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Thomas Higham

Roger Jacobi

Michèle Julien

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Thomas Higham[a,1], Roger Jacobi[b,c,2], Michèle Julien[d], Francine David[d], Laura Basell[a], Rachel Wood[a], William Davies[e], and Christopher Bronk Ramsey[a]

[a]Oxford Radiocarbon Accelerator Unit, Research Laboratory for Archaeology and the History of Art, University of Oxford, Oxford OX1 3QY, United Kingdom; [b]British Museum, Franks House, London N1 5QJ, United Kingdom; [c]Natural History Museum, London SW7 5BD, United Kindom; [d]Archéologies et Sciences de L'Antiquité, Unité Mixte de Recherche 7041, Centre National de la Recherche Scientifique, 92023 Nanterre, France; and [e]Centre for the Archaeology of Human Origins, Department of Archaeology, University of Southampton, Southampton SO17 1BF, United Kingdom

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There is extensive debate concerning the cognitive and behavioral adaptation of Neanderthals, especially in the period when the earliest anatomically modern humans dispersed into Western Europe, around 35,000–40,000 B.P. The site of the Grotte du Renne (at Arcy-sur-Cure) is of great importance because it provides the most persuasive evidence for behavioral complexity among Neanderthals. A range of ornaments and tools usually associated with modern human industries, such as the Aurignacian, were excavated from three of the Châtelperronian levels at the site, along with Neanderthal fossil remains (mainly teeth). This extremely rare occurrence has been taken to suggest that Neanderthals were the creators of these items. Whether Neanderthals independently achieved this level of behavioral complexity and whether this was culturally transmitted or mimicked via incoming modern humans has been contentious. At the heart of this discussion lies an assumption regarding the integrity of the excavated remains. One means of testing this is by radiocarbon dating; however, until recently, our ability to generate both accurate and precise results for this period has been compromised. A series of 31 accelerator mass spectrometry ultrafiltered dates on bones, antlers, artifacts, and teeth from six key archaeological levels shows an unexpected degree of variation. This suggests that some mixing of material may have occurred, which implies a more complex depositional history at the site and makes it difficult to be confident about the association of artifacts with human remains in the Châtelperronian levels.

Aurignacian | radiocarbon dating | ultrafiltration | Neandertal | Mousterian

The French site of the Grotte du Renne at Arcy-sur-Cure (Yonne) is critical to discussions regarding the nature of the transition from the Middle to Upper Paleolithic in Europe and the interaction between Neanderthals and anatomically modern humans (AMH) in the period leading up to Neanderthal extinction. The remains of personal ornaments, rings, pierced animal teeth, and ivory pendants have been excavated from the Châtelperronian levels at this site (1) (Fig. 1). This is, with the exception of the poorly documented site of Quinçay, a unique association. The presence of 29 Neanderthal teeth and a temporal bone has added support to the association of the Châtelperronian with Neanderthals (1–4), a link also documented at the French site of St. Césaire (Charente-Maritime) in 1979 (5).

Personal ornaments have often been associated with the beginnings of symbolic "modern" human behavior (6, 7). The earliest evidence for such activity has been linked with AMH in southern Africa, the Levant, and northwestern Africa from ≈75,000–90,000 B.P. (7, 8) or older, despite few associated fossil hominid remains. In Europe, the presence of personal ornaments is documented later in Aurignacian horizons (9). This industry is often linked with the initial dispersal of AMH into Europe around 35,000–40,000 B.P., albeit, again, with scant human fossil evidence (6). The discovery of ornaments in Neanderthal contexts at the Grotte du Renne (Fig. 1) has been explained as reflecting a phase of acculturation, when Neanderthals in France copied or mimicked the behavior of incoming AMH during a period of contemporaneity before their extinction (10). An alternative model, however, posits the independent localized development of complex symbolic behavior by Neanderthals in Western Europe before the arrival of AMH (2, 11). Material from the Grotte du Renne is at the very center of these models.

Two important variables contribute to establishing the relationship between the Châtelperronian and Aurignacian: stratigraphic context and a reliable chronometric framework. Although the second variable has been almost completely lacking, stratigraphic evidence suggests that the Châtelperronian is always found beneath Proto- or Early Aurignacian archaeological horizons (albeit with some debated instances of purported "interstratification" between the two) (12–14). Establishing a substantially earlier date for the Châtelperronian would provide strong support for independent Neanderthal development of some aspects of modern behavior before the arrival of modern humans in Western Europe. The reverse, or a more or less contemporaneous occurrence of the two, would favor an acculturation model on the basis of parsimony, because the appearance of symbolic behavior among Neanderthals at precisely the same time as the arrival of modern humans would amount to what Mellars (6, 10) has termed "an impossible coincidence."

The Grotte du Renne Site

The Grotte du Renne sequence comprises 15 archaeological levels (labeled I to XV, from top to base), which cover a depth of about 4 m (15). Levels V and VI contain a Gravettian technology, and below this, in level VII, is a Proto-Aurignacian industry similar to that found at sites on the Mediterranean coast such as Riparo Mochi (Italy) and the southern France sites of Isturitz, Esquicho-Grapaou, and La Laouza (16). Directly below the Proto-Aurignacian level are three Châtelperronian levels (VIII, IX, and X) and beneath these are Mousterian horizons. Of the Châtelperronian levels, level X assumes greatest importance, because the majority (25 of 40) of the ornaments and Neanderthal human remains co-occur in this level (17). Previous radiocarbon dating at the site

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[1]To whom correspondence should be addressed. E-mail: thomas.higham@rlaha.ox.ac.uk.

[2]Deceased December 9, 2009.

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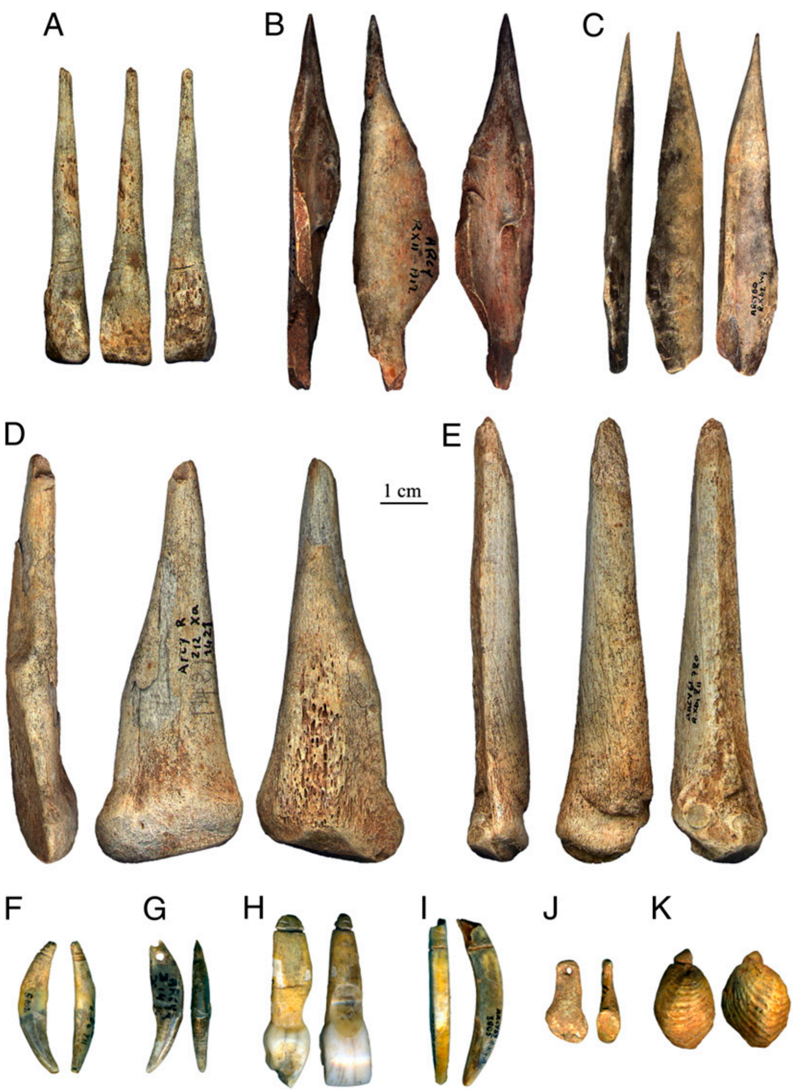

Fig. 1. The remains of some of the personal ornaments, awls, pierced animal teeth, and ivory pendants that have been excavated from the Châtelperronian levels at this site. Xa/c B9 no. 3657 (*A*); XII A12 sn, dated OxA-21594: 37 ± 1 kaBP (*B*); Xb2 W9 sn, dated OxA-21592: 36,200 ± 1,100 B.P. (*C*); Xa Z12 no. 1421, dated OxA-21557: 38,100 ± 1,300 B.P. (*D*); Xb1 Z11 no. 720, dated OxA-21590: 21,150 ± 160 B.P. (*E*); Xa Y11 no. 5102 (fox canine with groove) (*F*); Xb Z14 no. 96 (perforated fox canine) (*G*); Xa/c A/Z11 (bovid incisor with groove) (*H*); Xa A11 no. 3805 (marmot incisor with groove) (*I*); Xa Z13 sn (perforated reindeer phalange) (*J*); and Xb Y13 no. 3899 (*Rhynchonella* sp. fossil with groove) (*K*). [Image courtesy of M. Vanhaeren (Centre National de la Recherche Scientifique, Nanterre, France).]

has resulted in a wide range of ages covering 28,000–45,000 B.P., with little stratigraphic consistency (ref. 15, Fig. S1, and Tables S1 and S2). Questions remain over which of these dates are accurate, and whether those that appear aberrant are so for reasons of sample contamination or postdepositional mixing of material (a brief analysis of these determinations is offered in *SI Text*). This has resulted in confusion over the precise age of the Châtelperronian at this site.

Methods

Clearly, it is important to demonstrate stratigraphic integrity in any archaeological context. One useful way to do this is with a series of well-selected radiocarbon dates from throughout a succession of archaeological strata. Variation in the results outside that expected statistically might be held to herald problems with the sequence, whereas the reverse would improve confidence in its integrity. Experience has shown that to investigate the chronology of sites dating to the Paleolithic properly, one requires a large series of samples. We therefore took samples for radiocarbon dating from 59 pieces of humanly modified material from the Grotte du Renne, including cut-marked bones, horse teeth smashed by humans, bone points or awls, ornaments made of animal teeth, and mammoth ivory tusks interpreted as elements of structures (Table 1 and Table S3). These came from levels V to XII and were selected as far as possible to avoid areas of suspected disturbance and to focus on areas where the archaeological deposits were at their thickest. Samples were screened. Those acceptable on the basis of %N measurements (indicating the presence of protein) were prepared for accelerator mass spectrometry dating using a collagen extraction method incorporating the Oxford ultrafiltration protocol (18, 19) (*SI Methods* and Table S3).

The samples produced a wide range of ages (Table 2 and Fig. S2). We have used Bayesian modeling to identify outliers and analyze the overall sequence (Fig. 2) employing OxCal 4.1 software (20) and the INTCAL09 calibration curve (21). The basis of the Bayesian method is outlined in several publications to which the reader is referred (22–25). It allows archaeological information, in the form of stratigraphic data, to be combined with radiocarbon likelihood data. This so-called "prior" information, when incorporated mathematically with the radiocarbon likelihoods and analyzed using Markov Chain Monte Carlo (MCMC) simulation methods, acts to produce probability distributions known as posteriors. High posterior probabilities mathematically support the fact that sets of calibrated dates agree with the prior data and constraints imposed. The Bayesian modeling was undertaken on the assumption that the dated artifacts came from the archaeological levels identified at the time of excavation and had not been subject to movement or taphonomic influences. This relative information forms the basis of the priors in the Bayesian model. The priors can have a significant effect on the posterior distributions; thus, they must be used judiciously.

We first tested the fit of individual radiocarbon likelihoods through using overall agreement indices for each of a series of Bayesian models (24). This was applied to enable an objective assessment of the probability associated with individual measurements being outliers in the stratigraphic sequence. Potentially erroneous determinations within the sequence can be explicitly quantified, rather than remaining hidden. If the posterior probability (termed an agreement index) is >60%, there is a good agreement between the prior and posterior distributions, but values <60% imply the reverse is true and invite us to consider potential problems with radiocarbon likelihoods or priors in the model.

Table 1. Samples from the Grotte du Renne that failed to produce radiocarbon results

Lab. P. no.	Material	Species	Sample code, context, and description	Status
18989	Bone	Indeter.	Arcy 58 RVII D12 106 *retouchoir* on metapodial fragment	No collagen
18992	Bone	*Equus ferus*	Arcy 61 RXb 1b D9 1166 rib with ochre surface and regular incisions*	Low collagen
19739	Bone	Indeter. large carnivore with cut marks	Arcy 58 R VI D10 585, species indeter.	Low collagen
NA	Tooth	*Crocuta crocuta*	RVIII C6 448 y 59 pendant made from hyaena canine with "*rainurage*"	Failed on %N (0.5%)
NA	Bone	Indeter.	Arcy 58 VII B8 889 bone *lissoir* (16, figure 16.5)	Failed on %N (0.16%)
NA	Bone	*E. ferus*	Arcy1961 R Xb1 Z11 729 43 awl of horse lateral metapodial	No collagen despite 1.45%N
19740	Bone	Indeter.	Arcy 58 R VII C5, refitting basal fragment of an awl, 1.6%N, no collagen	No collagen despite 1.6%N
19745	Bone	*Rangifer tarandus*	Arcy R VII c B14 607 awl made from fragment of anterior face of metatarsal (ref. 33, figure 134:2)	Low collagen
19746	Bone	*E. ferus*	Arcy R VIII B12 20 (42) awl made on lateral metapodial (1.7%N).	Low collagen
19754	Ivory	*Mammuthus primigenius*	RXb1 c/D11 mammoth tusk fragment	No collagen
19756	Ivory	*R. tarandus*	Arcy 61 RXb1c C9 (463) right scaphoid with cut marks	Low collagen
19759	Ivory	*M.primigenius*	Arcy 61R Xb2 Z11 tusk fragment	No collagen
19763	Bone	*R. tarandus*	Arcy 1963 RXc C8 1822 awl made from portion of a reindeer metapodial	Too low collagen despite 1.76%N
19766	Bone	*R. tarandus*	Arcy R 56 XII C8 proximal femur (right?) with cut marks	No collagen
22143	Tooth	*E. ferus*	Arcy IX smashed horse tooth	C/N atomic ratio = 3.9, failed
22145	Tooth	*E. ferus*	Arcy IX smashed horse tooth	C/N atomic ratio = 6.3, failed
NA	Bone	*C. crocuta*	Arcy Rxa A13 (4) hyaena cut first phalange	3.1%N but not dated because too small
NA	Bone	*C. crocuta*	Arcy Rx(Xb) Z13 hyaena cut first phalange	Failed on %N (0.16%)
NA	Bone	*C. crocuta*	Arcy 62 X B2 A11 437 hyaena cut first phalange	3.0%N, not dated because sample of bone too small

For %N samples, we considered a bone to be worth pretreating if its %N was >0.76%. If the value is lower than this, the bone is failed. Samples with no or low collagen in the status column were treated at the Oxford Radiocarbon Accelerator Unit but produced an insufficient, or no, yield of collagen. Two samples that had C/N atomic ratios significantly over >3.5, our usual cutoff for acceptability, produced results and were failed. Indet., indeterminate; NA, not applicable.
*Treated with paraffin and/or Rhodopas M60 and/or polymul.

The first model failed to yield any results because of the wide degree of variation in the radiocarbon likelihoods; therefore, it was not possible to assess agreement. A null distribution was produced. The two obvious outliers in level X were therefore removed (OxA-21590 and OxA-X-2222-21). Subsequently, the model produced posterior results but an overall agreement index of only 0.2%. Again, this is attributable to the substantial variation in the dataset. Two determinations yielded agreement indices of about 0%; OxA-21683 and OxA-21575. OxA-21594 produced an agreement index of 3.9%, and OxA-21574 produced an agreement index of 3.0%. These determinations were therefore removed in the subsequent analysis. In addition, there were several other results with low indices: OxA-21573, OxA-X-2279-45, OxA-X-2279-44, OxA-21591, OxA-21595, and OxA-21577. These were all <60%. (It should to be noted that OxA-X-2279-44 was close enough to the limit of the INTCAL09 curve to be almost out of range). The third iteration of the model was then run without the first four determinations in it, and this produced another low overall agreement model of 4.8%, with OxA-21683 (0.3%), OxA-21593 (39.7%), OxA-21591 (12.8%), OxA-21577 (13.1%), and OxA-21595 (13.9%) all yielding indices <60% again. With the exception of OxA-21593, these were removed in the next analysis. This resulted in a model with acceptable agreement of 85.3%. Taken together, therefore, approximately one-third of the determinations using this method are in poor overall agreement with the modeling.

We also tested the sequence and model using an outlier detection approach (25). This produced similar results. The advantage of outlier detection is that all the data can be included; however, for certain values thought to be problematic, a higher prior outlier probability can be assigned. Significant outliers are effectively down-weighted in the subsequent model. To avoid bias in the model, we used a t-type outlier model with a probability of 0.05 for each value (with the exception of one of the awls dated from level XII, which has been suspected of being intrusive to that level) in the model. This outlier model is the best suited, because a proportion of the samples were expected to be out of context, given the age of the excavation and possible cryoturbation/depositional influences. These analyses showed that nine of the determinations were outliers (*SI Methods* and Table S4) and essentially confirm the results of the agreement indices described above. The final age model generated using outlier analysis methods is shown in Fig. 2.

Discussion

Our five dates from the Aurignacian level VII provide a mean age of 34,800 ± 300 B.P. and are broadly consistent with other dates we have obtained from European sites with a similar lithic industry. Therefore, material from below level VII ought to be older than or contemporary with the age determined for this level and not younger. Many of the dates from below level VII are, however, too young for their expected relative chronostratigraphic position. Within the Châtelperronian levels, the radiocarbon ages range from ∼21,000–49,000 B.P.. The most serious problems are associated with the lowest Châtelperronian level (X), where more than one-third of the radiocarbon ages are statistical outliers. There are three dates on cut-marked bones from this level that are directly comparable in age to those from the Proto-Aurignacian level (OxA-21577, OxA-21591, and OxA-21593, and probably also OxA-21592, a date from an awl; Fig. 1*C* and Table S3). This implies the presence of Aurignacian-aged material in the Châtelperronian levels. In the uppermost Châtelperronian level (VIII), there are two dates that are close to the ages obtained from level VII. In level IX, a result of 32,100 ± 550 B.P. was obtained on a cut-marked reindeer astragalus. This is clearly too young for its context. Two artifacts (OxA-21590, a bone awl, and OxA-X-2222-21, a *retouchoir*) from level X produced significantly younger dates, consistent with Proto-Solutrean and Gravettian ages, both of which are

Table 2. Radiocarbon determinations from the Grotte du Renne, Arcy-sur-Cure

OxA no.	^{14}C age B.P.	Used, mg	Yield, mg	%Yield	%C	δ^{13}C, ‰	C/N atomic ratio
Level V							
OxA-21567*	23,070 ± 210	456.4	4.7	1.0	41.6	−20.1	3.3
OxA-21568*	23,180 ± 210	572.7	4.5	0.8	42.5	−18.7	3.4
Level VI							
OxA-X-2279-12	34,850 ± 600	1,010	6.1	0.6	44.6	−21.0	3.3
Level VII							
OxA-21682	35,000 ± 650	1,130	7.2	0.6	44.1	−21.1	3.3
OxA-21569*	36,500 ± 1,300	479.5	4.3	0.9	41.3	−19.7	3.2
OxA-21570*	34,600 ± 800	236.5	3.4	1.4	42.4	−19.1	3.2
OxA-21571*	34,050 ± 750	491.6	6.6	1.3	41.1	−18.7	3.2
OxA-21572*	34,600 ± 750	528.9	10.8	2.0	42.7	−18.6	3.3
Level VIII							
OxA-X-2279-14	35,450 ± 750	1,310	4.1	0.3	42.2	−20.2	3.3
OxA-21683	40,000 ± 1,200	990	7.3	0.7	44.5	−21.0	3.3
OxA-21573*	36,800 ± 1,000	507.1	6.9	1.4	41.6	−19.2	3.2
Level IX							
OxA-21574*	38,800 ± 1,300	551.2	13.2	2.4	42.1	−19.0	3.2
OxA-21575*	32,100 ± 550	664.3	11.6	1.7	42.5	−19.0	3.2
Level X							
OxA-21565*	37,900 ± 900	600	12.3	2.1	40.0	−20.7	3.2
OxA-21557*	38,100 ± 1,300	240	2.7	1.1	41.1	−20.6	3.3
OxA-21576*	40,800 ± 1,700	529.1	5.6	1.1	42.2	−18.4	3.2
OxA-X-2222-21*	23,120 ± 190	506	3.8	0.8	43.4	−20.2	3.6
OxA-21577*	34,650 ± 800	636.2	5.4	0.8	41.8	−19.4	3.2
OxA-X-2226-7*	38,500 ± 1,300	620.1	3.2	0.5	44.3	−19.5	3.7
OxA-21590*	21,150 ± 160	470.3	5.7	1.2	45.2	−20.7	3.2
OxA-21591*	34,750 ± 750	620.2	9.9	1.6	44.4	−18.9	3.3
OxA-21592*	36,200 ± 1,100	213.5	2.3	1.1	43.1	−19.4	3.4
OxA-21593*	35,300 ± 900	440.3	7.9	1.8	42.1	−18.8	3.3
OxA-X-2226-12*	41,500 ± 1,900	458.3	3.0	0.7	43.1	−18.3	3.3
OxA-X-2226-13*	39,000 ± 1,400	451.2	3.4	0.8	44.2	−18.6	3.3
OxA-X-2279-18	40,600 ± 1,300	1,100	5.3	0.5	43.7	−21.2	3.2
OxA-X-2279-44*	48,700 ± 3,600	970	5.1	0.5	37.3	−20.9	3.3
OxA-X-2279-45*	40,900 ± 1,300	1,020	6.8	0.7	37.4	−20.4	3.3
OxA-X-2279-46*	38,700 ± 1,000	1,000	6.5	0.7	41.6	−20.4	3.3
Level XII							
OxA-21594*	37,000 ± 1,000	399.6	6.9	1.7	44.6	−19.0	3.3
OxA-21595*	38,200 ± 1,200	418.7	5.9	1.4	42.5	−20.7	3.3

All are ultrafiltered gelatin determinations. Stable isotope ratios are expressed in ‰ relative to Vienna Pee-Dee Belemnite (vPDB). Mass spectrometric precision is ±0.2‰. The weight used is the amount of bone pretreated, and the yield represents the weight of gelatin or ultrafiltered gelatin in milligrams. %Yield is the wt% collagen, which, ideally, should not be <1wt% at the Oxford Radiocarbon Accelerator Unit (ORAU). This is the amount of collagen extracted as a percentage of the starting weight. Collagen is not well preserved at the site. %C is the carbon present in the combusted gelatin. For ultrafiltered gelatin, this averages 41.0 ± 2%. C/N is the atomic ratio of carbon to nitrogen. At the ORAU, this is considered acceptable if it ranges between 2.9 and 3.5. In one case, a sample (OxA-X-2226-7) yielded a C/N of 3.7, which indicates the addition of carbon; therefore, one should view this result with caution. Initially, we calculated this as a ratio greater than age, and we accepted the result in our modeling. It was not flagged as an outlier. Subsequent recalculations using more recently obtained background measurements resulted in a finite age. We include it but acknowledge the potential for a contamination signal. OxA-X- prefixes are given where the chemistry is non-routine or experimental, or where the yields of %wt collagen or extracted collagen are lower than, or approaching, the thresholds set at the ORAU. Details of the sample materials dated are provided in Table S3 (*SI Methods*).

*Bones were pretreated before collagen extraction with a solvent sequence as a precaution before accelerator mass spectrometry dating. This is designed to remove any consolidants or glue-based contaminants. Careful observation and sampling mitigated against the presence of this, with the exceptions described in the paper.

known from the Arcy-sur-Cure complex of sites, albeit, for the former, from earlier excavations (26). The age for OxA-X-2222-21 is identical to the two available determinations from level V, the Gravettian level at Arcy. These two samples had low collagen yields and surface consolidation visible at the time they were sampled, but Fourier transform infrared analysis shows that this is Poly-Vinyl Acetate (PVA) in the case of the very young sample (OxA-21590), which is soluble in the pretreatment chemistries we applied and, as a ^{14}C-free material, would not act to make the ages younger than expected were it to remain unremoved. Our conclusion is that it was avoided and removed by (*i*) careful sampling of the bone before dating and (*ii*) the application of a solvent extraction sequence designed to mobilize this material before dating.

Another sample from the Châtelperronian levels produced a much older age than expected. A smashed horse tooth from level X gave a result of 48,700 ± 3,600 B.P. (OxA-X-2279-44)

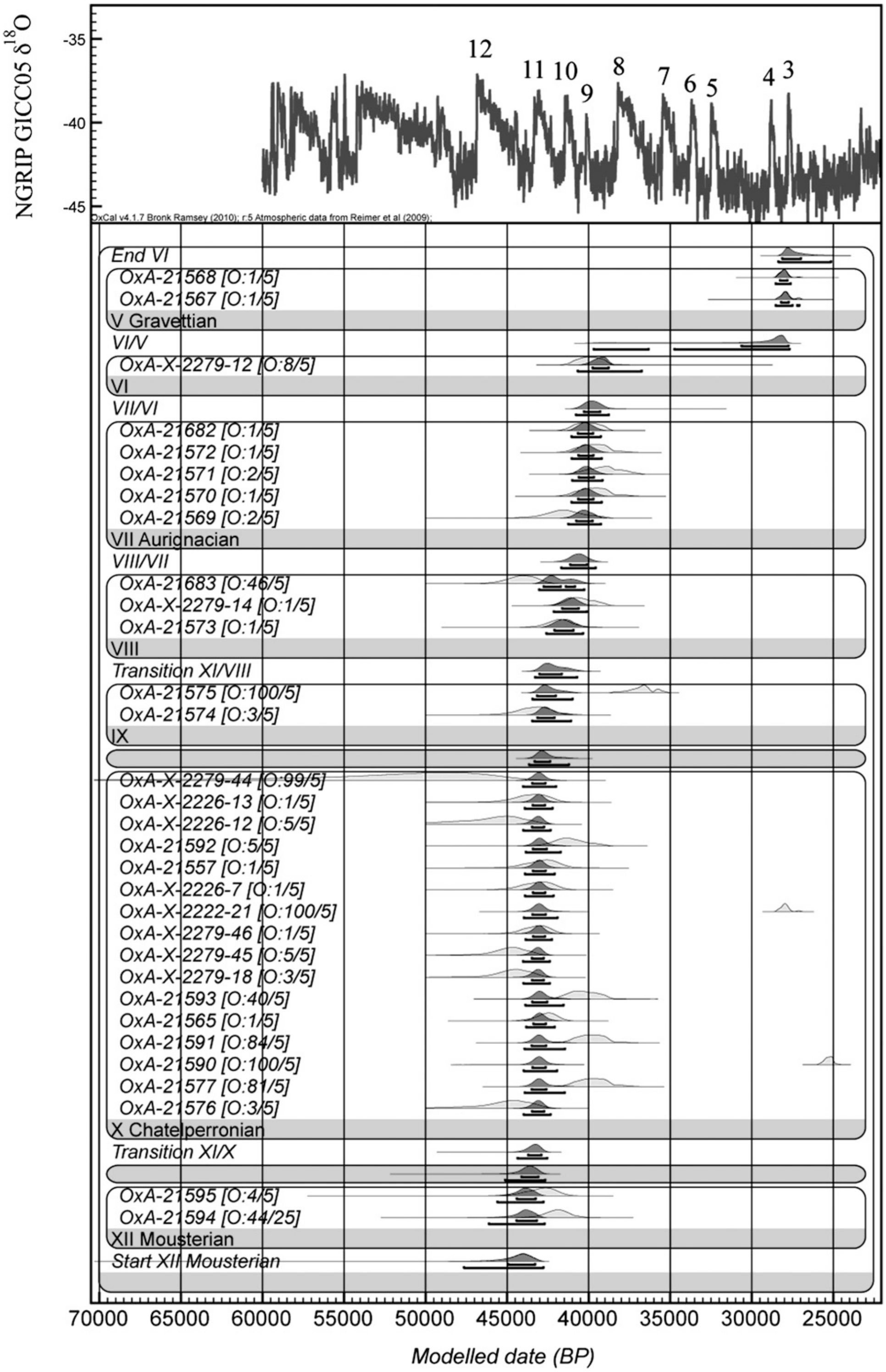

Fig. 2. Bayesian model for the radiocarbon dates obtained at the Grotte du Renne sequence. This model was generated using OxCal 4.1 (24) and the INTCAL09 calibration curve (21). The model is built based on the known stratigraphic sequence for the site, and the data are divided into phases. There are a large number of outliers in the Châtelperronian levels (Table S4). Lighter shaded distributions are calibrated radiocarbon likelihoods, whereas darker outline distributions are posterior probabilities after modeling the sequence. The outlier posterior and prior probabilities are given in brackets next to the OxA- and OxA-X numbers. The data are compared with the North GReenland Icecore Project (NGRIP) δ18O climate record (31, 32).

(Table 2). This suggests that some material is probably derived from the lower Mousterian levels. This could have occurred when the first Châtelperronian occupation began, as suggested previously (15). There is evidence for digging and leveling at the site during this period. Older than expected radiocarbon results are unlikely to be caused by contamination with exogenous carbon, because the proportion of old contaminating carbon required is unrealistically high (>50%). Modern contamination is much more significant at ages greater than ~30 ^{14}C kaBP, but the analytical chemistry associated with each sample was assessed, and with the exception of two cases, the samples yielded acceptable values (Table 2). Taken together, the evidence suggests that the radiocarbon results from the site are reliable, despite low recoverable collagen levels in some instances.

Among the other results obtained is a date for a bone awl that is among the earliest direct ages for this artifact type in Europe, at 38,100 ± 1,300 ^{14}C B.P. (OxA-21557; Table 2). The artifact is culturally nondiagnostic, but its age appears to provide evidence for late Neanderthal bone working before the arrival of AMH, if one accepts its context as secure. Another awl dated to 37,000 ±

1,000 B.P. is from the Mousterian level XII but was located in an area in which there had been extensive disturbance by Châtelperronian hearths and pit digging. Previous workers have suggested that these awls are derived from the Châtelperronian, as discussed previously (27).

Conclusions

Some researchers have argued that mixing is likely to be a serious problem at the Grotte du Renne (28, 29), whereas others have argued strongly for the integrity of the Châtelperronian levels at this site and the almost unique association between human remains and artifacts that this implies (2, 3, 17). No lithic or bone refitting studies or micromorphological analyses were presented, however, in support of these assertions, despite the widely acknowledged importance of such work in assessing stratigraphic integrity within Paleolithic archaeological sequences (30). Our results confirm that material from several contexts has moved both up and down the stratigraphic sequence into the Châtelperronian levels. We have identified material identical in age to that determined for level VII in levels lower than this. The evidence therefore necessarily raises questions regarding the confidence we ascribe to the context of material within this site and, importantly, the widely accepted association between the Châtelperronian and the Neanderthal remains. We conclude that the evidence from the Grotte du Renne ought to be viewed with extreme caution in terms of models of Neanderthal acculturation or of their independent development of symbolic behavior until further evidence is brought to bear on this issue. It has not yet been possible to date any ornaments directly, despite our best efforts. Direct dates could confirm or refute their stratigraphic position within the sequence. Similarly, direct dates on the Neanderthal teeth themselves are required to demonstrate that they are not of an age expected for the Mousterian and to exclude the possibility that they derive from earlier occupations than the Châtelperronian. Permission for dating the human teeth, however, could not be obtained by us. The preservation state of the other bone and teeth suggests that we will probably have to wait for further developments in the radiocarbon dating of very small amounts of remaining protein for this to be undertaken. Stratigraphic integrity is a vital prerequisite at any archaeological site and must be demonstrated before competing hypotheses regarding the association between the Châtelperronian and hominid remains and artifacts from the Grotte du Renne can be evaluated further.

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