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Supplementary Information for

MEGALITHS IN EUROPE: NEW EVIDENCE FROM RADIOCARBON DATING AND BAYESIAN MODELLING SUPPORT MARITIME DIFFUSION MODEL

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This PDF file includes:

Supplementary text
Figs. S1 to S2
References for SI reference citations

Other supplementary materials for this manuscript include the following:

Datasets S1 to S4

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Supporting Information Appendix (SI Appendix)

1 Materials

The list in dataset S1 shows the 2410 radiocarbon dates used to construct the chronology/scenario outlined in the paper including detail information for region, site, architecture, $\delta^{13}C$ values, $\delta^{15}N$ values, material, supplementary material information, context classification and source. The majority of these results are compiled from the research literature over the past decade from across Europe. Further sources include the available internet databases for Scotland and results from the radiocarbon laboratories in Lyon, Catalonia, Central Europe and Scandinavia (*1*).

The radiocarbon dates are sorted according to stratigraphic context and quality. We analyzed the correlation of the measurements of the archaeological remains and considered each item of data together with the contexts of the site as comprising the total data for each location. Radiocarbon dating samples, without contexts (*2*), as well as many of those currently available and considered for this analysis, represent *termini post quos* values for the construction of the megaliths. These radiocarbon dates are older than the monuments, as they originate from earlier pre-megalithic structures. The construction of a megalith intrudes into the ground, and during building activities material like charcoal, ceramics, and bones from layers under the grave may merge with the chamber or the mound (*Fig.S1*). Consequently, it was important to divide the data into *termini post quos* and *termini ante quos* values. *Termini post quos* values for the construction of the graves date pre-megalithic contexts, i.e. settlement layers under the grave, which are mostly independent from the grave-building event itself. *Termini ante quos* dates represent the use of the grave and are determined using human bones, grave goods, and samples from burial activities or other rituals around the grave. Only very few samples are directly associated with the construction of megalithic structures, such as birch bark used as a filling material between the slabs of dry walls in Danish passage graves (*3)* or deer antler which can be associated with construction and digging activities (*e.g. 4*). It was necessary for this analysis to evaluate each sample according to its context. Sorting the data was often only possible by means of a critical consideration of the sample contexts and their correlation with the archaeological remains. Radiocarbon dates obtained from charcoal from the mound filling were not discarded *a priori*, but considered together with other available results and the archaeological material from the chambers and the stratigraphical sequences of the sites, e.g. from possible pre-megalithic activities. While it is more plausible that human bones and the material within the chambers are associated to the burial activities and the graves, charcoal often originated from other pre-megalithic or surrounding activities. A far greater number than expected of the radiocarbon dates had no association with the construction or the use of the megaliths. 31% of all the charcoal samples considered in this analysis represent *terminus post quem values.* This amount is rather high, if we take into consideration that just a handful of these data can lead to complete misinterpretations regarding the beginning of a period or the emergence of megaliths. Especially problematic in this category were regions with little or no bone preservation, where it was necessary to depend instead mostly on charcoal samples, as was the case in in Brittany and the Northwest Iberian Peninsula. For Brittany, 41% of the charcoal samples with known context could be classified as *terminus post quem*-values.

The quality of the samples and radiocarbon dates was another factor to be considered. Several of the sample materials used are scientifically problematic. Charcoal and wood samples have the possibility of an inbuilt age and we took, as far as possible, available wood identification into consideration. Reservoir effects occur when the carbon that is incorporated into a sample during life is not in equilibrium with the contemporary atmosphere. Human material can be enriched with older carbon if marine or riverine components were an important part of the diet. We considered, as far as available, measurements of the stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) in the bone collagen in order to obtain information on the protein component of the diet and thereby to determine a possible reservoir effect on the radiocarbon results. The values for the megalithic population in all parts of Europe indicate a mainly terrestrial diet and there is no clear evidence for reservoir effects on human bones.

The largest portion of the 2410 radiocarbon results considered were obtained as 1065 samples from human bones. Most of them are uncalcined and only 19 samples derive from cremated bone material. 82 of the samples are animal bones or antlers. 51 are undetermined. 944 samples were taken from charcoal; 34 of those from charred plant remains, 36 are non-charred bark, wood or grass samples. 16 bulk sediment, sediment or peat samples are also available. The remaining 18 samples were taken from organic residue, humic acid, sea shell, ceramic or mixed material. From 164 samples, which are primarily measurements from the early days of radiocarbon dating, no information on the material is available. In the study presented here, 40 AMS measurements are highly accurate with a standard deviation between ±0 to ±25, whereas 947 determinations show a standard deviation between ±25 and ±50. 422 radiocarbon results have a standard error between ±100 and ±450, most of which were made in the early days of radiocarbon dating; these were considered with restrictions. Their significance is limited.

2 Methods
2.1 Bayesian approach

For this analysis with radiocarbon dates from regions across all of Europe, we adopted a Bayesian approach, which is applied here for a first time for such a wide geographical scope. The methodology of Bayesian chronological modeling has been discussed in detail in previous years in different publications (*cf. 5-16*) and will be presented here with reference to its main facets. The Bayesian statistical framework provides the possibility to considerably limit the proposed time interval for desired calendar dates, and it is possible to unify radiocarbon results, archaeological information, and the high precision curve into one calibration process. All the models and calibrated data presented in this analysis have been performed with the help of the program OxCal v4.1 (*5-6, 15-16*) and the calibration data of Reimer et al. (2009), Intcal09 (*17*). The program OxCal can accomplish automatic wiggle matches and calculate probability distributions for samples in sequences and phases (*12*). For the Bayesian approach, the models had to be defined first in OxCal in sequences and phases with the help of all available information from the sites, such as the vertical or horizontal stratigraphy. Depending on the problems or questions that arose, boundaries were determined and incorporated into the model structure. The program first calculates the probability distribution of each radiocarbon result and then attempts to reconcile this information by a repeated sampling of the distribution of these dates with the information previously determined. Thus, it builds up a set of solutions consistent with the structure of the model (*5, 11, 17*). For the available 2410 radiocarbon dates, the Bayesian approach was applied as much as possible. For each site with available radiocarbon results and a suitable sequence, we constructed one-phased or multi-phased models with phase boundaries with up to 27 radiocarbon dates. The stratigraphical arguments required for establishing the Bayesian models are described in detail in Schulz Paulsson (2017) (*18*). We limited the moment of construction either by the phase boundaries between the pre-megalithic and the phase of use or by the boundaries constraining the phase of burial activities or use of the megaliths. Our work in this area was concentrated on continental Europe and the Mediterranean. For northern Europe results from previous Bayesian approaches were available (*19-21*), which are cited in the text. By mapping the outcomes it was possible to reconstruct a scenario for the emergence and spreading of megaliths in Europe (*Figs.3–5*). The posterior beliefs are expressed as probability distributions known as 'posterior density estimates' and they are always given in *italics.*

2.2 OxCal model details and outputs

The datasets S2 and S3 provide the OxCal model details and outputs for the Bayesian statistical framework of the analysis. OxCal´s chronological query language (CQL) was defined in Bronk Ramsey (2009/2009a) (*5-6*) and the model specifications are presented in this form. Dataset S3 with the model outcomes includes the un-modelled and modelled calibrated ranges in their 68.2% and 95.4% probability. In order to test for unreliable chronological models or intrusive material, the agreement index A is calculated to exclude inconsistencies from a model. This has a value of ~100%, sometimes it is higher and it can fall down to 60%. The agreement index A overall is calculated as a whole for the model, which is likewise ~100%, it should not fall below 60%. These two indices represent a threshold value analogue to the 0.05 significance level in a χ^2-test. Furthermore, a posterior outlier probability is calculated for each of the radiocarbon dates in the models and represented with the model outcomes in dataset S3.

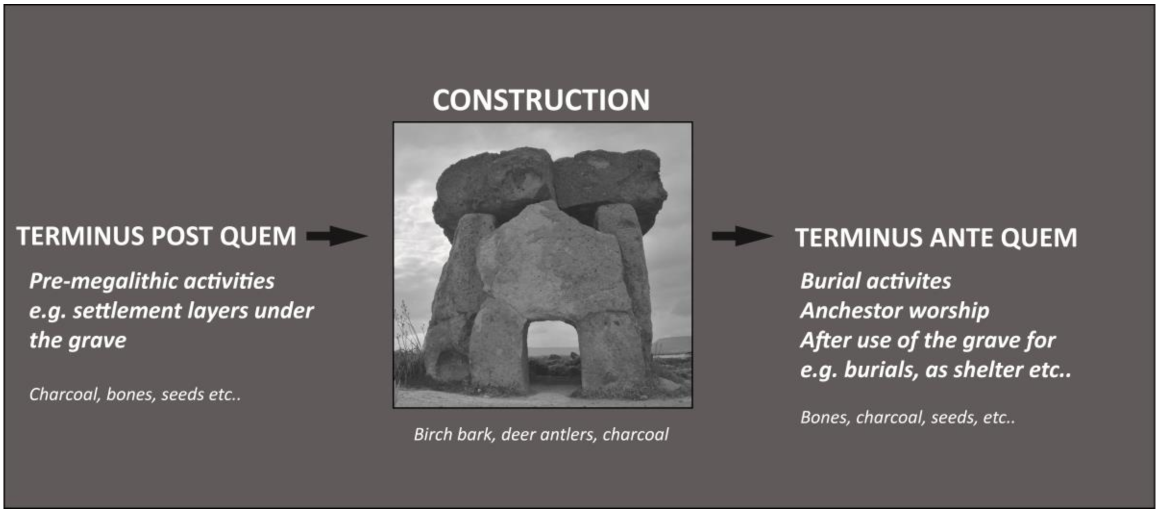

Fig. S1 *Classification of sample contexts.*

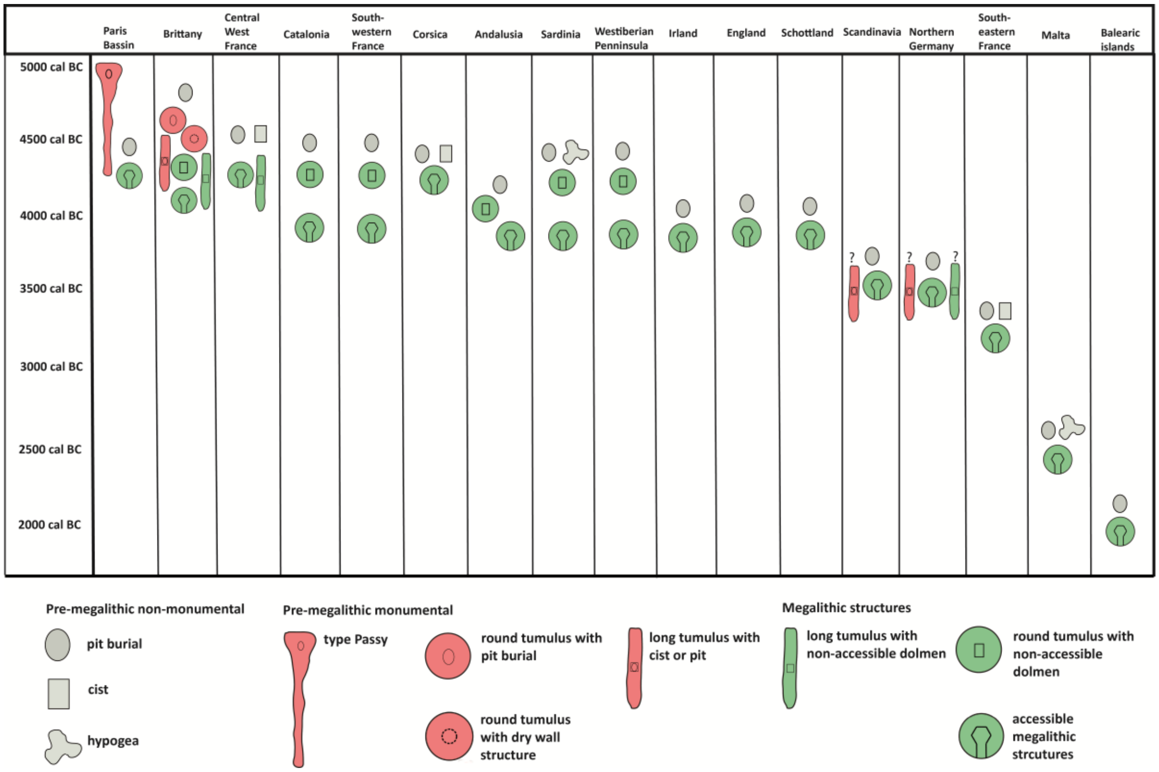

Fig. S2 *The emergence of monumental and megalithic grave architecture by region.*

Additional datasets S1-S4 (separate files)

Dataset S1 Database with 2410 radiocarbon dates (excel file)

Dataset S2 The OxCal model details (Pdf).

Dataset S3 The OxCal model outputs (excel file).

Dataset S4 References dataset S1 (Pdf).

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