A high-precision chronological model for the decorated Upper Paleolithic cave of Chauvet-Pont d'Arc, Ardèche, France

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Radiocarbon dates for the ancient drawings in the Chauvet-Pont d'Arc Cave revealed ages much older than expected. These early ages and nature of this Paleolithic art make this United Nations Educational, Scientific and Cultural Organization (UNESCO) site indisputably unique. A large, multidisciplinary dating program has recently mapped the anthropological evolution associated with the cave. More than 350 dates (by ^{14}C, U-Th, TL and ^{36}Cl) were obtained over the last 15 y. They include 259 radiocarbon dates, mainly related to the rock art and human activity in the cave. We present here more than 80 previously unpublished dates. All of the dates were integrated into a high-precision Bayesian model based on archaeological evidence to securely reconstruct the complete history of the Chauvet-Pont d'Arc Cave on an absolute timescale. It shows that there were two distinct periods of human activity in the cave, one from 37 to 33,500 y ago, and the other from 31 to 28,000 y ago. Cave bears also took refuge in the cave until 33,000 y ago.

Chauvet-Pont d'Arc cave | radiocarbon dating | Upper Paleolithic | Bayesian modeling

The cave of Chauvet-Pont d'Arc (Vallon-Pont d'Arc, Ardèche, Southern France), with its vivid red and black drawings and paintings, as well as engravings, is a prehistoric decorated cave of exceptional interest, recently classified as a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage site (1–5). Based on stylistic considerations, this art was first attributed to the Solutrean period (~22,000–18,000 B.P.). Surprisingly, however, the first ^{14}C dates of black drawings (the only depictions datable by this method) indicated a much older age (~32,000–30,000 B.P.) (6–9). These dates had a significant impact on commonly accepted theories of the evolution of prehistoric art (10) and thus emphasized the need to obtain a thorough understanding of the occupation history of the cave. A clear chronological framework would reveal the age not only of the art, but also of the periods of human and animal occupation and their relationship to the geomorphological evolution of the cave.

Chronologies can be relative or absolute. In this context, relative dating refers to the ordering of the art works and natural or animal related events within a relative temporal sequence, commonly based on patterns of superimposition of the different occurrences: for example, a painting that is overlain by another in a "stratigraphic sequence" is the oldest of the two, and a bear scratch on top of a drawing indicates that humans no longer occupied the cave when the scratch was made. Based on this information alone, however, we do not know how much older the underlying event is: thus the need to obtain absolute dates of parietal art works.

In the chronology presented here, we use all of the absolute dates obtained from the art works, as well as other data associated with the parietal art, and animal and human occupations. Our earlier sampling methods and ^{14}C methodology were criticized (11–13). Before publishing further rock art dating results, we therefore initiated a broad, international intercomparison program of ^{14}C dating, followed by a holistic chronological model based on an extensive corpus of dates obtained by several different methods.

A set of 259 radiocarbon dates is currently available (Fig. 1 and *SI Appendix*, Fig. S1 and Table S1). They were compiled over the last 15 y and include analyses performed on samples consisting of parietal elements, such as animal drawings and charcoal marks (including torch marks), as well as charcoal and bear bones found on the cave floor. This research includes two intercomparison programs performed by various laboratories (14, 15); the charcoal samples were recently integrated into the Sixth International Radiocarbon Intercomparison Program (16). A set of more than 80 previously unpublished ^{14}C results obtained from

Significance

We compiled a set of more than 250 radiocarbon dates related to the rock art, human activities, and bone remains in the Chauvet-Pont d'Arc Cave (Ardèche, France) and derive a modeled absolute chronology of the human and cave bear occupations of this site, presented here in calendar years. It provides an insightful framework for the successive events that occurred in the cave during the Paleolithic period.

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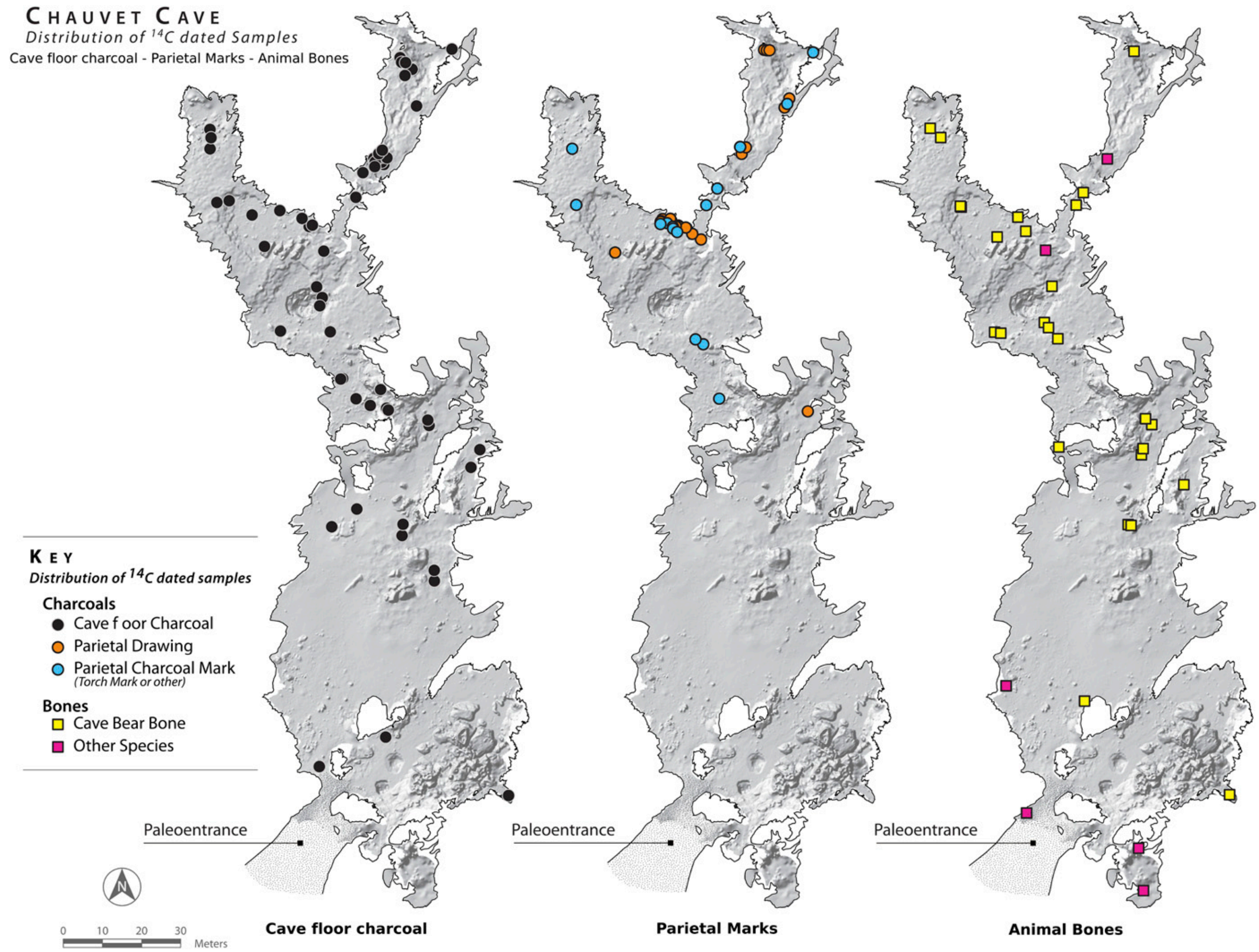

Fig. 1. Map of the Chauvet-Pont d'Arc Cave with localization of ^{14}C samples: cave floor charcoal (71 analyses), drawings and charcoal marks (42 analyses), and animal bones (30 *U. spelaeus*, 5 other species, and a burned bone specimen).

clearly delimited human occupation phases in the cave is presented here.

Other dating methods were applied to different materials. Heated wall fragments were dated by thermoluminescence to determine the age of hearth structures (17, 18). Uranium-series dating was applied to carbonate concretions superimposed on some ^{14}C-dated charcoal, yielding a *"terminus ante quem"* for the deposit of this charcoal (19, 20). The latter was recently confirmed by ^{36}Cl exposure dating of rock, indicating collapses that occurred in the past and that sealed off the (paleo) entrance of the cave (21) (Fig. 1), thereby confirming the early age of the art contained inside.

Currently, the Chauvet-Pont d'Arc Cave is the European Paleolithic rock art site with by far the largest number of independent dates obtained by different methods with the aim of comparing them to identify the occupation phases in the cave. This complex and substantial set of dates was purposefully attained from distinct archaeological and environmental remains. The results require integration into a high-precision Bayesian model, which also makes use of archaeological evidence. This approach enables the identification of distinct human and animal occupations in the cave in relation to past geomorphological events. Through this work, the complete history of the cave is now securely positioned on an absolute timescale.

Materials and Methods

A map of the Chauvet-Pont d'Arc Cave is shown in Fig. 1. The location of the ^{14}C samples is indicated. A multidisciplinary Geographical Information System (GIS) database has been used since 2008 (22). It allows precise and easy access to the documentation by incorporating accurate 3D spatial positioning of each object and sample.

Three independent sampling strategies were used:

i) An innovative strategy was developed for charcoal pieces lying on the cave floor. They were sampled uniformly throughout the cave to obtain a statistically significant chronological record of its human occupation (*SI Appendix*, Fig. S1). The main limitations were the accessibility of the charcoal pieces that lay on the floor at varying distances from the metallic pathway on which we were required to circulate, and their state of preservation. Seventy-one charcoal samples from the cave floor were selected, and 8 were integrated into three intercomparison programs (14–16) (*SI Appendix*, Table S1). In total, 159 radiocarbon determinations were made on charcoal. In some cases, the charcoal could be attributed to the species *Pinus* (23).

ii) Samples of black charcoal drawings and charcoal marks (including torch marks) were taken following the recommendations of the parietal art specialists. Twenty-three charcoal drawings were sampled from different panels in the Hillaire Chamber (Panel of the Horses, Panel of the Reindeer, Alcove of the Lions), Skull Chamber (Deer Calf Pendant), Megaloceros Gallery (Panel of the Megaloceroses, Horse with a Double Mane, Rhinoceros Panel), and the End Chamber (Panel of the Bison, Belvedere Gallery entrance) (26 analyses), and 15 charcoal marks were

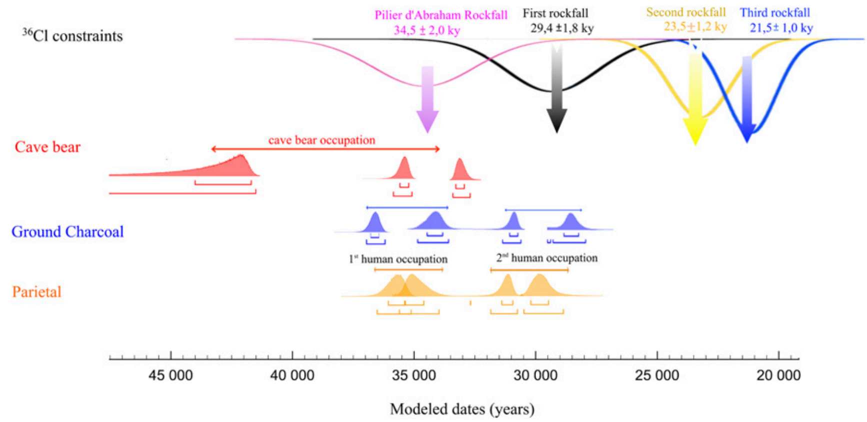

Fig. 2. High-precision Bayesian model obtained for the Chauvet-Pont d'Arc Cave. Modeled boundaries for the start and end of each occupation phase are represented in red for the Cave Bear model (postulating a continuous occupation), in blue for the Cave Floor Charcoal model, and in orange for the Parietal model. Two distinct human occupations are clearly identified, extending from 37,000 to 33,500 y ago for the first one, and from 31,000 to 28,000 y ago for the second one. Cave bear presence in the cave is attested until 33,000 y ago.

sampled from the sill to the end of the cave, in the Belvedere Gallery (16 analyses) (*SI Appendix*, Table S1).

iii) Dated bone samples were integrated into larger studies on paleontological remains (24, 25), including analysis of the stable isotopes ^{13}C and ^{15}N (26, 27), and cave bear DNA analysis (28). Bone species were selected randomly in the cave, taking into account their collagen preservation state. Thirty-six bone fragments found on the cave floor were analyzed, 30 of them belonging to *Ursus spelaeus* (*SI Appendix*, Table S1).

Cave floor charcoal and parietal occurrence analyses were mainly performed at the Tandetron [Laboratoire des Sciences du Climat et de l'Environnement (LSCE), Gif-Sur-Yvette, France] until 2001 (29) and, after this date, at the Artemis facility [3 MV-Pelletron accelerator, LSCE/Laboratoire de Mesure du Carbone 14 (LMC14), Gif-Sur-Yvette, France] (30), except for some of the oldest analyses, which were performed at the Radiocarbon Dating Center (Lyon, France) using conventional liquid scintillation counting or accelerator mass spectrometry (AMS) as a supplier. Intercomparison samples were analyzed in several laboratories worldwide (*SI Appendix*, Table S1). For the AMS analyses, charcoal samples were prepared using the standard acid–base–acid (ABA) method (31). The so-called "humic fraction" resulting from the base treatment was also dated to evaluate possible contamination of the charcoal (22 analyses) (*SI Appendix*, Table S1 and Fig. S2). The δ^{13}C values were measured for all samples for the purpose of fractionation correction, following the international convention (32). For bone samples, the collagen was extracted applying an improved version of the Longin method (33) before dating at the Groningen Radiocarbon Laboratory.

Very small samples were analyzed using mass-dependent "blank" values (34–38). The lower the mass of the sample, the larger the ^{14}C age uncertainty, up to 3 ka for samples containing less than 0.1 mg of carbon. The data reported are presented in *SI Appendix*.

Results and Discussion

A set of 259 radiocarbon determinations was obtained from samples taken from the cave floors and walls. Only one result was rejected because of obvious contamination due to taphonomic processes and/or laboratory handling (*SI Appendix*, Table S1). More than 95% of the radiocarbon ages were measured as older than 25 ka B.P., and the 71 charcoal samples from the cave floor clearly show the existence of two main periods. The oldest period, associated with most of the samples and the eight intercomparison samples, ranges from ∼32–30 ka B.P.; the second ranges from ∼27–24 ka B.P. Nearly all of the radiocarbon dates of the black drawings correspond to the oldest occupation phase; only two dates could be associated with the second phase. The charcoal marks on the walls date to between 27 and 26 ka B.P. and belong to the second occupation phase. The dates of the humic fractions of 22 samples (16 drawings and six charcoal marks) concur with the dates of the associated purified charcoal fractions, showing that these charcoal specimens were not contaminated. Among the 30 cave bear (*U. spelaeus*) bones analyzed, 26 fall within the time range of the first human occupation period, between 32 and 29 ka B.P. Four analyses (including one sample that was dated twice) yielded an age older than 34 ka B.P. Five other animal species were also dated: two *Canis lupus* (wolf), one *Capra ibex* (ibex), one *Capreolus capreolus* (roe deer), and one *Martes sp* (marten).

The radiocarbon dates were calibrated with the IntCal13 curve (39, 40) using OxCal software (v.4.2). All of the chronometric evidence leads to the same primary conclusions, showing two distinct human occupations, the first ranging from 37 to 33 ka cal (calibrated) B.P., followed by a second one from 31 to 28 ka cal B.P. The cave bear occupation extends from 42 to 33 ka cal B.P., thus almost in the same time range as the first human occupation phase. The *C. lupus* bones' ages fall into the human occupation phases whereas the *C. ibex* bone gives an age of 27.5–26.9 ka cal B.P. A *Martes* sp. bone yields a Holocene age, indicating a recent incursion of small mammals close to the entrance, probably linked with the *C. capreolus* bone.

The radiocarbon dates were used to generate a high-precision chronological sequence, using Bayesian modeling. The modeled results are expressed in ka cal B.P. with a 2σ uncertainty range. We selected only samples with an uncertainty of less than 1,500 ^{14}C y (1σ) and that yielded more than 0.1 mg of carbon. From the remaining 220 dates, three separate models were constructed and designated as the following: Cave Floor Charcoal, Parietal, and Cave Bear.

The initial archaeological premise was that several separate human occupation phases occurred during the prehistory of the cave. This hypothesis was based on empirical observations of independent archaeological information, as follows: (*i*) Several graphic superimpositions separated by bear scratches are visible on different panels (41); (*ii*) some charcoal marks (including torch marks) are superimposed on decorated panels (2); and (*iii*) several thin archaeological layers are present in three excavation pits (42). To test this initial archaeological hypothesis, the radiocarbon dates were sorted into two separate "phases," and "phase boundaries" were postulated (43). The measured calibrated date ranges were included as likelihoods in these two phases, without any other prior information about the absolute dating. Outlier probabilities (44) were defined for each sample based on its carbon mass (*SI Appendix*, Table S1 and Figs. S3 and S5).

The modeling of the dates of the charcoal from the cave floor shows that the first prehistoric human occupation could have been longer than the second one. To investigate the length of this occupation, the 88 dates of the intercomparison programs

Table 1. Results of human and animal occupation phase models using the IntCal13 calibration curve

Boundary	Number of ^{14}C dates in models (220)	IntCal 13 68% (ka cal B.P.) From	To	95% (ka cal B.P.) From	To
Cave floor charcoal					
Start I	157	36.7	36.4	37.0	36.2
End I		34.2	33.7	34.4	33.5
End I ^{36}Cl	69 Cave floor charcoal	34.2	33.7	34.4	33.5
Interval		2.6	3.2	2.3	3.5
Interval ^{36}Cl	88 Intercomparison analyses	2.6	3.2	2.3	3.5
Start II		31.1	30.8	31.4	30.7
End II		28.8	28.3	29.7	27.9
End II ^{36}Cl		28.8	28.3	29.5	27.9
Parietal					
Start I	33	36.1	35.4	36.6	35.2
End I		35.5	34.6	35.8	34.0
End I ^{36}Cl		35.4	34.6	35.7	34.0
Interval		3.3	4.3	2.7	4.6
Interval ^{36}Cl		3.3	4.2	2.7	4.9
Start II		31.4	31.0	31.9	30.5
End II		30.2	29.5	30.6	28.9
End II ^{36}Cl		30.1	29.5	30.5	29.0
Cave bear					
Start I	30	44.0	41.7	48.3	41.5
Intermediate		35.6	35.3	35.9	35.1
End I		33.3	33.0	33.5	32.7
End I ^{36}Cl		33.3	33.0	33.5	32.7

Results were obtained using the outlier approach.

were combined to obtain one sample age density (14–16). Such modeling substantially reduces the uncertainty of the sample determination. The resulting temporal densities obtained overlap and are strongly concentrated around 35.9 ka cal B.P., with a range of less than 500 y (*SI Appendix*, Fig. S4). They are clearly linked with the first human occupation (*SI Appendix*, Table S2).

The first five intercomparison samples were collected in the Megaloceros Gallery using the same random sampling strategy as that used for all of the other cave floor charcoal pieces, and we assume that they are representative of the first human occupation of the cave. Recently, the Sixth International Radiocarbon Intercomparison Program integrated charcoal pieces from the Chauvet-Pont d'Arc Cave into its study; they were dated by 47 laboratories worldwide and resulted in a mean value of 31,765 ± 136 B.P. (75 determinations, in addition to the 259 of this paper) (16). This result means that each time we succeeded in improving the precision of a charcoal sample, we obtained an average of about 32,000 B.P. It is interesting to note that the distribution of the calibrated ranges of the 69 cave floor charcoal dates is similar to the calibrated individual densities of the intercomparison analyses. This agreement shows that the intercomparison results are representative of all other cave floor charcoal samples, and thus also of the first human occupation phase. This first human occupation was at around 35.9 ka cal B.P.

Taken together, the 69 dates from individual cave floor charcoal samples and the combined intercomparison densities were integrated into the Cave Floor Charcoal model, and 33 dates (19 black drawings and 14 charcoal marks) were integrated into the Parietal model. The Cave Floor Charcoal model provides a chronological foundation for the human occupation in the cave, which extends from 37,000 to 28,000 y ago with two separate occupation phases. The first human occupation phase extends from 37.0–36.2 to 34.4–33.5 ka cal B.P., and the second one from 31.4–30.7 to 29.7–27.9 ka cal B.P. (Table 1 and *SI Appendix*, Table S2 and Fig. S4). The time interval between the end of the first phase and the beginning of the next one extends from 2.3 to 3.5 ka. Similar conclusions were obtained with the Parietal model. Due to the small number of dates, however, the modeled boundaries are wider in this case and overlap whereas the interval gap between them is also larger (Table 1 and *SI Appendix*, Table S3 and Fig. S6). These two models led to plausible and mutually compatible results showing that, statistically, the archaeological evidence and radiocarbon dates concur with each other.

No archaeological or paleontological evidence has been found to indicate that two separate cave bear occupation phases occurred in the cave. The Cave Bear model, which incorporated 30 dates, was constructed using one phase limited by an upper and lower boundary. An intermediate boundary was added to test the possibility of distinct phasing. The Cave Bear model yields boundaries extending from 48.3–41.5 to 33.5–32.7 ka cal B.P., indicating that the cave bear occupation was contemporaneous with the first human occupation phase. No remains of this species younger than 33 ka cal B.P. have been found in the cave (Table 1 and *SI Appendix*, Tables S4 and S5 and Fig. S7). Nevertheless, the resolution of the ^{14}C analysis is insufficient to refine the chronology between the first human occupation and the cave bear occupation, and in particular to determine whether these two occupations occurred at the same time. However, it is important to remember that a minimum of 200 individual cave bear skeletons have been identified thus far (24). Therefore, even if the first human occupation phase and the cave bear occupation phase fall within the same broad time interval, this overlap does not mean that both were present in the cave at the same time.

The dating strategy for the study of the Chauvet-Pont d'Arc Cave does not rely on radiocarbon analyses alone. An integrated and multidisciplinary approach was developed to define a common temporal framework of both human and animal activities, as well as environmental events. Two fires that burned the walls of the cave were thus dated by thermoluminescence (TL). The results fall within the first ^{14}C-dated human occupation phase (17, 18). In addition, the ^{36}Cl cosmic-ray exposure method was used to date the different rockfalls that sealed the (paleo) entrance of the cave (21, 42). This study identified three successive rockfalls with mean ages of 29.4 ± 1.8 (E1), 23.5 ± 1.2 (E2), and 21.5 ± 1.0 ka (E3). They were preceded by a first boulder rockfall near the Abraham Pillar (PAbr), which is located on the access path to the (paleo) entrance and is dated to 34.5 ± 2.0 ka. In addition, uranium-series dating was performed on a speleothem deposited on the rockfall and sealing the cave entrance, showing that this rockfall occurred more than 11.5 ka (20).

Comparing the set of calibrated radiocarbon dates with the four distinct rockfall events dated by ^{36}Cl shows that the beginning of the gap between the two human occupations could be contemporaneous with the Abraham Pillar rockfall and that the end of the second human occupation could have coincided with the E1 rockfall. Because the ^{36}Cl densities are independent of any radiocarbon information, we postulated that, a priori, the temporal distributions of the Abraham Pillar and E1 rockfalls could have occurred in conjunction with the end of both occupation phases. These Gaussian temporal densities were integrated as a priori boundaries for the end of the first and second human occupation phases in the Cave Floor Charcoal and Parietal models. For the Cave Bear model, we successively tested the Abraham Pillar and E1 temporal distributions as a priori boundary distributions for the end of cave bear occupation. By default, we kept uninformative distribution functions for the beginning of all "phase boundaries."

The Cave Floor Charcoal and Parietal a posteriori models confirmed the plausibility of correlating these geological events with the abandonment of the cave by humans (*SI Appendix*, Tables S2 and S3). For the Cave Bear model, the use of the Abraham Pillar rockfall estimate results in a more plausible model than the one constructed based on the E1 rockfall estimate, which does not set any constraints on the simulated temporal density associated with the end of cave bear occupation (*SI Appendix*, Table S4). Based on our data, the Abraham Pillar rockfall and the end of the cave bear occupation phase statistically concur. These models raise the question of the consequences of such rockfalls on the human and animal occupations of the cave.

The high-precision Bayesian model that we derived using an outlier approach provides a coherent and insightful framework for the successive events that occurred in the Chauvet-Pont d'Arc Cave during the Paleolithic period. It has enabled us to derive a robust chronological record of the cave, from the perspective of both the human and animal occupation phases, as well as its environmental evolution. This chronological model revises the history of the prehistoric people who frequented the Chauvet-Pont d'Arc Cave (Table 1). Most of the dated samples originate from black charcoal drawings on panels at the end of the cave and the main fireplaces in the Megaloceros Gallery, which are attributed to a first period between 37,000 and 33,500 y ago. In parallel with this occupation, cave bears also took refuge in the cave between 48,500 and 33,000 y ago. The rockfall of a boulder section near the Abraham Pillar on the access path of the (paleo) entrance of the cave, 34,500 y ago, correlates with a period of nonoccupation between 33,500 and 31,000 y ago. Then, between 31,000 and 28,000 y ago, a second prehistoric occupation began and lasted ∼2,000–3,000 y. The people who frequented the cave during this period in turn left their marks on the walls in the form of numerous torch marks and possibly two charcoal drawings in the second part of the cave. Another rockfall occurred at the entrance of the cave 29,400 y ago, partially closing off its access. The end of the second human occupation phase correlates with this geological event. No cave floor charcoal, drawing, or charcoal mark since that time has been identified in the cave, despite the extensive sampling of charcoal lying on the present cave floor where the most recent remains are expected to be found. A solitary ibex bone has been dated to ∼27,000 cal B.P., thus before the two last rockfall events that sealed the cave entrance 23,500–21,500 y ago. Since that time, no human or animal, other than small mammals and what they had scavenged, entered the cave until its rediscovery in 1994 (Fig. 2).

Using a robust interdisciplinary approach, our modeled results clearly support previous hypotheses postulating two different occupations of the Chauvet-Pont d'Arc Cave. They definitively show that humans frequented the site during two distinct time periods, between 37,000–33,500 and 31,000–28,000 y ago and that cave bears also took refuge in the cave until around 33,000 y ago. These clear results, based on a large number of dates obtained from diverse materials introduced into the cave through various biological or anthropogenic processes, provide a decisive argument in favor of the realization of the parietal art works before 28,000 y ago. They now enable further extensive exploration of the remarkable rock art created in the Chauvet-Pont d'Arc Cave during these two occupation phases.

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