Further constraints on the Chauvet cave artwork elaboration

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Since its discovery, the Chauvet cave elaborate artwork called into question our understanding of Palaeolithic art evolution and challenged traditional chronological benchmarks [Valladas H et al. (2001) Nature 413:419–479]. Chronological approaches revealing human presences in the cavity during the Aurignacian and the Gravettian are indeed still debated on the basis of stylistic criteria [Pettitt P (2008) J Hum Evol 55:908–917]. The presented 36Cl Cosmic Ray Exposure ages demonstrate that the cliff overhanging the Chauvet cave has collapsed several times since 29 ka until the sealing of the cavity entrance prohibited access to the cave at least 21 ka ago. Remarkably agreeing with the radiocarbon dates of the human and animal occupancy, this study confirms that the Chauvet cave paintings are the oldest and the most elaborate ever discovered, challenging our current knowledge of human cognitive evolution.

Chauvet cave, in Vallon Pont d’Arc, Ardèche, France, is a site of exceptional scientific interest for a number of reasons: (i) the variety of its majestic parietal; (ii) very good conservation of the floor and wall ornamentations, exhibiting human and animal imprints; (iii) revelations of unknown techniques in Palaeolithic rock art (such as stump drawing); (iv) predominance of rare themes such as felines and rhinoceroses; and (v) unequalled aesthetic delivery (1). On the basis of stylistic comparison with known elements, the Chauvet cave rock ornamentations were initially estimated as being Solutrean (22–17 ka BP) and Magdalenian (17–10 ka BP) (2). The first radiocarbon dates ranging from approximately 30 to approximately 32 14C ka BP (3, 4) thus disagreed with stylistic analyses such as formalized by Leroi-Gourhan (5). Although currently confirmed by 82 radiocarbon dating (6, 7), by crossing dating methods (8, 9), and supported by the recent discovery of manifestations of standardized Aurignacian prehistoric art (40–28 ka BP) in the Swabian Jura (10), it still remains unclear whether the current stylistic framework should be abandoned in favor of radiocarbon chronologies. Additional robust chronological constraints are therefore critical in establishing Chauvet cave as a reliable benchmark in the absence of comparable equivalent (1, 11, 12). If corroborated by an independent method, the absolute chronological framework of the Chauvet drawings will indeed establish them as the oldest and most elaborate Aurignacian paintings ever discovered. This will furthermore confirm the existence of an already extremely mature art at that time period during which only few elaborate engraving are known (10), but no other paintings (13, 14). To fill this knowledge gap, a geomorphological study combined with 36Cl dating of rockslide surfaces overhanging the cave entrance was conducted.

The Chauvet Cave Closure

Geomorphological studies carried out at Chauvet cave during the last 10 y have unambiguously demonstrated that only one entrance to the cave existed at the time it was visited by humans (1, 15). Delannoy et al. (15, 16) definitely rule out the possibility of another entrance, demonstrating that any other hypothesized access would imply either going through an 80 m vertical access or entering on the other side of the plateau with a 2-km walk underground through karst systems disconnected from the Chauvet cave one (Fig. 1).

This study aims to date the blocking of the paleo-entrance by rockfall deposits, which definitely closed access to Chauvet cave until its rediscovery in 1994. In addition to geomorphological and geological evidences of rockfall deposits, an original 3D survey method was used to map the extension of the rockfall in this highly secured and protected site. The deposit (between 185 and 198 m asl), whose maximum thickness is 10 m, has a total run-out distance of approximately 80 m from the top of the cliff [mean elevation of 245 m above sea level (asl)], the height of the cliff being 47 m (Fig. 2). The location and geometry of the paleo-cave entrance were reconstructed using 3D mapping tools (15). The total rock mass volume obstructing the cave entrance was estimated to be approximately 4,500 m3 using a high-density digital model (precision ±2 cm) produced by terrestrial Light Detection and Ranging (LiDAR) from the missing cliff volume corresponding to the well-preserved subcircular concave rockfall scars overhanging the paleo-entrance. In addition, located on lower Cretaceous limestone (Urgonian), the area in front of the paleo-entrance has the geometrical characteristics of an accumulation zone (15). A detailed survey of the 47-m high cliff overhanging the cave entrance revealed three concave rockslide scars that may be linked to the dislocation of several limestone monoliths. The morphology of the overhanging cliff corroborates that the sources of the rockfalls lie between the Pilier d’Abraham, a prominent monolith east of the cave entrance, and another prominent arête roughly 25 m from the Pilier d’Abraham to the west. In between these two prominent features, two embossed edges as well as surface differences allow three surfaces to be defined, from west to east: E1, E2 and E3. These probably correspond to three different gravitational events involving debris volumes of 500 m3, 1,300 m3 and 2,100 m3 (±10%), respectively (15, Fig. 2).

The blocks resulting from the collapse of the limestone monoliths have formed an apron of fallen rocks on the hillside as well as inside the cave, which can be identified thanks to several objects characteristic of the endokarst system in their genetic place.


The authors declare no conflict of interest.

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In addition to the heterogeneous arrangement of the collapsed blocks, the oldest stalagmitic flowstones (>300 ka, 9) on the cave walls show some block impacts, suggesting the occurrence of highly energetic processes (12). These impacts rule out a cryoclastic agent on the deposit’s emplacement. Furthermore, the fallen rocks are currently in a progressive compaction phase rather than accretion by the addition of cryoclastic elements (15). The closure of Chauvet cave has most likely resulted from several successive rockfalls, the last of which definitively sealed the entrance. In an attempt to date the collapses and the closure of the entrance, previous studies used U/Th dating of speleothems sealing the top of the rockfall deposit, yielding a maximum age of 11.5/C60.2 ka (9, 15). However, interruption of calcite precipitation during the Last Glacial Maximum hampers the use of this dating method between 25.5 to 15 ka (9), and thus only allows a minimum age estimate for the closure of the cave. Finally, 14C dating of archaeological layers underlying the rockfall deposits into the cave have shown Aurignacian occupancy phases at the entrance (15). As in Hillaire Room and Megaloceros Gallery (7, 8), these archaeological layers are indeed older than 27 cal 14C kA BP.

Rockfall events that expose deeply buried limestone can be directly dated using in situ-produced 36Cl concentrations accumulated in scar surface samples, because they have been continuously exposed to cosmic rays (17, 18). Twenty-two samples were collected on the E1, E2, E3, and the Pilier d’Abraham surfaces; two samples were collected on the top surface above the studied cliff to estimate the local denudation rate, and a sample was taken from the Treuil cave, which constitutes part of the same karstic network as the Chauvet cave (Fig. 1). Samples were prepared according to Stone et al. (19), and 36Cl concentrations were measured at the national AMS facility ASTER (CEREGE, Aix-en-Provence, France). The raw data are presented in Table S1. The 36Cl concentrations measured in the Pilier d’Abraham samples range from 3.1 to 3.4 × 10^5 atoms 36Cl/g rock. The 36Cl concentrations measured in the scar samples are significantly lower, ranging from 1.6 to 3.0 × 10^5 atoms 36Cl/g rock. Compared to the scars and the Pilier d’Abraham samples, the 36Cl concentrations measured in the top surface samples are one order of magnitude higher, at 1.2 and 1.1 × 10^6 atoms 36Cl/g rock. This latter concentration was measured in a sample laterally shielded by 12.4 m of limestone and thus represents the natural background 36Cl concentration at that depth from in situ muogenic production.

Both samples collected on the top surface, old enough to have reached steady-state (20) with respect to the accumulation of 36Cl (21), yielded similar denudation rates of 18.5 and 21.5 mm/ka. This indicates that the mean denudation rate for a horizontal limestone surface at our site is approximately 20 mm/ka. Considering that the scars and the Pilier d’Abraham samples lie on an almost vertical cliff on which water does not stagnate, thus experiencing a lower denudation rate than on an horizontal surface and according to previously published values on similar environments and settings (22), the exposure age of the samples collected on the rockfall scars and the Pilier d’Abraham were calculated using a denudation rate of 10 mm/ka.

Moreover, the samples from the scar surfaces have probably accumulated nucleogenic production underneath the shielding...
provided by rock slab that has then subsequently fallen to the cliff base. To calculate accurate rockfall scar sample surface exposure ages, it is therefore necessary to subtract this $^{36}$Cl contribution. The LiDAR-based 3D reconstruction of the cliff overhanging Chauvet cave entrance constrained the minimum shielding depth, thus the rock slab thickness, at each sampling point. They range from 4.5 to 6.5 m (Table S2). Maximizing the nucleogenic production underneath the rock slab implies considering that the exposure time beneath the rock slab is similar to the calculated oldest age ($35.4 \pm 2.1$ ka, Table 1) of the most stable closest arête, the Pilier d’Abraham. This latter age was in addition maximized by subtracting the minimum muogenic $^{36}$Cl background component of $1 \times 10^4$ atoms $^{36}$Cl/g rock, as deduced from the Treuil cave sample. Applying this maximum exposure duration, the nucleogenic $^{36}$Cl contribution from the shielded rock slab were then calculated for each rockfall scar surface sample at the reconstructed shielded depths prior to the rockfall and subtracted from the measured concentration. The obtained values range from $1.4$ to $2.7 \times 10^4$ atoms $^{36}$Cl/g rock (Table S1), about 10% of the total $^{36}$Cl inventory on those samples. The geographic location, production rates (23), scaling (24) and shielding factors (25), and CRE ages of the rockfall scar surface samples accounting for both denudation rate and maximized (muogenic $^{36}$Cl background component: $1.4 \times 10^4$ atoms $^{36}$Cl/g rock) shielded $^{36}$Cl contribution, are presented in Table 1 and Tables S1 and S2. In a very conservative way, because in all calculations all possible contributions of $^{36}$Cl production prior to the rockfalls have been maximized, the presented ages are minimized rockfall scar ages.

**Results and Discussion**

The CRE age distribution of all rockfall scar surface samples (Table 1 and Fig. 3) attests to three temporally distinct events that spatially correlate with the three surfaces previously identified by the LiDAR study and their surface state of evolution. Those ages yielded minimized weighted mean ages of $29.4 \pm 1.8$ ka for the E1 surface, $23.5 \pm 1.2$ ka for the E2 surface, and $21.5 \pm 1.0$ ka for the E3 surface. The particularly well-constrained E3 surface age implies that the most recent rockfall occurred at least 21 ka ago and that no major gravitational event affecting the overhanging paleo-entrance has occurred since then. Considering that the final closure of the paleo-cave entrance could only be attributed to rockfall talus, and that a more recent collapse would have left a morphological imprint associated with younger CRE ages on...
the minimum ages derived from U/Th results obtained on speleothems that sealed the rockfall deposit (9, 15) but, more importantly, they also agree with the reported $^{14}C$ dating and thus support the deduced phases of human and animal occupancy of the cavity. Indeed, none of the available radiocarbon dates (32 determinations on large mammal bones and 82 on charcoal samples) calibrated using the INTCAL09 curve (26) is younger than 23 cal $^{14}C$ ka BP. The distribution of ages obtained on charcoal from both the walls and floor (3, 7, 8), some of which being produced in the framework of a cross-comparative project between several independent laboratories confirming the validity of radiocarbon dating (8), indicate two successive phases of human occupancy: the first one from 37.5 to 33.5 cal $^{14}C$ ka BP, and the second one from 32 to 27 cal $^{14}C$ ka BP (Fig. 3).

None of the charcoal dates is younger than 27 cal $^{14}C$ ka BP. $^{14}C$ dating of large mammal bones, all species being included ($Ursus$ $spelaeus$ and $Capra$ $ibex$), range from 42 cal $^{14}C$ ka BP to 23 cal $^{14}C$ ka BP (27, 28, 29)—the youngest age being associated with an ibex bone (19.105 $\pm$ 150 $^{14}C$ yr BP). This date fits tightly with the last two rockfall events. Despite the number of samples taken for floor surface dating, the absence of more recent ages (Fig. 3) strongly supports a direct link between the end of human and large animal occupancy and the closure of the Chauvet cave entrance by the two major rockfalls dated at 23.5 $\pm$ 1.2 ka and 21.5 $\pm$ 1.0 ka. In fact, this remarkable concordance between the end of the animal occupancy in the cave and the obstruction of its unique entrance by rockfalls (Fig. 3) inevitably leads to the conclusion that the Chauvet rock art is most likely older than 21 ka and thus at least Gravettian.

Although not specifically dedicated to the dating of the Parietal ornamentation of the Chauvet cave, this interdisciplinary approach has yielded important data for the chronology of Chauvet cave by directly dating the different collapses that affected the rock wall overhanging the entrance. The results corroborate previous $^{14}C$ and U/Th chronologies on paintings, charcoal on the ground, animal bones, speleothems and mean that a Magdalenian and/or Solutrean age for the cave artwork can be discarded. All these internally consistent dates obtained on several material types (bones, charcoal, charcoal pigments, speleothems, rockfall scars) using three different and independent methods demonstrate that the Chauvet cave can now be considered as a bench.

Table 1. $^{36}Cl$ ages of the surface samples from the rockfall scars overlying the Chauvet cave entrance. Yellow, orange and blue correspond to samples belonging to the three scars, E1, E2 and E3, respectively, while light yellow outlines the two Pilier d’Abraham samples.

<table>
<thead>
<tr>
<th>Sample identity</th>
<th>$^{36}Cl$ age (ka)*</th>
<th>$^{36}Cl$ weighted mean age (ka)†</th>
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<tr>
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<td>24.1 ± 1.5</td>
<td>23.5 ± 1.2</td>
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<td>22.6 ± 1.5</td>
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</tr>
<tr>
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<td>25.9 ± 1.6</td>
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<td>25.0 ± 1.6</td>
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<tr>
<td>6.02</td>
<td>33.7 ± 1.9</td>
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</tbody>
</table>

*Individual ages are reported with 1σ uncertainty considering analytical errors only.
†Weighted means were calculated after disregarding outliers in italic. These outliers are identified using a Chi-square test with 95% confident interval. Mean ages are reported with 1σ uncertainty considering both analytical and the production rate uncertainties. Note that the identified outlier yields an age younger than the weighted mean which is coherent with minor post gravitational readjustment of the cliff.

the rockwall, closure of the Chauvet cave entrance must at least coincide with the last rockfall event dated at 21.5 ± 1.0 ka. The presented $^{36}Cl$ CRE ages are not only coherent with the minimum ages derived from U/Th results obtained on speleothems that sealed the rockfall deposit (9, 15) but, more importantly, they also agree with the reported $^{14}C$ dating and thus support the deduced phases of human and animal occupancy of the cavity. Indeed, none of the available radiocarbon dates (32 determinations on large mammal bones and 82 on charcoal samples) calibrated using the INTCAL09 curve (26) is younger than 23 cal $^{14}C$ ka BP. The distribution of ages obtained on charcoal from both the walls and floor (3, 7, 8), some of which being produced in the framework of a cross-comparative project between several independent laboratories confirming the validity of radiocarbon dating (8), indicate two successive phases of human occupancy: the first one from 37.5 to 33.5 cal $^{14}C$ ka BP, and the second one from 32 to 27 cal $^{14}C$ ka BP (Fig. 3).

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Fig. 3. Probability density plot of the $^{36}Cl$ ages in ka of the rockfall scar samples and of the calibrated radiocarbon ages of the human and animal occupation inside Chauvet cave. Note the good agreement between the end of human and animal occupation and the age of the cave’s closure. A stands for Pilier d’Abraham ages, and E1, E2, and E3 are for the ages corresponding to the three scars.
mark in archaeology and rock art science. These results have significant implications for archaeological, human, and rock art sciences and seriously challenge rock art dating based on stylistic criteria (4, 30).

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Sadier et al.