

Authors:

Kevan Edinborough, Stephen Shennan*, Anne Teather, Jon Baczkowski, Andy Bevan, Richard Bradley, Gordon Cook, Tim Kerig, Mike Parker Pearson, Alexander Pope, Peter Schauer.

* Corresponding author

Title: New radiocarbon dates show Early Neolithic date of flint-mining and stone quarrying in Britain.

Keywords: Radiocarbon, Neolithic, Flint mines, Quarries, Axe production, Boom-bust economics, Great Britain.

Abstract

New radiocarbon dates suggest a simultaneous appearance of two technologically and geographically distinct axe production practices in Neolithic Britain; igneous open-air quarries in Great Langdale, Cumbria, and from flint mines in southern England at ~4000-3700 cal BC. In light of the recent evidence that farming was introduced at this time by large-scale immigration from northwest Europe, and that expansion within Britain was extremely rapid, we argue that this synchronicity supports this speed of colonisation and reflects a knowledge of complex extraction processes and associated exchange networks already possessed by the immigrant groups. Although we can model the start of these new extraction activities, it remains difficult to estimate how long significant production activity lasted at these key sites given the nature of the record from which samples could be obtained.

Significance statement: New radiocarbon dates show that the extraction of high-quality rock material from both the Great Langdale igneous hard-stone quarries in the North-west of England and the flint mines of the South Downs and Wessex started simultaneously around 4000-3700 cal BC. Our results suggest that large-scale quarry and mine production emerged in Great Britain far more abruptly than previously thought, simultaneously with the arrival of immigrant farmers, and that long-range connections developed as colonisation rapidly expanded.

Introduction: Project Background

Introduction

In this paper we present new radiocarbon dates from Neolithic mines and quarries in Britain. These have been generated through the collaborative research efforts of the authors, and primarily funded by the Leverhulme Trust as part of the project “Supply and demand in prehistory? Economics of Neolithic mining in NW Europe”. This project aimed to address the question of what economic factors, if any, influenced the scale of mining and quarrying in the Neolithic. There is no doubt that many of these sites were large and there was a huge quantity of raw material extracted, however chronological sensitivity has been very weak until now. Obtaining a reliable measure of the period of use of individual mines and quarries is critical to determining whether particular extraction sites were exploited contemporaneously or concurrently, which can then allow for further inferences to be made relating to factors that potentially affected extraction activity, such as demand generated by local or regional population levels (Schauer et al. submitted).

In this paper we present some surprisingly consistent results based on a collation of all existing dates and a programme of systematic re-dating of excavated mines and quarries in Great Britain. This addresses two key questions. First, is there any dating evidence that mining began in the late Mesolithic, before the arrival of farming? Secondly, are there systematic patterns in the dates of flint-mining and stone quarrying in Britain or are the dates randomly distributed in time through the Neolithic? This has a bearing on whether all mines were producing at the same time, perhaps because they were all responding to a period of high regional demand; or whether they went in and out of use successively, perhaps because new sources were discovered and/or working conditions at existing mines became increasingly difficult. Thus our primary question is when did extraction begin at these different sites, and how long did it last?

Flint mining was a widespread European prehistoric phenomenon demonstrated from archaeological excavations at mining sites from Britain to Poland and Sweden to southern Italy. The mines are located predominantly on primary flint-bearing geology where the flint is laid down as horizontal seams within the chalk or limestone bedrock, in tabular or nodular form (Weisgerber 1987). These mines exhibit a method of extracting flint by either quarrying or using a system of vertical and horizontal shafts. In general terms chronologies for flint mining have been broad, with a reliance on historic radiocarbon dates. The start of the main phases of mining in northern Europe had been estimated at c. 4500-4200 cal BC (Whittle et al 2011, 257-262) although mines in Italy and Spain date back to the 6th millennium BC

(Tarantini et al 2011, 257; Díaz-del-Río et al, 2010). It has long been conjectured that the flint extracted from mines was used to manufacture axes for forest clearance during the primary phase of land cultivation, a view which seems to be increasingly supported through new dates on the beginnings of agriculture (e.g. for Scandinavia, Sørensen and Karg 2014).

In Britain, as elsewhere, the radiometric dating of mines and quarries has been uneven. Until these projects commenced, there were only a total of 20 radiocarbon dates for seven of the early Neolithic mining sites in southern Britain, that indicated mining activity from possibly as early as 4500 cal BC at Cissbury, Sussex, to as late as 2700 cal BC at Easton Down, Wiltshire (Holgate 1991, 39-40; 1995, 141-50; Barber et al 1999, 81-2; Russell 2000, 55-6). Bayesian modelling of these dates for the start of mining activity were suggested for Cissbury to be 4600-3705 cal BC and Harrow Hill 4250-3705 cal BC (Whittle et al. 2011, 256) and so extremely early in the Neolithic sequence of southern England. Over half (four of the seven) of the flint mining sites were represented by single radiocarbon determinations and there were additionally concerns regarding the quality of some of the earlier samples (Barber et al 1999, 68-9; Russell 2000, 55-6). Thus, re-dating these sites has great potential to provide new data on the spread of Neolithic technologies from the continent (Baczkowski 2014), and to address the project's questions. In contrast, the Late Neolithic site of Grime's Graves has been extensively studied, repeatedly excavated and subjected to detailed analyses. A recently-completed programme of re-dating artefacts has produced 305 radiocarbon determinations (256 individual contexts) for the mining phases and subsequent Bronze Age activity at Grime's Graves (Healy et al. 2018; 2014, 16). This has resulted in a detailed understanding of the chronology of the site and has narrowed the estimated duration of mining activity at Grimes Graves to 2665 cal BC to 2360 cal BC (Healy et al. 2014, 55).

Dateable organics from chalk mining sites excavated in the last century and a half are ubiquitous, however the accompanying archives or early curation of materials are not always robust enough to identify individual samples to the level of individual stratigraphic context. Where organic, dateable samples relating directly to mining activities are well-preserved, for instance antler picks left or deposited in situ at the work face (e.g., Holgate 1995, 154-5; Russell 2000, 84-92; Barber et al 1999, 66-7; Healy et al. 2014; Berggren 2016), collagen yields for dating can often be too low for radiocarbon laboratories to measure despite many pre-treatment advances over the last decades. For quarrying sites, organic materials are rare, and are often poorly preserved. There are a small number of human remains in the European mines (Barber et al 1999, 62-3; Russell 2000, 128-32; Collet 2006) but they may represent later intrusions into the original depositional sequence, like the Iron Age burials in

the 1971 Pit at Grime's Graves (Healy et al. 2014, 63). In short, precision radiocarbon dating of lithic extraction horizons requires robust archives, is expensive and can be unsuccessful. Quarrying sites have also only received scant attention in establishing chronologies. Although more quarry sites have been identified and excavated over the past 30 years, it has been common for only a few dates to be generated from excavated material, largely due to post-excavation costs. Combining research efforts has allowed more dates to be generated in this project to gain a better understanding of the chronology of extraction.

Finally, extraction sites often contain mixed deposits from repeated use in the prehistoric or historic periods that may be unrelated to mining activities, which are therefore intrinsically challenging to sequence accurately. Furthermore, underground mining tunnels connect and may have been accessed at a temporally later time than the accompanying vertical shaft. Thus, it is very difficult to achieve fine grained chronological resolution within sites (Healy et al. 2014), as the stratigraphy is confined to individual discrete pits that rarely overlap. We have negated this issue somewhat by dating shaft fills that do provide stratigraphic information, though this therefore restricts the ability for inter-site comparisons without further dating work. Half the new dated samples were identified by one of the authors (AT) during her doctoral and postdoctoral research; nine of these were dated as part of the NEOMINE project and the remaining ten by the NERC-AHRC National Radiocarbon Facility as part of another project (see Teather in press).

Materials and methods

Samples

New samples from the following areas and sites were dated (for full details see SI).



Figure 1. Left panel: Schematic reference map of sites in Great Britain and Ireland mentioned in text. 1 Great Langdale; 2 Black Patch Hill; 3 Church Hill; 4 Cissbury; 5 Long Down; 6 New Barn Down; 7 Harrow Hill; 8 Martin's Clump; 9 Easton Down; 10 Grime's Graves; 11 Mynydd Rhiw East; 12 Graig Lwyd; 13 Lambay Island; 14 Tievebulliagh. Base map photo by "Unknown Author" is licensed under CC BY-NC. For a detailed map of site locations and other mines and quarries, see Bradley and Edmonds 1993 and Neomine project website <http://www.ucl.ac.uk/neomine/maps> Right panel: Broken wooden haft with Neolithic axe from Cumbria, Ehenside Tarn near Whitehaven; POA.190.6. AN753777001 image released by British Museum under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) license.

Site	Sample	Species	Lab Code	¹⁴ C age (years BP)	Error (1σ)	δ ¹³ C (‰)	δ ¹⁵ N (‰)	C/N rasion (Molar)	Context	Reference
Blackpatch	Antler	<i>Cervus elaphus</i>	OxA-35921	5060	33	-22.19	N/A	N/A	Shaft 1 Layer 13, excavated by John Pull 1922-4, with the assistance of the Worthing Archaeological Society between 1922-4 and proved to be 3.4m deep and 5.2m in diameter with seven galleries at the base	Teather, A; Goodman et al. 1924, 73; Pull 1932, 34-40; Russell 2001a, 27-34
Blackpatch	Bone	<i>Equus</i> sp.	OxA-35916**	2114	27	-23.02	N/A	N/A	Shaft 1 Layer 1, excavated by John Pull 1922-4, with the assistance of the Worthing Archaeological Society between 1922-4 and proved to be 3.4m deep and 5.2m in diameter with seven galleries at the base	Teather, A; Goodman et al. 1924, 73; Pull 1932, 34-40; Russell 2001a, 27-34
Blackpatch	Bone	<i>Equus</i> sp.	OxA-35917**	2076	27	-22.91	N/A	N/A	Shaft 1 Layer 1, excavated by John Pull 1922-4, with the assistance of the Worthing Archaeological Society between 1922-4 and proved to be 3.4m deep and 5.2m in diameter with seven galleries at the base	Teather, A; Goodman et al. 1924, 73; Pull 1932, 34-40; Russell 2001a, 27-34
Blackpatch	Antler	<i>Cervus elaphus</i>	OxA-34609	5108	31	-21.5	N/A	N/A	Shaft 1 Gallery 1, excavated by John Pull 1922-4, with the assistance of the Worthing Archaeological Society between 1922-4 and proved to be 3.4m deep and 5.2m in diameter with seven galleries at the base	Teather, A. Goodman et al. 1924, 73; Pull 1932, 34-40; Russell 2001a, 27-34
Blackpatch	Antler	<i>Cervus elaphus</i>	SUERC-78910	5128	29	-22.5	3.1	3.2	Shaft 1 Gallery 3, excavated by John Pull 1922-4, excavated by John Pull 1922-4, with the assistance of the Worthing Archaeological Society between 1922-4 and proved to be 3.4m deep and 5.2m in diameter with seven galleries at the base	Teather, A; Goodman et al. 1924, 73; Pull 1932, 34-40; Russell 2001a, 27-34

Blackpatch	Antler	<i>Cervus elaphus</i>	SUERC-78909*	5126	30	-21.4	3.1	3.2	Shaft 1 Gallery 3, excavated by John Pull 1922-4, with the assistance of the Worthing Archaeological Society between 1922-4 and proved to be 3.4m deep and 5.2m in diameter with seven galleries at the base	Teather, A; Goodman et al. 1924, 73
Blackpatch	Antler	<i>Cervus elaphus</i>	OxA-33963*	5474	37	-21.5	N/A	N/A	Shaft 1 Gallery 3, excavated by John Pull 1922-4, with the assistance of the Worthing Archaeological Society between 1922-4 and proved to be 3.4m deep and 5.2m in diameter with seven galleries at the base	Teather, A; Goodman et al. 1924, 73; Pull 1932, 34-40; Russell 2001a, 27-34
Blackpatch	Antler	<i>Cervus elaphus</i>	OxA-35918	5116	31	N/A	N/A	N/A	Shaft 1 Layer 3, excavated by John Pull 1922-4, with the assistance of the Worthing Archaeological Society between 1922-4 and proved to be 3.4m deep and 5.2m in diameter with seven galleries at the base	Teather, A; Goodman et al. 1924, 73; Pull 1932, 34-40; Russell 2001a, 27-34
Blackpatch	Antler	<i>Cervus elaphus</i>	OxA-35919	5127	33	N/A	N/A	N/A	Shaft 1 Layer 8, excavated by John Pull 1922-4, excavated by John Pull 1922-4, with the assistance of the Worthing Archaeological Society between 1922-4 and proved to be 3.4m deep and 5.2m in diameter with seven galleries at the base	Teather, A; Goodman et al. 1924, 73; Pull 1932, 34-40; Russell 2001a, 27-34
Blackpatch	Antler	<i>Cervus elaphus</i>	OxA-35920	5133	32	N/A	N/A	N/A	Shaft 1 Layer 12, excavated by John Pull 1922-4, with the assistance of the Worthing Archaeological Society between 1922-4 and proved to be 3.4m deep and 5.2m in diameter with seven galleries at the base	Teather, A; Goodman et al. 1924, 73; Pull 1932, 34-40; Russell 2001a, 27-34

Blackpatch	Antler	<i>Cervus elaphus</i>	OxA-33929	5094	38	-23.5	N/A	N/A	Shaft 1 Gallery 6, excavated by John Pull 1922-4, with the assistance of the Worthing Archaeological Society between 1922-4 and proved to be 3.4m deep and 5.2m in diameter with seven galleries at the base	Teather, A; Goodman et al. 1924, 73; Pull 1932, 34-40; Russell 2001a, 27-34
Church Hill	Bone	<i>Microtus agrestis</i>	OxA-34681	3639	29	-21.6	N/A	N/A	Shaft 4 Gallery X, excavated by John Pull between 1946-1948, Shaft 4 was 16 feet in diameter, with a 12 foot diameter base, 16.5 feet deep, with four horizontal flint seams. The galleries were 3-4 foot high, 4-7 foot in width, and up to 30 feet long	Teather, A; Russell 2001a, 94-102
Church Hill	Animal tooth	<i>Sus scrofa</i>	SUERC-75315	3940	34	-23.1	6.6	3.4	Shaft 4, 4 ft, excavated by John Pull between 1946-1948, Shaft 4 was 16 feet in diameter, with a 12 foot diameter base, 16.5 feet deep, with four horizontal flint seams. The galleries were 3-4 foot high, 4-7 foot in width, and up to 30 feet long	Teather, A; Russell 2001a, 94-102
Church Hill	Wood	Poplar	SUERC-75316	3521	34	-27	N/A	N/A	Shaft 4 Layer 6, excavated by John Pull between 1946-1948, Shaft 4 was 16 feet in diameter, with a 12 foot diameter base, 16.5 feet deep, with four horizontal flint seams. The galleries were 3-4 foot high, 4-7 foot in width, and up to 30 feet long	Teather, A; Russell 2001a, 94-102
Cissbury	Tooth	<i>Homo sapiens</i>	OxA-34470	4775	34	-20.6	N/A	N/A	Shaft 27 G1, 15 feet (Layer 10) excavated by John Pull in 1953, stratigraphy for this shaft is well recorded and the selected samples are reliably contextualized	Teather, A; Russell 2001a, 178-89

Cissbury	Antler	<i>Cervus elaphus</i>	SUERC-75324	5027	34	-24	6.5	3.4	Shaft 27, 12 feet (Layer 8) excavated by John Pull in 1953, stratigraphy for this shaft is well recorded and the selected samples are reliably contextualized	Teather, A; Russell 2001a, 94-102
Cissbury	Ox Bone	<i>Bos sp.</i>	SUERC-75317****	4688	34	-22.9	5.8	3.3	Shaft 27, 11 feet (Layer 8) excavated by John Pull in 1953, stratigraphy for this shaft is well recorded and the selected samples are reliably contextualized	Teather, A; Russell 2001a, 94-102
Cissbury	Ox Bone	<i>Bos sp.</i>	SUERC-75318****	4659	34	-22.8	6	3.3	Shaft 27, 11 feet (Layer 8) excavated by John Pull in 1953, stratigraphy for this shaft is well recorded and the selected samples are reliably contextualized	Teather, A; Russell 2001a, 94-102
Cissbury	Antler	<i>Cervus elaphus</i>	SUERC-75319	4613	34	-22.1	5.1	3.4	Shaft 27 (?), c.3 ft (Layer 3) excavated by John Pull in 1953	Teather, A; Russell 2001a, 94-102
Cissbury	Bone	? <i>Cervus elaphus</i>	SUERC-75323	4583	34	-22.6	6.5	3.4	Shaft 27, 3ft (Layer 3)	Teather, A; Russell 2001a, 94-102

Easton Down	Bone	?Aurochs	SUERC-68376	5176	43	-22.6	3.8	3.3	Sampled from central beam of broken/worked antler. 1929 - 1935 Area B Excavations, The samples all came from Stone's excavation collection held at Salisbury Museum, curated by the museum's director Adrian Green. All samples were from Layer3/4, from pit B49, as identified from Stone's original excavation notes held at the museum by Alexander Pope (Stone, N.D. 159, 162)	Pope, A ; Stone 1932, 351.
Easton Down	Antler	<i>Cervus elephus</i>	SUERC-68377	5358	34	-22.9	4	3.3	Sampled from a scapula reportedly from an aurochs, where no repair glue was present to right of spinal area, 1929 - 1935 Area B Excavations, The samples all came from Stone's excavation collection held at Salisbury Museum, curated by the museum's director Adrian Green. All samples were from Layer3/4, from pit B49, as identified from Stone's original excavation notes held at the museum by Alexander Pope (Stone, N.D. 159, 162)	Pope, A; Stone 1932, 351
Easton Down	Antler	<i>Cervus elephus</i>	SUERC-68378	4948	36	-22.1	3.4	3.3	Sampled from the central beam of what appeared to be broken or worked antler, 1929 - 1935 Area B Excavations. The samples all came from Stone's excavation collection held at Salisbury Museum, curated by the museum's director Adrian Green. All samples were from Layer3/4, from pit B49, as identified from Stone's original excavation by Alexander Pope (Stone, N.D. 159, 162)	Pope, A. Stone 1932, 351

Great Langdale Stake Beck	Charcoal	<i>Salix/Populus</i> sp.	SUERC-68365	4957	34	-26.6	N/A	N/A	Sampled from context 7, within an extensive artefact scatter with possible structural evidence (sealed by blanket peat and exposed by path erosion) excavated in 1987. Sample identified by Phil Austin	Bradley and Edmonds 1993: 112
Great Langdale Loft Crag	Charcoal	<i>Betula</i> sp.	SUERC-68364	3543	34	-25.4	N/A	N/A	Sampled from context 4, excavated in 1986. This charcoal sample was obtained from a refitting knapping cluster. It was sealed by blanket peat. Sample identified by Phil Austin	Bradley and Edmonds 1993: 119.
Great Langdale Site 98	Charcoal	Nutshell	SUERC-68366	4942	34	-25.1	N/A	N/A	Spit B, comes from a carbonized nut shell from the upper filling of a surviving quarry, the contents of which were protected by overhanging rock. Sample identified by Phil Austin	Bradley and Edmonds 1993:122
Great Langdale Site 98	Charcoal	<i>Betula</i> sp.	SUERC-68367	4983	34	-26.4	N/A	N/A	Spit C, from the upper filling of a surviving quarry, the contents of which were protected by overhanging rock. Sample identified by Phil Austin	Bradley and Edmonds 1993:122

Great Langdale Site 98	Charcoal	<i>Corylus avellana</i>	SUERC-68368	5042	34	-27.5	N/A	N/A	Spit G, sample identified by Phil Austin	Bradley and Edmonds 1993:122
Great Langdale Site 98	Charcoal	<i>Betula</i> sp.	SUERC-68372	4907	34	-26.4	N/A	N/A	Spit H, sample identified by Phil Austin	Bradley and Edmonds 1993:122
Great Langdale Site 98	Charcoal	<i>Corylus avellana</i>	SUERC-68373	4936	35	-29.7	N/A	N/A	Spit I, from the lower filling of a surviving quarry, the contents of which were protected by overhanging rock. The spits were excavated in 10cm units. Sample identified by Phil Austin	Bradley and Edmonds 1993:122
Great Langdale Site 95	Charcoal	<i>Salix/Populus</i> sp.	SUERC-68374	4807	34	-26.2	N/A	N/A	Top Buttress Site 95, Spit K, from the lower filling of an artificial cave excavated to extract raw material, located on the ledge immediately above Site 98. The distinctive form of this feature protected its filling from later disturbance. Sample identified by Phil Austin	Bradley and Edmonds 1993:126

Great Langdale Site 95	Charcoal	<i>Corylus avellana</i>	SUERC-68375	4769	34	-28.3	N/A	N/A	Top Buttress Site 95, Spit K, from the lower filling of an artificial cave excavated to extract raw material, located on the ledge immediately above Site 98. The distinctive form of this feature protected its filling from later disturbance. Sample identified by Phil Austin	Bradley and Edmonds 1993: 126
Long Down	Antler	? <i>Cervus elaphus</i>	SUERC-73468	4863	32	-22.6	4.7	3	Certainly belonged to the Neolithic flint mines located at Long Down and were excavated either directly from the backfill of shafts or from associated axe production working floors, however, it was not possible to improve the provenience to these samples, due to the antiquity of original archiving of the excavated sites	Baczkowski, J.; Salisbury 1961
Long Down	Antler	? <i>Cervus elaphus</i>	SUERC-73470	4828	32	-23	6.5	3.2	Certainly belonged to the Neolithic flint mines located at Long Down and were excavated either directly from the backfill of shafts or from associated axe production working floors, however, it was not possible to improve the provenience to these samples, due to the antiquity of original archiving of the excavated sites	Baczkowski, J.; Salisbury 1961

Long Down	Antler	? <i>Cervus elaphus</i>	SUERC-73463	4681	32	-23.3	7.4	3.3	Certainly belonged to the Neolithic flint mines located at Long Down and were excavated either directly from the backfill of shafts or from associated axe production working floors, however, it was not possible to improve the provenience to these samples, due to the antiquity of original archiving of the excavated sites	Baczkowski, J; Salisbury 1961
Long Down	Antler	? <i>Cervus elaphus</i>	SUERC-73469	4544	32	-21.5	5.6	3.3	Certainly belonged to the Neolithic flint mines located at Long Down and were excavated either directly from the backfill of shafts or from associated axe production working floors, however, it was not possible to improve the provenience to these samples, due to the antiquity of original archiving of the excavated sites	Baczkowski, J; Salisbury 1961
Long Down	Antler	? <i>Cervus elaphus</i>	SUERC-73464	3493	32	-22.4	5.5	3.1	Certainly belonged to the Neolithic flint mines located at Long Down and were excavated either directly from the backfill of shafts or from associated axe production working floors, however, it was not possible to improve the provenience to these samples, due to the antiquity of original archiving of the excavated sites	Baczkowski, J; Salisbury 1961

New Barn Down	Charcoal	Ash	SUERC-73471	5082	32	-24.7	N/A	N/A	Pit X, samples were obtained from two connected pits, the large Pit X and the smaller Pit Xa, both of which contained flint mining debitage, axes and Carinated Bowl pottery, c. 600 meters south of the Harrow Hill mines and c. 1.3km northwest of Blackpatch, represent the first dates for this site	Baczkowski, J; Holgate, R; Curwen 1934
New Barn Down	Charcoal	Ash	SUERC-73472	5075	32	-24.8	N/A	N/A	Pit X, samples were obtained from two connected pits, the large Pit X and the smaller Pit Xa, both of which contained flint mining debitage, axes and Carinated Bowl pottery, c. 600 meters south of the Harrow Hill mines and c. 1.3km northwest of Blackpatch, represent the first dates for this site	Baczkowski, J; Holgate, R; Curwen 1934

For Peer Review

Table 1. New radiocarbon results.*** = sampled from same artefact******= sampled from same artefact******** = sampled from same artefact****1. Great Langdale quarries (see map: figure 1)**

The Great Langdale lithic production complex covers an area of 500 sq km, with a 7-20 km wide span, exploiting a horseshoe-shaped igneous greenstone band of epidotised tuff. Fieldwork has revealed 35 groups of 566 distinct working sites (Claris et al., 1989), with the main concentration at Harrison Stickle. Approximately 30% of all non-flint stone axes identified and found deposited across Great Britain are sourced to this area (i.e. Group VI, Clough and Cummins 1988).

Until now, secure radiocarbon dates have been rare (see below and supplementary information). Excavations by Bradley and Edmonds (1993) produced a number of radiocarbon dates and their assessment of variability within and between the assemblages of Great Langdale led to the conclusion that there were two main phases of exploitation, primarily in the Later Neolithic (Bradley and Edmonds 1993, 105). A further fourteen undated charcoal samples obtained during this fieldwork were kindly provided to the NEOMINE team by Prof. Richard Bradley and examined by Phil Austin in 2017, in order to determine the best short-lived species samples that would provide a secure association between anthropogenic depositional activity and the sample in question. As a result of this analysis, nine samples were selected for dating.

2. South Downs and Wessex flint mines

Flint mines have been subject to episodic excavation to varying extents since the nineteenth century (Holgate 1995, 136-50; Barber et al. 1999, 4-14; Russell 2000, 12-34). There are two main geographic clusters of early Neolithic mine sites: South Downs and Wessex.

Located on the southern coast of England, near the West Sussex towns of Worthing and Chichester, is an extensive group of prehistoric excavation pits termed the South Downs flint mine group. The entire group consists of Blackpatch, Church Hill, Cissbury, Harrow Hill, Long Down and Stoke Down. New samples for dating were obtained from Blackpatch, Church Hill, Cissbury, Long Down, and New Barn Down.

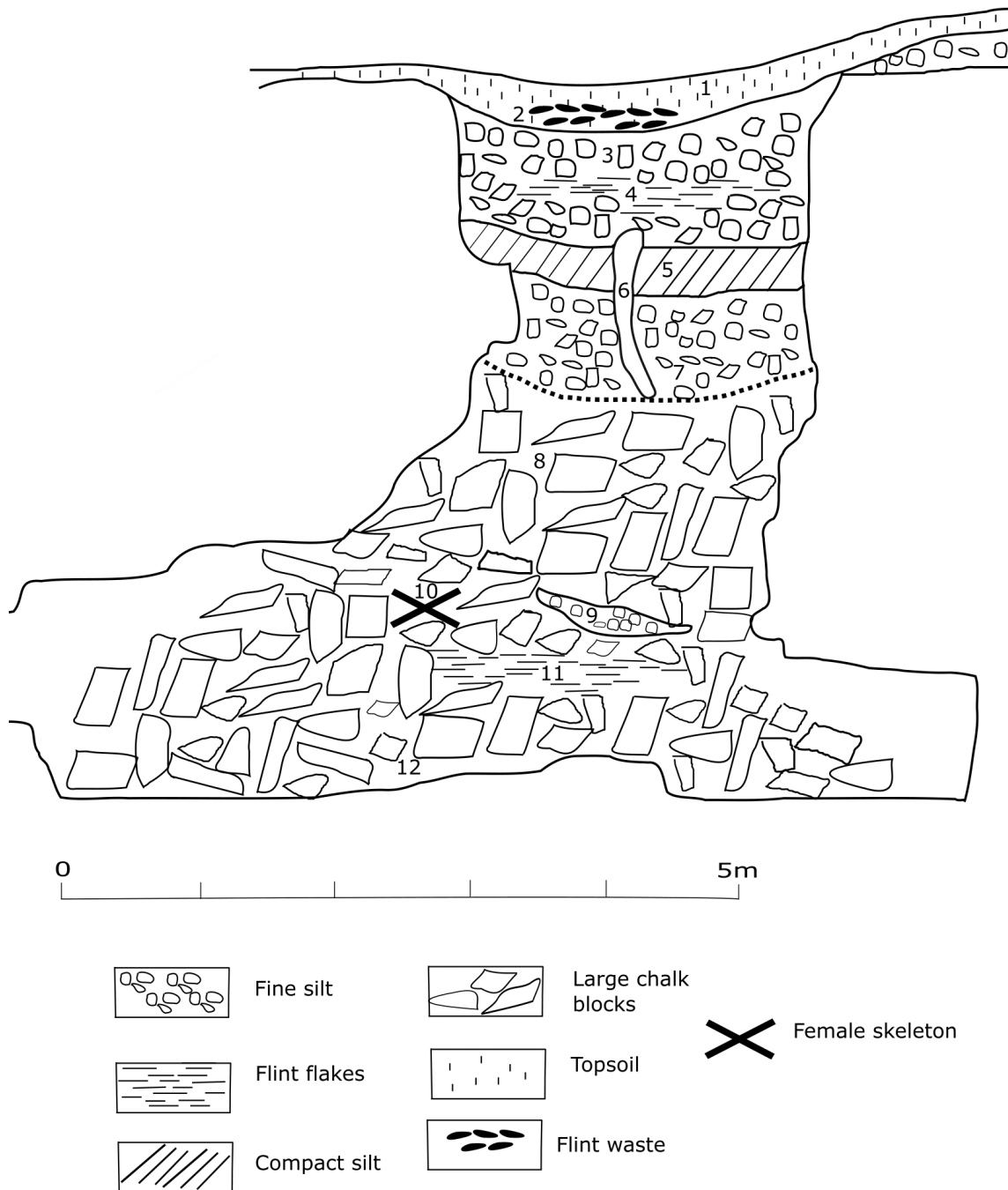


Figure 2. Cissbury Shaft 27 section (after Pull in Russell 2001b, 179). Stratigraphic layers interpreted by Anne Teather and relate to dated deposits in Table 1.

Northwest of the South Downs Group, on the Hampshire Wiltshire border, the Wessex flint mine group consists of Martin's Clump, Durrington, and the site of Easton Down. New samples could be obtained from Easton Down only. See figure 2 for an example of mine shaft stratigraphy.

Sample Pre-treatments and Processing

The samples were processed and measured in collaboration with the Scottish Universities Environmental Research Centre (SUERC) Radiocarbon Dating Laboratory at East Kilbride, Glasgow. All methods including sample pretreatment, CO₂ generation and purification, graphitization, and accelerator mass spectrometry (AMS) measurement were as described in Dunbar et al. (2016).

Radiocarbon Calibration Methods

Two different calibration-modelling methods were used to assess the new dates for each site, CalPal (Weninger 1986; et al., 2015) and OxCal (Ramsey 1997; 2009).

CalPal

CalPal software uses 2-D Dispersion Calibration, a method of calibration and graphic display of a series of calibrated dates in which all quantifiable errors (dates and calibration) can be included without any assumptions about bounded archaeological units or the depositional process (Weninger 1986; Weninger 2015 et al). CalPal can be used to create bespoke calibration curves, although here we choose to use the industry standard IntCal 13 (Reimer et al 2013). Using a combination of Ottoway's dispersion diagram (Ottoway 1973) and Geyh's histogram (e.g., Geyh and de Maret 1982) methods to display calibrated results, CalPal software calculates a calibrated probabilistic histogram that integrates to one on the X axis in calendar years (Weninger et al 2015). Results are relatively easy to read and interpret, as this calibration method makes no prior assumptions about the uncalibrated ages, stratigraphy of the sites from which radiocarbon is measured, or further complicating depositional processes. CalPal has repeatedly been proven a robust and parsimonious calibration tool when compared alongside competing calibration programs when comparing a single calibrated radiocarbon result (e.g., Aitchison et al 1989). CalPal also provides an elegant method for comparing distributions of summed and stacked groups of calibrated

radiocarbon dates from different sites, in order to obtain an idea of their general temporal relationships before any more complex assumptions are made or modelled (Bevan et al. 2017).

For Peer Review

Bayesian modelling with OxCal

We then constructed a Bayes radiocarbon calibration model (Whittle et al. 2011) to obtain the calibrated start and date range of each mine and quarry region we examined, using OxCal software (Ramsey 2009; version 4.2) and the industry-standard radiocarbon calibration curve IntCal 13 (Reimer et al 2013). For our purposes this has a significant modelling advantage over CalPal so long as the assumptions made about the underlying archaeological processes are correct. Here we make an explicit effort to reduce the chance of overfitting chronological models to the available radiocarbon data. Each group of mine shafts or quarry locations (in the same locale) is treated as a single bounded archaeological phase in OxCal. The minimum numbers of dates were removed from each bounded phase to achieve an acceptable OxCal Agreement index for each radiocarbon model ~ 60% or above, to retain the maximum amount of modelled radiocarbon data (Edinborough 2005; 2009; et al 2017; Burley et al 2014; Brace et al 2019). This approach assumes somewhat less than complete stratigraphic knowledge of each mine, as discussed above. In our models we assume that each group of dates from a site (the same as previously calibrated by CalPal, above), has a discrete start and end date, and so the OxCal 'Start' and 'End' commands are used to bound each discrete aggregated phase. This enables us to identify clear outlier results (see "?" in figures), cross reference them with CalPal, then remove them from our final favoured OxCal results. This means we can better calculate the temporal span of each bounded phase using the OxCal 'Span' command.

Results (see table 1 for full details of new samples, table S1 for details of all legacy samples)

1. Site data

Great Langdale quarries

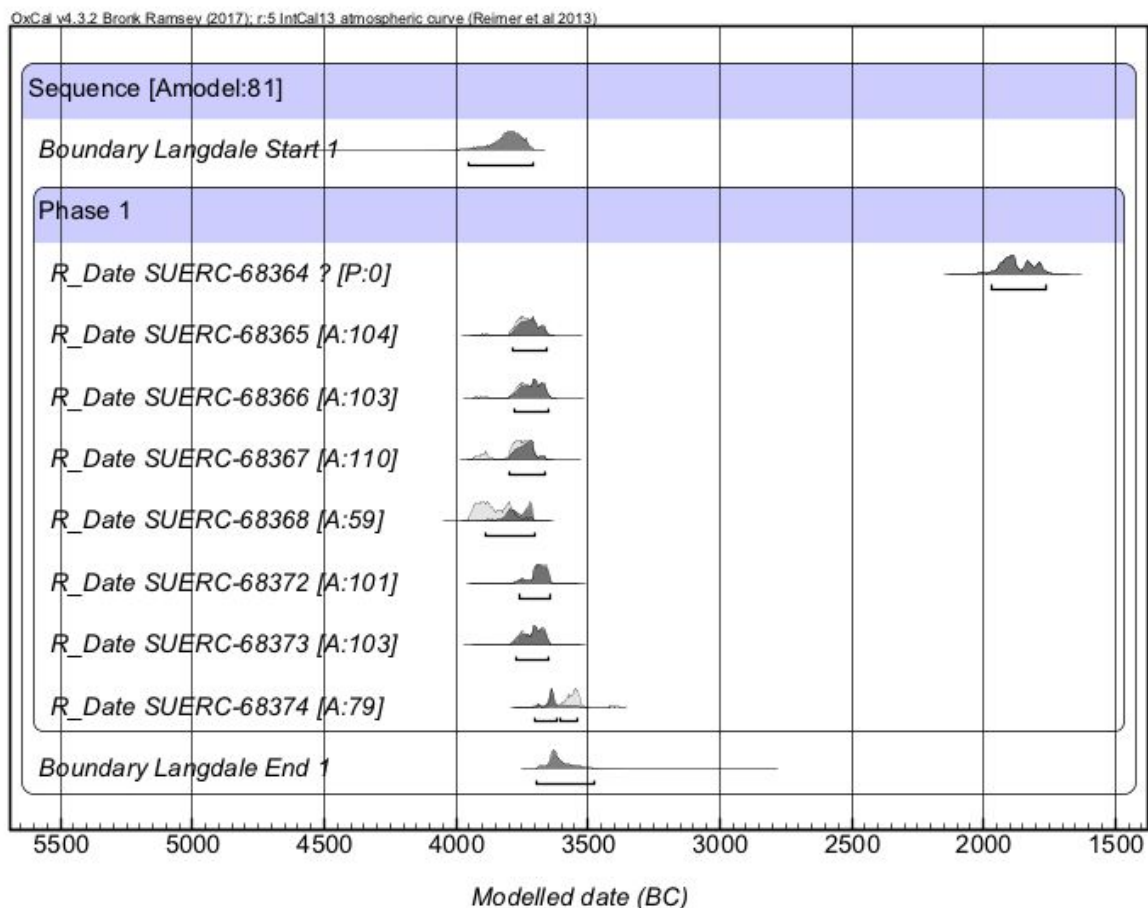


Figure 3. OxCal calibration model of new radiocarbon dates from Great Langdale grouped as a single phase, using new samples identified from short-lived species. Horizontal bars under the distributions are at a 95.4% probability range. SUERC-68364 is excluded from the single phase analysis as an outlier [P:0]; Whilst SUERC-68368 has a slightly poor agreement index A= 58.5% (A'c= 60.0%), we accept it here.

New radiocarbon results for Great Langdale are modelled here as a single phase, using new charcoal samples of short-lived species (figure 3). SUERC-68364 is plotted, but excluded from this single phase analysis as an outlier [P:0]. On the basis of the OxCal model shown in figure 3 the 95.4% probability range for the start date is 3955-3711 cal BC. For the end date the 95.4% probability range range is 3696-3484 cal BC. Note that one individual sample SUERC-68368 has slightly poor agreement within this model, A= 58.5% (A'c=60%), whilst

the overall model itself remains consistent (Amodel: 81). These dates contradict Bradley and Edmonds' (1993) initial assessment that the main phase of exploitation in Langdale was the later Neolithic.

For Peer Review

South Downs and Wessex flint mines

Blackpatch

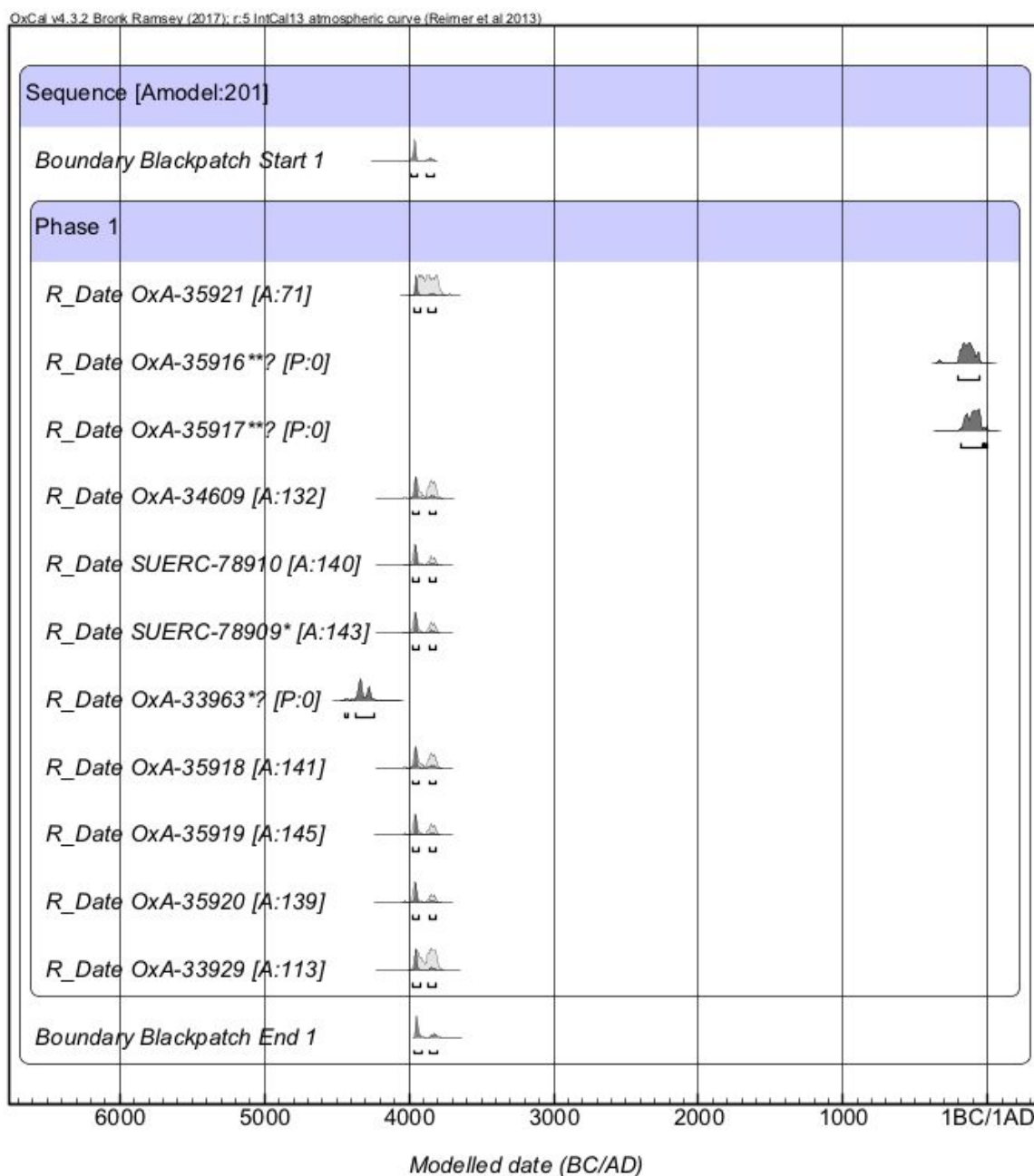


Figure 4. Our preferred OxCal model for Blackpatch with outliers OxA-33963, OxA-35916, and OxA35917 calibrated and plotted, but removed from this single-phase analysis. The results suggest that mining activity at Blackpatch was short-lived. Horizontal bars under the distributions are at a 95.4% probability range.

Blackpatch Hill is northwest of the village of Findon, immediately to the east of Harrow Hill, and northwest of Church Hill. It was excavated by Pull between 1922-30 with eight shafts investigated in addition to a number of barrows and working floors (Pull 1932; Russell 2001a, 24-84). Figure 4 shows our preferred model for the start and end dates of Blackpatch. The results suggest that the exploitation of Blackpatch was very short-lived, starting between 3991-3824 cal BC and ending between 3964-3797 cal BC at a 95.4% probability range. See figures S3-S4 for further models.

Church Hill

The site is east of Findon in West Sussex, southeast of the Blackpatch mining complex and northeast of Cissbury. It was excavated by Pull between 1932-9 and 1946-52 (Russell 2001a, 85-158). Seven shafts were excavated in addition to a number of barrows and working floors.

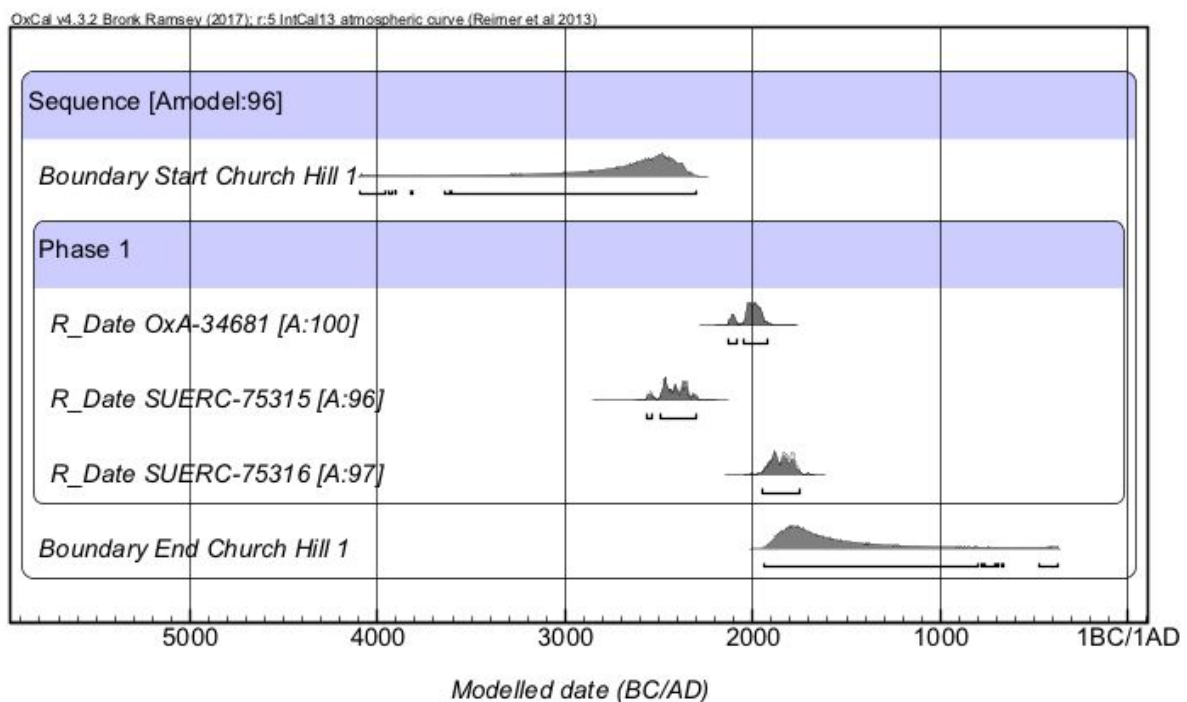


Figure 5. New radiocarbon results from Church Hill grouped as a single phase. Horizontal bars under the distributions are at a 95.4% probability range.

Figure 5 shows calibrated new dates from Church Hill. These suggest that activity began in the mid-third millennium cal BC and continued into the early second. See figure S6 for OxCal

phase models with older dates including an alternative model with an early British Museum result that is not consistent with these new results but might suggest an earlier phase of use.

For Peer Review

Cissbury

There have been three main episodes of excavation at Cissbury. Colonel Augustus Henry Lane Fox commenced excavations during 1867/8 but his excavations were not of a great enough depth to uncover the shafts beneath the Iron Age hillfort. He returned to Cissbury for excavations between 1875 and 1877, when approximately thirteen shafts were excavated either in whole or part (Holgate 1991, 23-4; Barber et al 1999, 4-6; Russell 2000, 12-21; Teather 2016, 5-6). These span two separate areas at the top of the hill on the south side. Pull's excavations continued at Cissbury between 1952 and 1956, on the southern slope of the hill (Russell 2001a, 170-92).

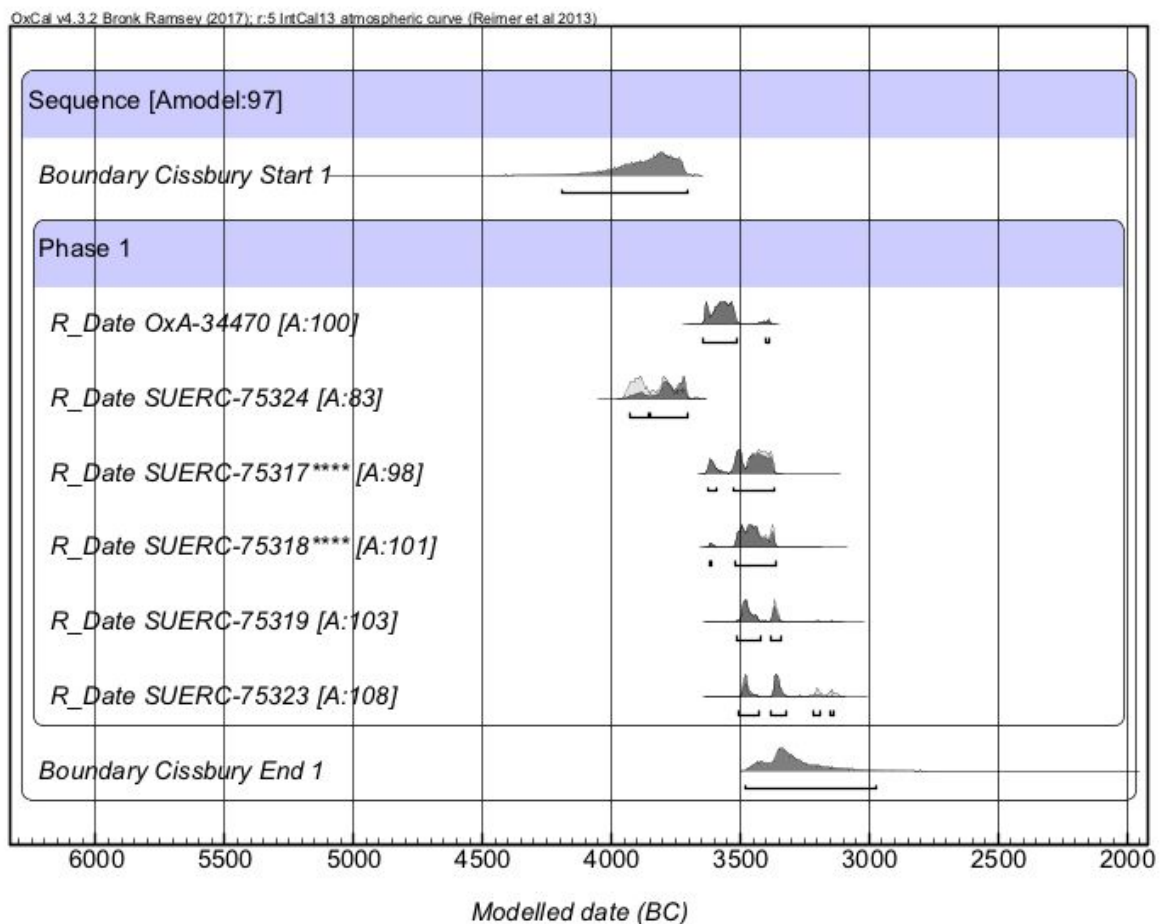


Figure 6. OxCal single-phase model for Cissbury with new radiocarbon data.

******sampled from the same artefact. Horizontal bars under the distributions are at a 95.4% probability range.**

Figure 6 shows an OxCal phase model for Cissbury using only newly acquired radiocarbon data, with a start date range of 4200-3650 cal BC at 95%, and end date 3500-2950 cal BC at 95%, see figure S7 for a model using all the available dates).

Long Down

The site of Long Down is situated within the more dispersed western group of the South Downs group of Neolithic flint mines, bounded by Cissbury in the East and Nore Down in the West (Barber et al. 1999, 42). The monument was partly excavated in 1955-57 and 1984, when several shafts and a number of associated working floors were investigated (Salisbury 1961; Baczkowski and Holgate 2017).

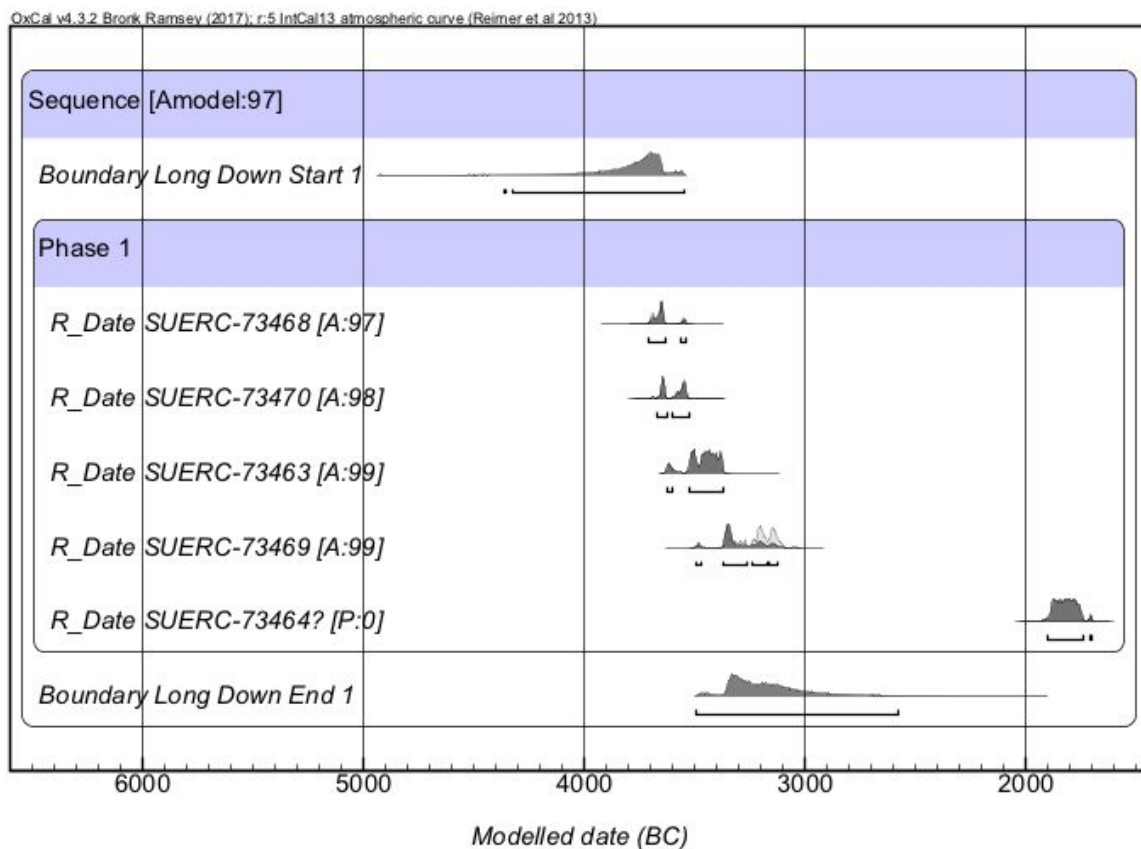


Figure 7. OxCal Single Phase model for Long Down with new radiocarbon dates. Horizontal bars under the distributions are at a 95.4% probability range.

The OxCal phase model for Long Down (figure 7) has very wide 95.4% probability ranges for both the beginning and end of activity, starting in 4319-3543 cal BC at 95.4% probability range, but the bulk of the probability for the start date is in the range 4000-3500 cal BC. SUERC-73464 is excluded from this analysis as a clear outlier. The end of the phase is in 3484-2584 at a 95.4% probability range; see figure S8 for a model using all available dates.

New Barn Down at Harrow Hill

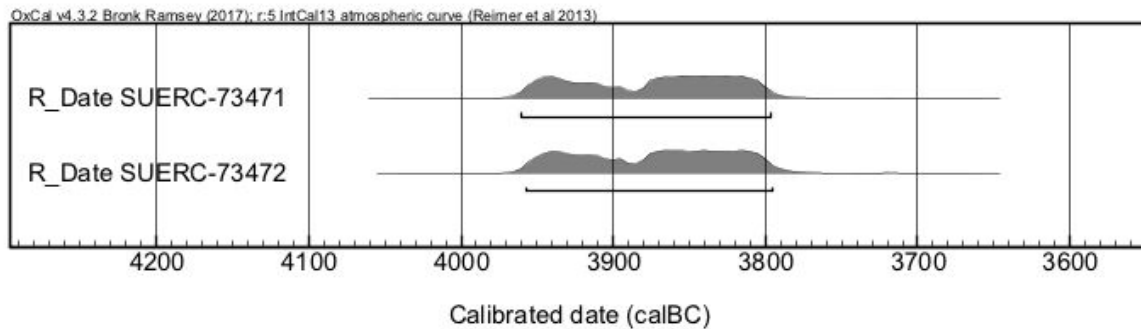


Figure 8. New radiocarbon results from New Barn Down. Horizontal bars under the distributions are at a 95.4% probability range.

The New Barn Down samples were obtained from a large pit containing flint mining debitage, axes and Carinated Bowl pottery, c. 600 metres south of the Harrow Hill mines and provide the first dates for this site (Curwen 1934). The results (figure 8) are not placed in an OxCal phase model here as there are just two radiocarbon measurements. They fall in the first quarter of the 4th millennium cal BC, with a 95.4% probability range of 3960-3800 cal BC and are consistent with the results of a phase model of the adjacent Harrow Hill flint mine that uses older radiocarbon results (See figure S9), suggesting that the opening and backfilling of the New Barn Down pit coincides with the earliest mining activity at Harrow Hill.

Easton Down, Winterslow, Wiltshire, in the Wessex Group of Neolithic Flint Mines

The Easton Down flint mines are located near East Winterslow, Wiltshire, northeast of Salisbury. The site was discovered by J.F.S. Stone in 1929 and excavated by him from 1930 to 1934 (Stone 1932; 1933; 1935).

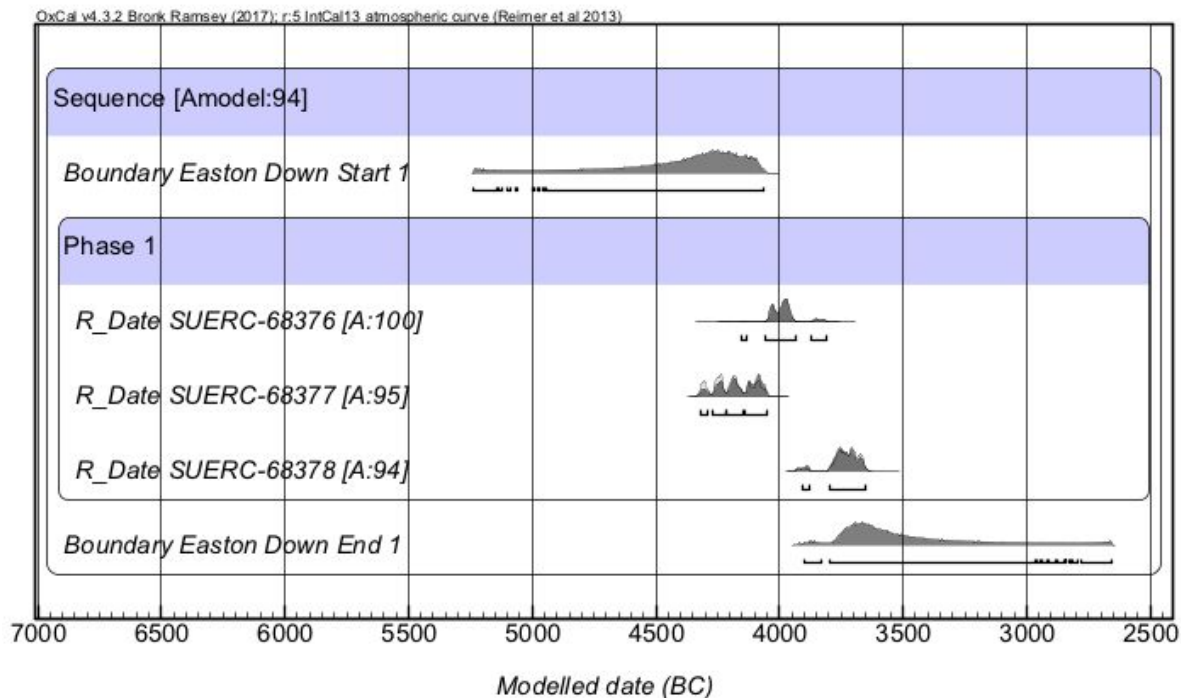


Figure 9. OxCal single phase model with new radiocarbon results from Easton Down. Horizontal bars under the distributions are at a 95.4% probability range.

Figure 9 shows the Oxcal phase model for Easton Down, which differs from the other sites considered here in having a 95% start range that ends before 4000 cal BC, extending back before 5000 cal BC. More precisely, the model yields a start date range of 5560-4054 cal BC at a 95.4% probability range, while the 95.4% probability end range end date range is similarly long-tailed, in 3729-1714 cal BC at 95% with a median date of 3114 cal BC. See figure S10 for a model using all available dates.

2. Inter-site comparison

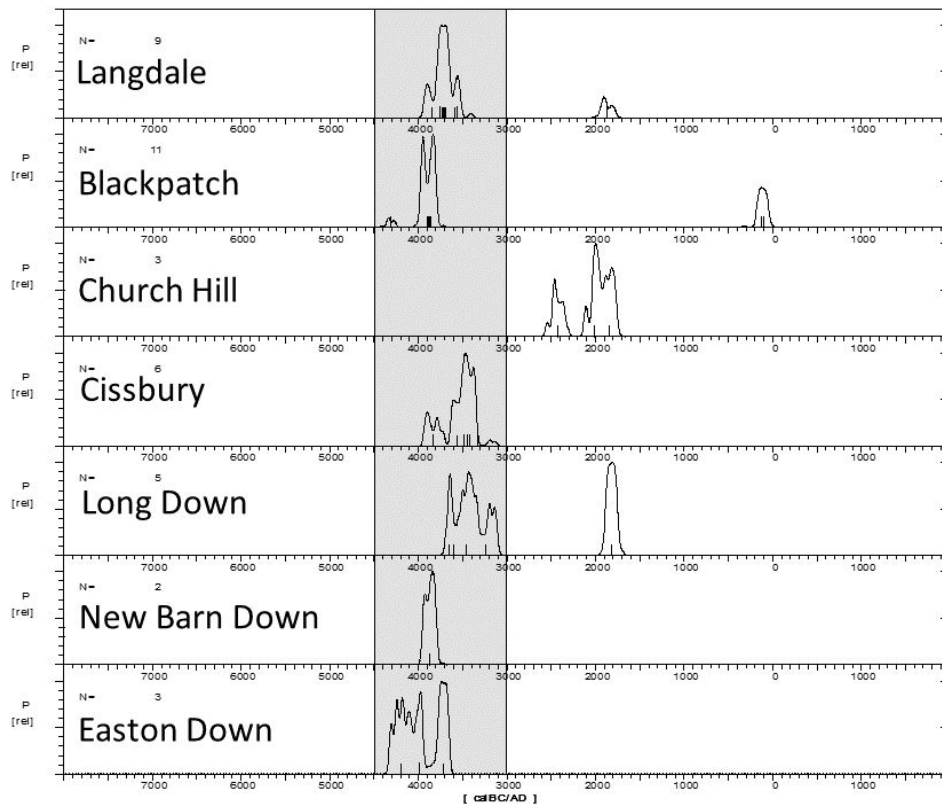


Figure 10. CalPal calibration model of new radiocarbon results.

The CalPal results for the new samples obtained are shown in figure 10. The South Downs and Wessex distributions cover the range ~4000-3300 cal cal BC, as does Langdale. There are indications of a later phase of use ~2000 cal BC at Langdale, as there are at the South Downs site of Church Hill. It is clear that these represents a different phase of exploitation from the other mines and quarries. This may relate to the sourcing of Langdale tuff for archers' bracers during the Beaker period and Early Bronze Age (Woodward and Hunter 2011). See SI and figure S11 for details of models including older results not included here for the sake of consistency (and see discussion below).

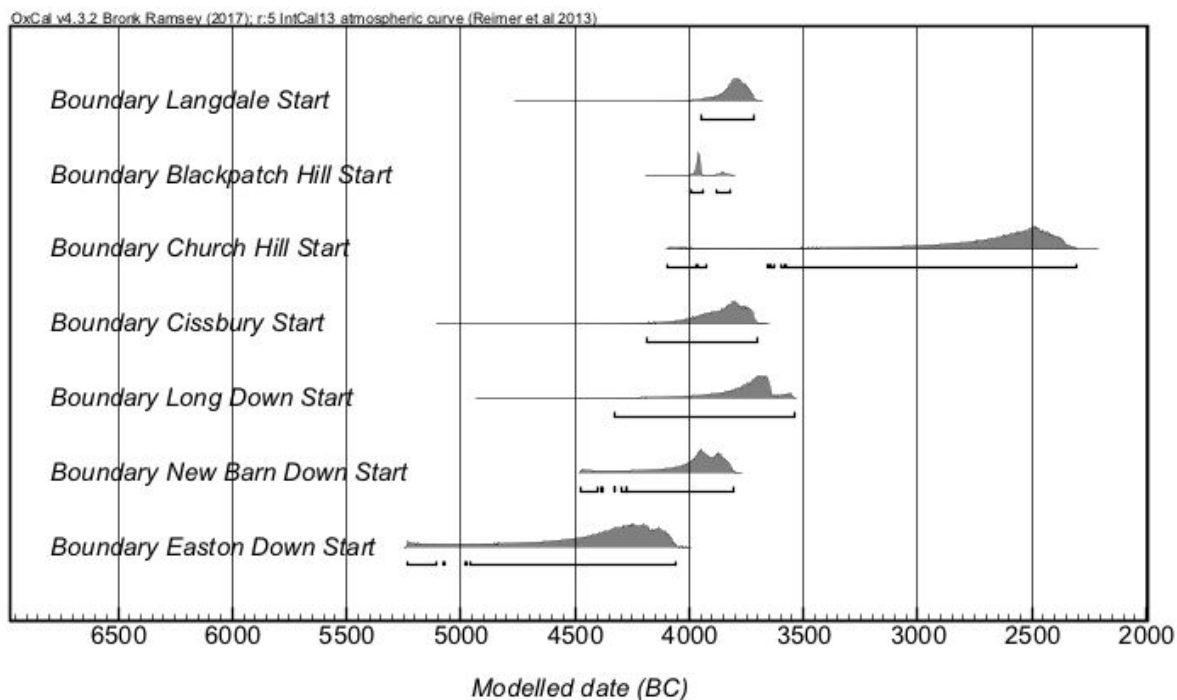


Figure 11. OxCal mine-start date model result using new radiocarbon data.

Horizontal bars under the distributions are at a 95.4% probability range.

Figure 11 brings together the start dates from the individual site OxCal models presented above for individual sites. Results for six out of seven of the aggregated sites' overlap at 2 sigma and suggest a synchronised start date for mining and quarrying around 4000-3700 cal BC. The New Barn results are modelled as phases here for comparison although they only have two dates per phase. See supplementary figure S11 for details of models with older results not included here for the sake of consistency, but which confirm the tightly bracketed start dates ~4000 BC.

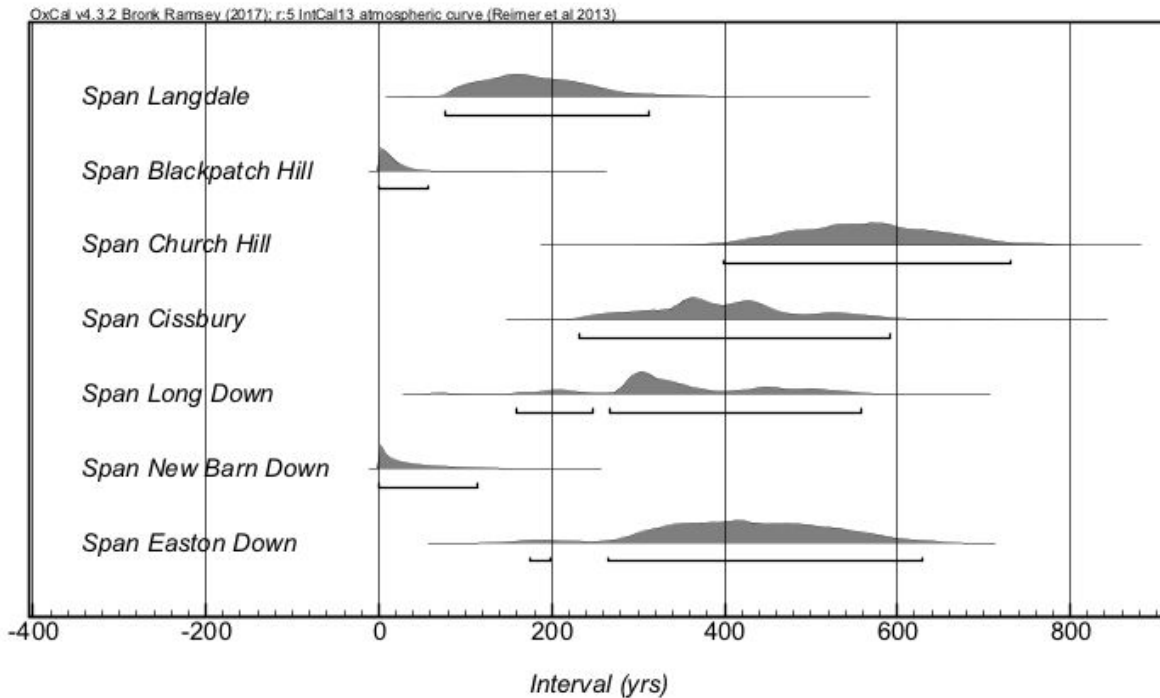


Figure 12. OxCal model of the temporal span of sites in calendar years using new radiocarbon data. Horizontal bars under the distributions are at a 95.4% probability range

The modelled calibrated temporal span distributions for the sites are shown in figure 12. Blackpatch is clearly short-lived on the preferred model, with a span of no more than 50 years. Cissbury, Long Down and Langdale span 250-750 years, while the span of Easton Down and Church Hill on the available evidence are much longer.

3. Comparison of OxCal and CalPal results

Despite the arguments and complexities, both OxCal and CalPal generally yield similar results (Aitchison et al., 1989) although a critical comparison of the two can yield significant improvements for radiocarbon calibration model evaluation (Weninger et al. 2015).

Due to the calibration algorithm OxCal can result in dramatically spiked calibrated date distributions when they are summed (Weninger et al 2015), as well as agreement indices (likelihood functions) which can sometimes make it difficult to evaluate competing chronological models (Riede and Edinborough 2012; cf. Hamilton and Krus 2018). In contrast, probabilistic CalPal models assume much less, and claim less precision than OxCal models in archaeological contexts. A CalPal model results in a calibrated histogram of a date probability distribution that sums to one – which is relatively easy to cross-compare.

When comparing the OxCal results for the mine and quarry dates in our sample and if the surprisingly long tailed distributions in the OxCal start models are ignored, the calibrated distributions at two standard deviations are tightly clustered. As the bulk of these results overlap at a 95.4% probability range, they suggest a synchronised start date for mining around 4000-3700 cal BC. The OxCal results are therefore in broad agreement with those from CalPal.

Discussion

We present 39 new radiocarbon results from Neolithic mining and quarrying sites modelled with two different calibration methods. The results of both CalPal and OxCal calibration models are similar. They show that stone-quarrying and flint-mining activities in both the north and south of England began ~4000-3700 cal BC and that the great majority were in contemporary use in the early 4th millennium. The dates at mines have focused on deposition within individual shafts and this shows what would be expected for rapid and discrete extraction events. While some sites lasted longer than others and more could be gained from a wider sampling strategy, there is evidence of later phases of extraction at Church Hill, Long Down and Langdale although these are not contemporaneous with the late Neolithic mining at Grime's Graves. The scatter of available dates from several other mine and quarry sites in Britain and Ireland not discussed in this paper (see figures S11) show the same pattern, including Martin's Clump flint mine in Wessex, the Graig Lwyd and Mynydd Rhiw quarries in North Wales, and the Tievebulliagh and Lambay Island quarries in Ireland. Dates from deposition contexts of axes from the petrologically-determined but unknown Cornish sources also fall in this range (Whittle et al. 2011).

The similarity of the start dates is not consistent with a pattern of independent local innovation of new mining and quarrying practices in different parts of Britain. They are consistent with an association with the immigrant groups from northwest Europe who introduced farming to Britain at this time (Brace et al. 2018). Farming groups in Brittany had been exploiting fibrolite for prestige axes imitating those from the Alps for much of the 5th millennium cal BC (Pailler 2012), while the dates from the metadolerite 'A' source of Plussulien/Seledun in central Brittany indicate that quarrying to produce axes began here around, or shortly before, 4000 cal BC (Le Roux 1999). Similarly, flint-mining also began in northwest Europe in the late 5th millennium. The complex shaft and gallery technology used

at deep sites such as Spiennes and Jablines was also used at Cissbury which likely required prior knowledge that had gradually been developed earlier (Baczkowski 2014).

Given that the axes produced from these sites were extensively distributed over considerable distances, and that they all began production at more or less the same time, it can be concluded that the production was responding to the abrupt appearance of a new demand on a considerable scale. This demand was sufficient to support the opening of a number of mines at the same time in the same local area of Sussex, for example, at the same time. In general our data do not permit us to be very precise about end dates but there is no evidence that different mines replaced one another. Rather, production seems to continue at different sites for different lengths of time though all have faded out by the end of the Early Neolithic population boom phase (Shennan et al. 2013, Bevan et al. 2017).

While there may have been a symbolic/ritual dimension to some of the activities associated with flint mining and specialised quarrying in Britain, Schauer et al (2019; and see Woodbridge et al. 2014) show that their axe production was a response to the need to clear climax forests for agricultural activities by the immigrant farmers. The effectively simultaneous start of production both in the south of England and the north and west can be seen in this light. The colonisation of Britain was extremely rapid and had already reached Scotland by 3800 cal BC (Whittle et al. 2011). The first colonists in the south of England would have had access to the products of the flint mines but as settlement expanded rapidly to the north and distances increased, contact with these exchange networks would have been lost; this is seen in the distribution of flint axes, which is largely restricted to the south of England, and the chalklands in particular (Pitts 1996). The beginning of quarrying at Langdale is linked with the provision of high-quality axes to large areas of the midlands and north, where group VI axes from the Langdale occur at high frequency (Clough and Cummins 1988).

Although its location might seem remote, it is much less so if we think of it in the context of a western spread of farming and farmers to Britain through the Irish Sea, rather than an overland spread from the south, or from the east coast. In the case of Langdale the beds of the rivers leading down from the mountains to the Irish Sea would have contained rocks that provided clues to the potential of the mountains (Bradley and Edmonds 1993, 201). From this western perspective, the quarries at Langdale and its start date becomes part of a broader pattern that includes the quarrying activity at the Graig Lwyd and Mynydd Rhiw sources on the Irish Sea coast of North Wales, and at Tievebulliagh and Lambay Island on the Irish coast (figure S11), as well as at currently unknown sites in Cornwall. This would

indicate a likely initial discovery and exploitation of rock sources by western colonists, perhaps specifically immigrants from Brittany, who were already familiar with hard rock quarrying techniques (cf. Sheridan 2003, Pioffet 2015, Pailler 2012, Le Roux 1999).

Conclusion

Due to the lack of new excavations of mines in the UK, our dating programme is, of course, not exhaustive. Yet this collaborative project has more than doubled the existing suite of radiocarbon dates for the early Neolithic flint mines while producing more certainty for the chronology of the Langdale quarries. Overall, it has supported the dates gained from earlier dating programmes, and indicated the potential to more fully chronologically characterise the influx of immigrant farmers at the beginning of the Neolithic. This is particularly important as extraction activity is shown to pre-date monument building, whose construction begins at c. 3800 cal BC (Whittle et al. 2011). Extraction activity is therefore a primary expression of the Neolithic in the UK and Ireland (Barber et al 1999, 68-9; Russell 2000, 55-9; Russell 2004, 174-5; Barber 2005). The currently available data consistently show that in Britain mining and quarrying were a response to the demand created by the colonisation of the first farmers, who brought relevant extraction technological knowledge with them. The subsequent decline in mining and quarrying reflects both a decrease in clearance activity and the population decline during the middle of the 4th millennium BCE (Schauer et al. submitted, Bevan et al. 2017). While this was initially suggested by Bradley (1978) and Whittle (1978), it is now supported through a range of recent work to produce a much clearer picture of the early Neolithic in Britain and Ireland (Shennan 2018).

Acknowledgements

We are very grateful to the Leverhulme Trust for Research Project Grant RPG-2015-199 for the financial support that made this project possible. In addition, the NERC-AHRC National Radiocarbon Facility funded 10 radiocarbon dates on the Sussex mines through two small projects (NF/2015/2/17; NF/2017/1/11, led by Andrew Chamberlain). We wish to thank Phil Austin for his meticulous identification of short-lived species for our new Langdale radiocarbon samples. We thank Alex Bayliss for her sampling advice and loan of a dental drill at the start of this project. We also thank the Director of the Salisbury Museum, Adrian Green, Amy Roberts at the Novium Stores in Chichester and Gerry Connolly and James Sainsbury at Worthing Museum and Art Gallery, for access to their collections. At the University of Reading we thank Duncan Garrow. At University College London we thank Ulrike Sommer and Jon Sygrave for valuable discussions. Finally, we wish to thank the two

anonymous reviewers of this paper for their detailed comments which have helped improve it considerably.

For Peer Review

References

Aitchison TC, Leese M, Michczynska DJ, Mook WG, Otlet RL, Ottaway BS, Pazdur MF, Van Der Plicht J, Reimer PJ, Robinson SW, Scott EM. 1989. A comparison of methods used for the calibration of radiocarbon dates. *Radiocarbon* 31(3):846-63.

Baczkowski J, and Holgate R. 2017. Breaking chalk: the archaeological investigations of Early Neolithic flint mines at Long Down and Harrow Hill, West Sussex, 1984-86. *Sussex Archaeological Collections* 155: 1-29.

Baczkowski J. 2014. Learning by Experience: The Flint Mines of Southern England and Their Continental Origins. *Oxford Journal of Archaeology*. 33(2):135-53.

Barber M, 2005. Mining, burial and chronology: the West Sussex flint mines in the Late Neolithic and Early Bronze Age. In P Topping and M Lynott (eds.), *The Cultural Landscape of Prehistoric Mines*; 94-109. Oxford: Oxbow.

Barber M, Field D, Topping P. 1999. *Neolithic Flint Mines in England*. London: English Heritage.

Bradley, R, 1978. *The Prehistoric Settlement of Britain*. London: Routledge.

Berggren Å, Högberg A, Olausson D, Rudebeck E. 2016. Early Neolithic flint mining at Södra Sallerup, Scania, Sweden. *Archaeologia Polona* 54:167-80.

Bevan A, Colledge S, Fuller D, Fyfe R, Shennan S, Stevens C. 2017. Holocene fluctuations in human population demonstrate repeated links to food production and climate. *Proceedings of the National Academy of Sciences*. Nov 15:201709190.

Bradley R, Edmonds M. 1993. *Interpreting the axe trade: production and exchange in Neolithic Britain*. Cambridge University Press; 2005 Feb 17.

Brace S, Diekmann Y, Booth TJ, van Dorp L, Faltyskova Z, Rohland N, Mallick S, Olalde I, Ferry M, Michel M, Oppenheimer J. Ancient genomes indicate population replacement in Early Neolithic Britain. *Nature ecology & evolution*. 2019 Apr 15:1.

Burley DV, Edinborough K. Discontinuity in the Fijian archaeological record supported by a Bayesian radiocarbon model. *Radiocarbon* 56(1):295-303.

Burley D, Edinborough K, Weisler M, Zhao JX. 2014. Bayesian modelling and chronological precision for Polynesian settlement of Tonga. *PLoS One* 2015 Mar 23;10(3):e0120795.

Clough TH, Cummins WA. 1979. Stone Axe Studies. Archaeological, Petrological, Experimental, and Ethnographic. *GBR* (23):1-37.

Clough TH, Cummins WA, 1988. Stone Axe Studies 2: The petrology of prehistoric stone implements from the British Isles. *CBA Research Report* 67.

Claris P, Quartermaine J, Woolley AR. 1989. The Neolithic quarries and axe factory sites of Great Langdale and Scafell Pike: a new field survey. In, *Proceedings of the Prehistoric Society* 1989 Jan (Vol. 55, pp. 1-25). Cambridge University Press.

Curwen EC. 1934. A Later Bronze Age farm and a Neolithic pit dwelling on New Barn Down, Clapham, near Worthing. *Sussex Archaeological Collections* 75: 137-70.

Díaz-del-Río P, Consuegra S, Capdevila E, Capote M, Casas, C, Castañeda N, Criado, C, Nieto A, 2010. The Casa Montero Flint Mine and the Making of Neolithic Societies in Iberia. In P. Anreiter et al. (eds.), *Mining in European History and its Impact on Environment and Human Societies – Proceedings for the 1st Mining in European History-Conference of the SFB-HIMAT, 12.–15. November 2009, Innsbruck*, pp. 351-355. Innsbruck University Press.

Dunbar E, Cook GT, Naysmith P, Tripney BG, Xu S. 2016. AMS 14 C dating at the Scottish Universities Environmental Research Centre (SUERC) radiocarbon dating laboratory. *Radiocarbon* 58(1):9-23.

Edinborough, K. Evolution of bow-arrow technology (Doctoral dissertation, University of London).

Edinborough, K., 2009. Population history and the evolution of mesolithic arrowhead technology in South Scandinavia. In: Shennan, S. (Ed.), *Pattern and Process in Cultural Evolution*. University of California Press, Berkeley, pp. 191–202.

Fox A. Lane. 1876. Excavations in Cissbury Camp, Sussex; Being a Report of the Exploration Committee of the Anthropological Institute for the Year 1875." *The Journal of the Anthropological Institute of Great Britain and Ireland* 5 (1876): 357-390.

Geyh MA, Maret PD. 1982. Research notes and application reports histogram evaluation of ¹⁴C dates applied to the first complete Iron Age sequence from west central Africa. *Archaeometry*. 1982 Aug;24(2):158-63.

Goodman C, Frost M, Curwen E, and Curwen EC. 1924. Blackpatch flint mine excavation 1922. *Sussex Archaeological Collections* 65: 69-111.

Hamilton WD, Krus AM. 2018. The Myths and Realities of Bayesian Chronological Modeling Revealed. *American Antiquity* 83(2):187-203.

Healy F, Marshall PD, Bayliss A, Cook G, Ramsey CB, van der Plicht J, Dunbar E. 2014. *Grime's Graves, Weeting-with-Broomhill, Norfolk: Radiocarbon Dating and Chronological Modelling*. English Heritage.

Healy, F., Marshall, P., Bayliss, A., Cook, G., Bronk Ramsey, C., Van der Plicht, J., & Dunbar, E. 2018. When and Why? The Chronology and Context of Flint Mining at Grime's Graves, Norfolk, England. *Proceedings of the Prehistoric Society* 84, 277-301.
doi:10.1017/ppr.2018.14

Holgate R. 1991. Prehistoric Flint Mines. Princes Risborough: Shire.

Le Roux CT. 1999 L'outillage de pierre polie en métadolérite du type A: Les ateliers de Plussulien (Côtes-d'Armor): Production et diffusion au Néolithique dans la France de l'ouest et au delà. *Travaux du Laboratoire anthropologie, préhistoire, protohistoire, quaternaire armoricains* (43):1-240.

Ottaway B. 1973. Dispersion diagrams: a new approach to the display of carbon-14 dates. *Archaeometry* 15(1):5-12.

Pailler Y. 2012. La fibrolite, un matériau pour façonner des haches, mais encore ? Le travail de la fibrolite au Néolithique dans l'Ouest de la France. In de Labriffe PA, Thirault E, (eds.), *Produire des Haches au Néolithique: de la Matière Première à l'Abandon*: Paris : Société préhistorique française: 121-136.

- Pioffet HC. 2015. Sociétés et Identités du Premier Néolithique de Grande-Bretagne et d'Irlande dans leur contexte ouest européen: caractérisation et analyses comparatives des productions céramiques entre Manche, Mer d'Irlande et Mer du Nord (Doctoral dissertation, Durham University).
- Pitts M. 1996. The stone axe in Neolithic Britain. *Proceedings of the Prehistoric Society* 62, 311-371.
- Pull J. 1932. *The Flint Miners of Blackpatch*. London: Williams and Norgate.
- Ramsey CB. 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal program. *Radiocarbon* 37(2):425-30.
- Ramsey CB. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon*. 51(1):337-60.
- Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Ramsey CB, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55(4):1869-87.
- Riede F, Edinborough K. 2012. Bayesian radiocarbon models for the cultural transition during the Allerød in southern Scandinavia. *Journal of Archaeological Science* 39(3):744-56.
- Russell M. 2001a. *Rough Quarries, Rocks and Hills: John Pull and the Neolithic Flint Mines of Sussex*. Oxford: Oxbow.
- Russell M. 2001b. *The Early Neolithic Architecture of the South Downs*. BAR Brit. Ser. (321).
- Russell M. 2000. *Flint Mines in Neolithic Britain*. Stroud: Tempus.
- Russell M. 2004. The treachery of images: deconstructing the Early Neolithic monumental architecture of the South Downs. In J Cotton and D Field (eds.), *Towards a New Stone Age*, pp. 168-76. York: CBA Research Report 137.
- Schauer P, Shennan S, Bevan A, Cook G, Edinborough K, Fyfe R, Kerig T, Pearson MP. Supply and demand in prehistory? Economics of Neolithic mining in northwest Europe. *Journal of Anthropological Archaeology*. 2019 Jun 1;54:149-60.

Shennan, S. 2018. *The First Farmers of Europe*. Cambridge: Cambridge University Press.

Shennan S, Downey SS, Timpson A, Edinborough K, Colledge S, Kerig T, Manning K, Thomas MG. 2013. Regional population collapse followed initial agriculture booms in mid-Holocene Europe. *Nature Communications* 1;4:2486.

Sheridan A. 2003. French connections I: spreading the marmites thinly. In, Armit I, Murphy E, Nelis E, Simpson D. (Eds.), *Neolithic Settlement in Ireland and Western Britain*. Oxbow, Oxford: 3–17.

Stone J. 1932. Easton Down, Winterslow, South Wiltshire, flint mine excavation 1930. *Wiltshire Archaeological and Natural History Magazine* 45: 350-65.

Stone J. 1933. Excavations at Easton Down, Winterslow, 1931-32. *Wiltshire Archaeological and Natural History Magazine* 46: 225-42.

Stone J. 1935. Excavations at Easton Down, Winterslow, 1933-4. *Wiltshire Archaeological and Natural History Magazine* 47: 68-80.

Sørensen, L. & S. Karg. 2014. The expansion of agrarian societies towards the north – new evidence for agriculture during the Mesolithic/Neolithic transition in Southern Scandinavia. *Journal of Archaeological Science* 51: 98–114.

Tarantini, M., A. Galiberti & F. Mazzaocchi 2011. Prehistoric flint mines of the Gargano: an overview, in M. CAPOTE, S. CONSUEGRA, P. DÍAZ-DEL-RÍO, & X. TERRADAS. (ed.) *Proceedings of the 2nd International Conference of the UISPP Commission on Flint Mining in Pre- and Protohistoric Times (Madrid, 14-17 October 2009)* BAR International Series 2260. Oxford: Archaeopress, p. 253-63.

Teather, A. 2016. *Mining and materiality: Neolithic chalk artefacts and their depositional contexts in southern Britain*. Oxford: Archaeopress.

Teather, A. (in press) Radiocarbon dating on mining shaft fills at Blackpatch, Cissbury and Church Hill, Sussex. In Teather, A. Topping, P. and Baczkowski (eds). *Mining and Quarrying in Neolithic Europe. Neolithic Studies Group Seminar Series* Oxford: Oxbow.

Weisgerber G. 1987. The technological relationship between flint mining and early copper mining, in G. de G Sieveking & M. H. Newcomer (ed.) *The Human Uses of Chert and Flint: Proceedings of the Fourth International Flint Symposium, held at Brighton Polytechnic 10-15 April 1983*:131-35. Cambridge: Cambridge University Press.

Weninger B. 1986. High-precision calibration of archaeological radiocarbon dates. *Acta Interdisciplinaria Archaeologica*. 4(1):1-53.

Weninger B, Clare L, Jöris O, Jung R, Edinborough K. 2015. Quantum theory of radiocarbon calibration. *World Archaeology*. 47(4):543-66.

Whittle, AWR. 1978. *Resources and population in the British Neolithic*. *Antiquity* 52:34-42

Whittle AWR, Healy FM, Bayliss A. 2011. *Gathering time: dating the early Neolithic enclosures of southern Britain and Ireland*. Oxbow Books.

Woodbridge, J. Fyfe, R., Roberts, N., Downey, S., Edinborough, K. Shennan, S. 2014. The impact of the Neolithic agricultural transition in the British Isles: a comparison of pollen-inferred land-cover change and archaeological 14C date distributions. *Journal of Archaeological Science* 51: 216–224.

Woodward, A. and Hunter, J. 2011. *An Examination of Prehistoric Stone Bracers from Britain*. Oxbow Books.