic methods to understand the use of space within buildings. Although such investigations have proved productive elsewhere,[5] the complexity of the deposits at Ness of Brodgar has made the identification of large areas of undisturbed floor surfaces difficult. The use of magnetic properties to identify activities within structures remains a fruitful area for future study, in combination with chemical and micromorphological analysis.

Archaeomagnetic dating

Archaeomagnetic dating uses known variations of the past magnetic field of the earth to provide a date for the last time archaeological material such as hearths, burnt soils and ceramics were heated. The geomagnetic field at a given location has a directional component (declination and inclination) and a strength, known as its intensity. The method relies on two principles: the first is that the geomagnetic field has varied in the past, a phenomenon known as palaeosecular variation. The second is that this past behaviour can be recorded and preserved through a variety of mechanisms.

Archaeomagnetic dating usually takes advantage of the thermoremanent magnetisation mechanism, in which iron bearing minerals in an archaeological material become magnetised to reflect the ambient geomagnetic field when heated to above *c*.400 °C. The fundamental advantage that archaeomagnetic dating has over other absolute dating methods is that the event dated is the last time the archaeological material was heated, which is usually directly related to human activity. This allows the dates to be used to inform discussion about phases of use and abandonment of archaeological sites.

The success of archaeomagnetic dating relies on accurately defining the past geomagnetic field beyond direct observations.[6] Key papers detail how research has increased the quantity and the quality of the UK geomagnetic dataset over the past 60 years.[7] One fundamental aim of archaeomagnetic research is to obtain measurements of the past geomagnetic field which are independently dated by another method, thus improving our knowledge of field behaviour and allowing future archaeological sites to be dated. This is particularly important in time periods where the geomagnetic field is poorly understood, for example in extending the capabilities of archaeomagnetic dating further back into prehistory. The British Neolithic is a period which would benefit from further study[8] and, elsewhere in Europe, archaeomagnetic studies on fired archaeological features from the period have been very successful at improving the technique.[9] Studies of the direction of the

15.2 Example of a formal hearth setting from Hearth Group 6309 in Structure 8 with archaeomagnetic samples *© Sam Harris* geomagnetic field require material to have remained *in situ* since heating, for example hearths, whereas studies of intensity can also use material that is no longer *in situ*, for example pottery.

The Ness of Brodgar has been, and will continue to be, a key archaeological site for unlocking important information about palaeosecular variation during the Neolithic. The large quantity of well-preserved hearths are ideal candidates for studies of magnetic direction, with most samples originating from formal hearth settings with varying depths of deposits *(Figs 15.1 & 15.2)*. The range of pottery recovered also gives us a wide choice of material for studies of archaeointensity. In addition, the excavations offer large quantities of chronologically diagnostic artefacts and a comprehensive radiocarbon dating programme which are vital for providing independent dating evidence.

The following sections discuss the scope and scale of the archaeomagnetic studies carried out at the Ness of Brodgar. The first presents a summary of the largest collection of archaeomagnetic samples from a single site in Neolithic Europe; the second discusses the first archaeointensity study on UK Neolithic material.

Sample Code	No. of Samples	AM No.	Context No.	Structure No.	Year Sampled	Reported in
NOB 1	20	AM 206	3802	8	2012	Harris (2015)
NOB 2	25	AM 207	2659	7	2012	Harris (2015)
NOB 3	25	AM 208	3648	1	2012	Batt and Outram (2013)
NOB 4	20	AM 209	3805	8	2012	Harris (2015)
NOB 5	25	AM 210	2679	7	2012	Unmeasured
NOB 6	20	AM 211	3604	1	2012	Batt and Outram (2013)
NOB 7	21	AM 212	4264	8	2012	Harris (2015)
NOB 8	21	AM 213	3152	8	2013	Batt and Outram (2013)
NOB 9	24	AM 214	4656	14	2013	Batt and Outram (2013)
NOB 10	30	AM 215	3814	8	2013	Batt and Outram (2013)
NOB 11	15	AM 216	4612	14	2013	Unmeasured
NOB 12	31	AM 217	4660	14	2013	Batt and Outram (2013)
NOB 13	25	AM 218	4630	14	2013	Unmeasured
NOB 14	25	AM 219	4511	12	2013	Batt and Outram (2013)
NOB 15	23	AM 220	4667	14	2013	Batt and Outram (2013)
NOB 16	16	AM 221	4659	16	2013	Unmeasured
NOB 17	17	AM 222	4674	14	2013	Batt and Outram (2013)
NOB 18	26	AM 223	5013	14	2013	Batt and Outram (2013)
NOB 19	20	AM 224	5014	16	2013	Batt and Outram (2013)
NOB 20	20	AM 225	5019	14	2013	Batt and Outram (2013)
NOB 21	25	AM 245	5332	12	2015	Harris (2020)
NOB 22	20	AM 246	4264	8	2015	Harris (2020)
NOB 23	25	AM 247	5051	14	2015	Harris (2020)
NOB 24	25	AM 248	3851	8	2015	Harris (2020)
NOB 25	25	AM 249	3857	8	2015	Harris (2020)
NOB 26	30	AM 257	3851	8	2016	Harris (2020)
NOB 27	30	AM 258	6339	8	2016	Harris (2020)
NOB 28	30	AM 259	6348	8	2016	Harris (2020)
NOB 29	30	AM 260	6351	8	2016	Harris (2020)
NOB 30	25	AM 261	6354	8	2016	Harris (2020)
NOB 31	20	AM 262	6356	8	2016	Harris (2020)
NOB 32	25	AM 263	6311	8	2016	Harris (2020)
NOB 33	25	AM 264	5669	12	2016	Harris (2020)
NOB 34	20	AM 287	3851	8	2017	Harris (2020)
NOB 35	20	AM 288	6396	8	2017	Harris (2020)
NOB 36	20	AM 289	8213	8	2017	Harris (2020)
NOB 37	25	AM 290	7046	14	2017	Harris (2020)
NOB 38	26	AM 291	8216	8	2017	Harris (2020)
NOB 39	15	AM 292	7392	12	2017	Harris (2020)
NOB 40	20	AM 293	8136	5	2017	Harris (2020)
NOB 41	16	AM 294	8137	5	2017	Harris (2020)
NOB 42	25	AM 295	8138	5	2017	Harris (2020)
NOB 43	21	AM 283	8429	Trench Y	2018	In prep
NOB 44	25	AM 284	8851	Outside 32	2018	In prep
NOB 45	32	AM 285	8429	Trench Y	2018	In prep
NOB 46	25	AM 286	8611	26	2018	In prep
NOB 47	20	AM TBC	8216	8	2019	Unmeasured
NOB 48	20	AM TBC	9017	17	2019	Unmeasured
NOB 49	20	AM TBC	9021	8	2019	Unmeasured
NOB 50	20	AM TBC	9271	32	2019	Unmeasured

Table 15.1 Summary of sampled features (as of August 2019) from the Ness of Brodgar

Archaeomagnetic dating by direction

The primary aim of this research was to use archaeomagnetic studies of *in situ* fired material of known date to define and better understand variations in the direction of the past geomagnetic field throughout the British Neolithic. The most common calibration curve in the UK until recently[10] only allowed calibration of archaeomagnetic directions as far back as 2000 BC. The current calibration curve[11] extended this period back to 5000 BC and represented a crucial step for archaeomagnetic dating in the UK. However, archaeomagnetic data for the Neolithic period represents <1% of the entire dataset, with only five points independently dated to between 4000 BC and 2000 BC, which creates large uncertainties when calibrating archaeomagnetic directions in this period.

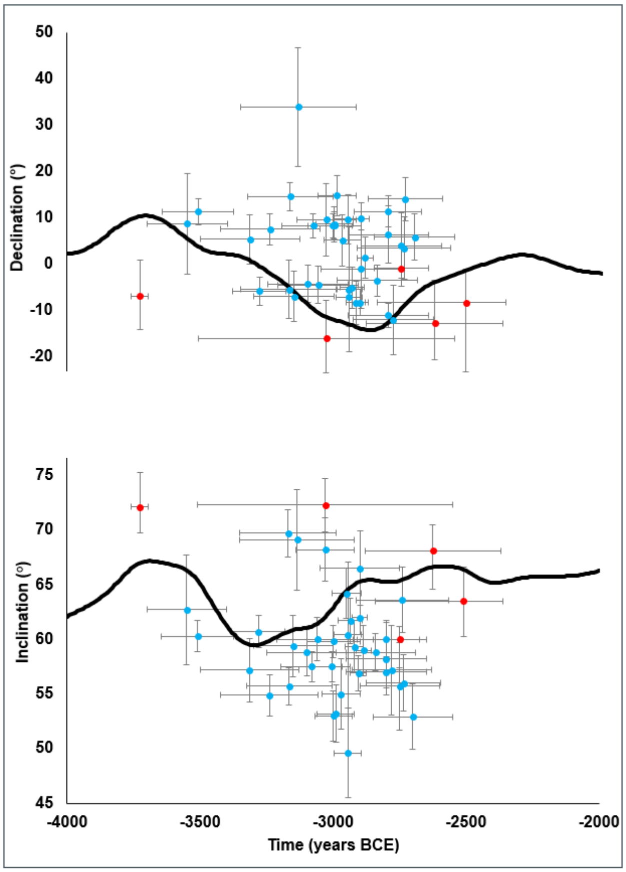
The Ness of Brodgar has supplemented the dataset with 50 new archaeomagnetic sample sets *(Table 15.1)* which represent 1154 samples, currently believed to be the largest collection of samples from a single site in Neolithic Europe. Dating evidence from the site suggests that the piered architecture at the Ness of Brodgar started around 3065-2950 cal BC and that activity ended on the site around 2285-2100 cal BC.[12] That said, the presence of several sherds of Carinated Bowl pottery suggests even earlier Neolithic occupation (Towers, pers. comm.). The longevity of activity at the Ness of Brodgar and the quantity of fired material available present ideal criteria for investigating the past geomagnetic field.

Samples were taken from features across the site. Initial investigations, between 2012 and 2016, focussed on hearths and fired contexts in Trench P with material from Structures 1, 7, 8, 12, 14, 16, 17, and 26. Later studies were extended to also include Trench J, which was sampled during 2017, 2018 and 2019, with material connected to Structures 5 and 32. Trench Y was also sampled in 2018.

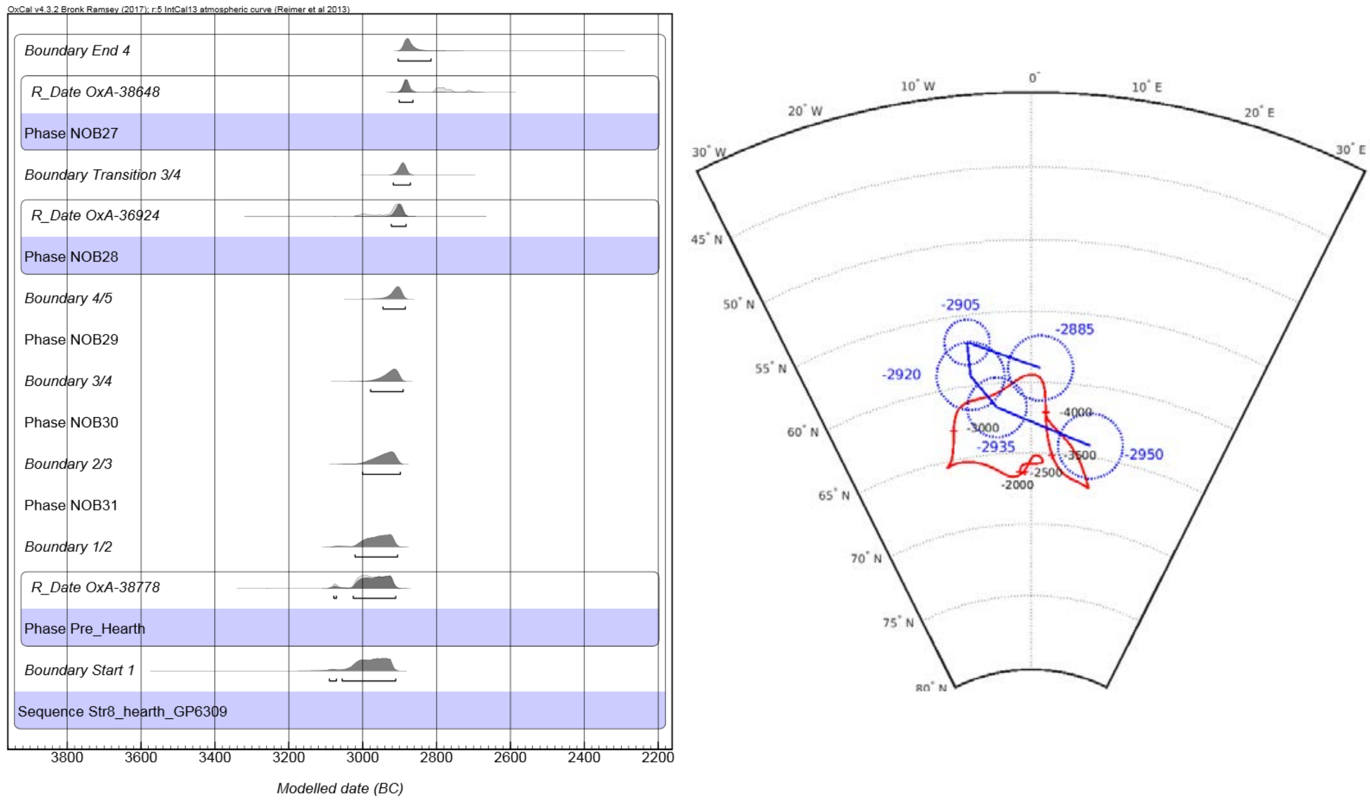
Sampling of the features was carried out by the insertion of plastic tubes, as the material was uniformly soft; orientation was with magnetic compass.[13] The samples were measured on a Molspin spinner magnetometer and the stability of the magnetisation was assessed using alternating field demagnetisation followed by principal component analysis.[14] All sample sets followed established quality control procedures,[15] before calculation of the overall mean utilising Fisher's statistics for points distributed on a sphere in the PalaeomagTools v5 program.[16] The α_{95} value was used to give the error associated with the measurements, equivalent to a 2-sigma or 95% confidence interval.[17]

The formal hearth settings were all excellent recorders of the geomagnetic field with approximately 85% of the sample sets showing an α_{95} error of 4° or less. Less than 5° is generally considered to be suitable for dating. The low scatter reflects the homogeneity of burning across each sampled horizon and the success of sampling and measurement methods. Figure 15.3 shows the significantly increased quantity of data for the Neolithic in Britain. Prior to our work at the Ness of Brodgar only five data points existed for the period 4000-2000 BC. Following this study, there is an almost tenfold increase in dated measurements of the past geomagnetic field.

Whilst the new data are all within the ranges expected for the past geomagnetic field, it is clear that there are significant differences between them and the current calibration curve.[18] This is not due to imperfections in the new data but arises from the fact that the existing



15.3 Comparison of current UK calibration curve ARCH-UK.1 with previous data (red) and new data produced from the Ness of Brodgar (blue). All archaeomagnetic data has been re-located to Meriden (52.43° N, -1.62° E) following Noel and Batt.[19] Errors for declination and inclination are at 95% confidence and errors in time are derived from the independent dating evidence



15.4 a. Model for the radiocarbon dates for Hearth Group 6309, Structure 8; *b.* The Lambert projection shows secular variation through the five fired layers from Hearth Group 6309, Structure 8 (in blue). The magnetic directions are linked in stratigraphic order NOB27-NOB31, with associated α_{95} error. Dates are given as mid-point of radiocarbon ranges from 15.4a. Also shown (in red) is the UK secular variation curve with date midpoints at 500-year intervals

calibration curve is based on so few points. Calibration curves are always limited by the quantity and quality of the data used to create them, underlining why this study is critical in the development of archaeomagnetic studies in the UK. The next step in this research is to integrate the new data into a revised calibration curve to produce an updated version for use in dating other Neolithic sites.

The multi-layered hearths are particularly important; they show that the geomagnetic field changed considerably over the time that they were used. This is invaluable for developing our understanding of past secular variation. By bringing the archaeomagnetic study together with the radiocarbon dating of associated material, it is possible to look at detailed changes in the geomagnetic field.

One of the multi-layered hearths from site shows how archaeomagnetic study will aid future dating by direction. Hearth Group 6309 in Structure 8 contains five distinct layers of fired material (NOB 27, 28, 29, 30, and 31). By bringing together the stratigraphy for the hearth and three radiocarbon dates acquired as part of the targeted radiocarbon dating programme, within a Bayesian framework, date ranges can be assigned to each fired horizon, assuming an even distribution over time *(Fig. 15.4a)*. This provides the independent dating evidence necessary for incorporating the archaeomagnetic directions into future archaeomagnetic calibration curves and shows the longevity of some of these multi-layered hearths. Hearth Group 6309 could potentially have been in use for as long as 200-300 years. Each fired layer was found to reliably record the geomagnetic field from when it was last heated and in combination, they show how the geomagnetic field varied over the lifespan of the hearth *(Fig. 15.4b)*. Crucially, the secular variation through the lifetime of the hearth is larger than the errors associated with the individual archaeomagnetic directions and the independent dates show a reasonable match with current knowledge of secular variation.

Our archaeodirectional studies have had a major impact on archaeomagnetic dating in the British Isles, significantly increasing the number of data points for the Neolithic. The development of the next calibration curve will reflect the variations observed at the Ness of Brodgar and allow archaeomagnetic dating to be applied on other Neolithic sites in the UK. The analysis of multi-layered hearths has brought new insights on their ability to reflect short term variations in the geomagnetic field. The excavation of earlier structures, beneath those currently exposed, will allow us to expand our dataset in future seasons.

Archaeomagnetic dating by intensity

In the UK, the focus of archaeomagnetic dating has been on direction (*i.e.* utilising measurements of inclination and declination, as described above). However, a major disadvantage to this technique is that the material must be *in situ* when sampled, which limits investigation to features such as hearths and kilns. Investigating the past intensity of the field (archaeointensity) becomes an important method, as it is based on the magnitude (strength) of the past geomagnetic field, rather than the direction, and can be applied to archaeological materials that are no longer *in situ*. A site such as the Ness of Brodgar, with a plethora of pottery finds and independent dating evidence, offers considerable potential to incorporate this material into the archaeomagnetic history of the site. Archaeointensity can also be a useful method for other sites that do not have burnt *in situ* features preserved.

At present, archaeointensity work at the Ness of Brodgar, and indeed across the rest of the UK, is limited to pilot studies. An overview of the Ness of Brodgar pilot study is covered here.[20] The aim of the project was to see if the Neolithic pottery from the Ness was suitable for archaeointensity experiments (which is more rigorous and time consuming than archaeodirectional work), and if they provided acceptable results, to improve the approach in the UK.

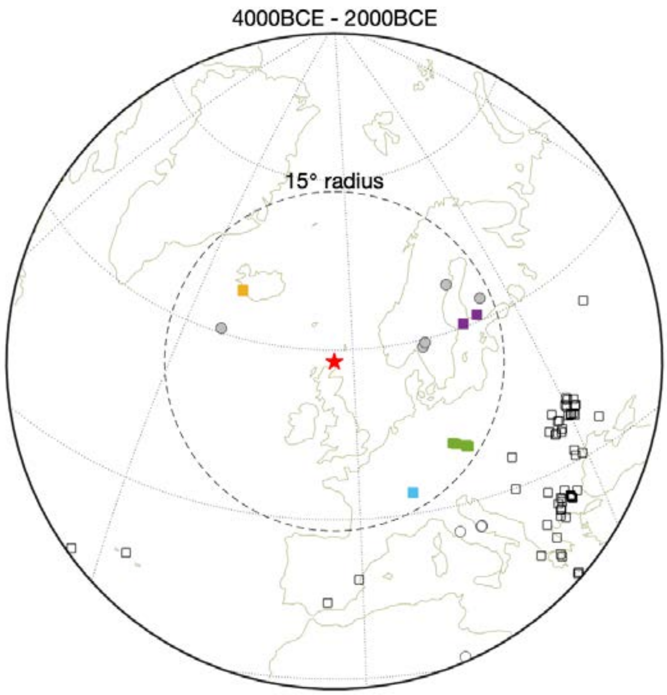
Twenty-five pottery sherds of known date were taken from a selection of contexts and structures. All samples were excavated between 2010 and 2015 and five of them have directly associated radiocarbon dates, produced from organic residues on the pottery as part of the *Times of Their Lives* project.[21]

Archaeointensity experiments aim to produce an estimate of the strength of the geomagnetic field when an archaeological material acquired its thermoremanent magnetisation (TRM).[22] The ancient TRM is removed in steps and a new TRM is applied simultaneously in the laboratory. The laboratory temperature steps and the field strength are both selected prior to the start of the experiment. The ratios of the two TRMs are indicative of the ancient field.[23] To remove the ancient TRM, the sample must be demagnetised; this process requires an input of energy into the sample. Thermal energy is generally used, as was the case in this pilot study. The experiment was undertaken with a Magnetic Moments Thermal Demagnetiser (an oven where the temperature can be precisely set, and a magnetic field applied inside) as the demagnetiser/remagnetiser. An AGICO JR6 spinner magnetometer was used as the magnetometer.

Alongside the archaeointensity experiments, an investigation into magnetic mineralogy composition was also undertaken. Understanding magnetic mineralogy is important for archaeointensity experiments, as it can help indicate how the magnetisation of a sample is carried, the magnetic grain size and type (*e.g.* magnetite and haematite) and whether the sample has undergone significant alteration since its original heating. If there has been alteration, the magnetic intensity recovered from the sample may not be representative of the magnetisation obtained during the pottery's original firing.

Similar magnetic mineralogy results were obtained for all sherds analysed, which suggest that the magnetic mineralogy is predominantly titanomagnetite. At lower temperatures (under 300 °C), there is a transformation to a higher magnetisation mineral. There is also evidence for alteration at high temperature (above 600 °C) to a less magnetic phase such as oxidation of magnetite to haematite. These results suggest that alteration is widespread, which can affect the success of archaeointensity experiments. This is reflected in the 18% success rate (three samples) of the experiments in obtaining an archaeointensity estimate.

The successful archaeointensity results have an average of 38.4 μT ± 1.6 μT, which is consistent with the limited European archaeointensity data and geomagnetic field model predictions from the same time period. There is one archaeointensity dating curve constructed for the UK, ARCH-UK.1.[24] This is an archaeomagnetic field model created specifically for UK magnetic studies, in which more weight is placed on UK data (from latitudes 49° N to 61° N and longitudes of 11° W and 2° E) during the modelling process. These new results fall just outside the range of this model, but this just highlights the sparsity of data upon which the model is based. For instance, there are fewer than 20 archaeointensity estimates for the Neolithic (4000-2000 BC) within a 1666 km radius from the Ness of Brodgar *(Fig. 15.5)*. This highlights the need for more European countries to begin archaeointensity investigations.



15.5 The location of archaeointensity and sedimentary samples from Geomagia50.v3.3 during the Neolithic period 4000-2000 BC [25]

These three archaeointensity estimates are important as they are the first measured in the UK for the Neolithic period and provide a solid basis for the further development of archaeointensity dating in Britain. This pilot study also shows how to improve success rates of experiments from Ness of Brodgar pottery in the future, by initial screening of samples and selecting those showing minimal alteration for archaeointensity experiments.

Resource exploitation

Fire is used to provide heat and light, to prepare food, and to produce items. Every society has utilized fire, and by default fuels. According to Picornell-Gelabert and Servera-Vives,[26] fuel is fundamental to subsistence activities among human societies; the gathering of fuel in the landscape and consumption within domestic spaces being core components of social practice. As population and fuel needs increase, so does the industry of fuel collection.[27]

Fuel collection can range from gathering dead branches and forest litter, to felling trees in large quantity or large-scale peat cutting operations that can significantly alter the landscape.[28] Fuel is needed year-round regardless of climate, yet harsher and more extreme climates, like Orkney, create higher demands for fuel, as more fire is needed to counteract colder, damper, or darker conditions.[29] Different fuels are suitable for different purposes: for example, peat can reach higher temperatures than wood or dung fuels, while wood fuel produces more light.[30] According to Rotherham,[31] the expenditure of fuel for pottery production, tool manufacturing, and food preparation increases with the status and size of a site; however, the fuel needs of a given population can outgrow what the local environment can sustain, forcing people to travel further to find fuel. The over-exploitation of fuel resources can ultimately lead to the failure of an occupation site.[32]

The manipulation of fire allowed humans to implement land management practices such as slash and burn agriculture, to modify materials including hardening wood for spears by removing moisture or annealing stone to aid in knapping, and to produce iron, pottery, glass, and ceramics.[33] Based on the assemblage of artefacts from the Ness of Brodgar it is known that pottery was being produced (typical temperatures required would be 400 °C or over), food was being prepared (approx. 200 °C), and stone was being fashioned into tools and weapons (400 °C for annealing) during the Neolithic.[34]

Analysis at Ness of Brodgar

The use of modern analogue ash material as a comparative dataset to aid in the identification of archaeological fuels can offer insight into what heating temperatures were obtained and which type of fuel was being used to sustain fires. Griffin developed a method to identify fuels and provide an insight into connections between activities on a site and the wider environment.[35] Modern analogue ash was produced from several cuts of peat, driftwood, seaweed, grasses, heather, willow, hazel, cattle dung, sheep dung, and animal bone, which were heated to 200 °C, 400 °C, and 900 °C. The modern analogue ash and the archaeological samples were analysed using magnetic susceptibility, scanning electron microscopy with energy dispersive X-ray spectroscopy, pH, and Munsell colour assignment.

The Ness of Brodgar fuel analysis was a small part of wider research. In this study, 24 samples were taken from hearths and ash dumps in Structures 7, 8, 12, 14, and 19 and middens in Trench T. These were compared with modern analogues using principal components analysis of the parameters measured. The most common fuel match is peat heated to higher temperatures, with only two samples matching to wood heated to 200 °C and no other fuels identified. The higher heating temperatures

(>400 °C) could indicate production using heat, possibly linked to the multiple pottery finds from the site.[36] The hearth material matching wood (willow) heated to 200 °C could indicate a fire used solely for cooking represented by one burnt horizon within the hearth.

In addition to the hearth sample, there is one ash dump sample that also matches the low temperature ash from modern analogue willow heated to 200 °C. The Ness of Brodgar samples suggest that wood was in limited use in the later deposits within Structure 19 and a later layer in Hearth 6039 from Structure 8, but peat is the only fuel identified in the earlier deposits *(Fig. 15.6)*. This sporadic use of wood fuel could show the decline in woodland vegetation causing the transition to primarily peat fuels as woodlands became depleted.

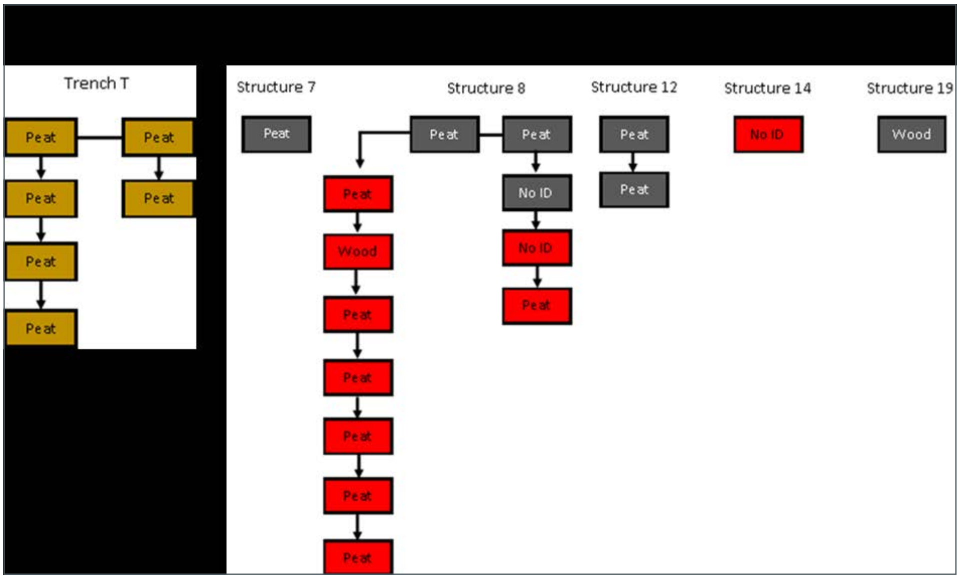
Among the Ness of Brodgar material, there are 9 samples from the same western hearth in Structure 8 *(Fig. 15.6)*. Within the stratigraphic sequence of this hearth, the upper horizon is unidentifiable, one horizon in the sequence matches to willow heated to 200 °C, but all other samples match peat fuels heated to higher temperatures. As 78% of the samples match peat, the change in fuel use for two horizons might indicate a change in fuel use specifically for a heating activity requiring different fuels and heating temperatures, or the use of alternative fuels in times of scarcity.

The absence of evidence for other fuels may reflect their less frequent use and / or the limited number of contexts sampled. Throughout the Neolithic, when community identities were increasingly being given material expression, it is interesting to note that a fuel like peat appears to be predominant.[37] Peat requires a community effort to accumulate sufficient amounts and prepare it for burning, as woodland resources grow scarcer throughout the Neolithic.[38]

Future potential

Magnetic studies at the Ness of Brodgar have been very fruitful to date, yielding the largest collection of archaeomagnetic directions from any Neolithic site in Europe, the first archaeointensity measurement on British Neolithic pottery, and insights into use of fuels over time. As excavations continue, more information will be added to these already extensive datasets. These results have implications beyond the site; suggesting methodological developments, offering the potential to improve archaeomagnetic dating throughout the British Neolithic, and contributing the data needed to understand the origin and behaviour of the earth's magnetic field.

Future studies may be expanded to include the use of methods such as analysis of magnetic mineralogy, to identify activities within structures or to source magnetic materials such as pumice. However, the most exciting phase of the research lies ahead; the integration of the data from the magnetic studies with other investigations on the site, including radiocarbon, soil micromorphology, chemical analysis and the artefactual evidence.



15.6 Harris matrix showing modern fuel matches and indicating sample type. Red for hearth, dark grey for ash dump/hearth rake out, and brown for midden[39]

In combination, these will provide even greater insight into the chronology, resource exploitation and use of space in this remarkable site.

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Chapter 16 The rocks that don't belong

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Chapter 17 The Ness of Brodgar flaked stone assemblage: 2004-2018

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