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A radiocarbon chronology for the complete Middle to Upper Palaeolithic transitional sequence of Les Cottés (France)

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A B S T R A C T

The Middle to Upper Palaeolithic transition is the key period for our understanding of Neanderthal and modern human interactions in Europe. The site of Les Cottés in south-west France is one of the rare sites with a complete and well defined sequence covering this transition period. We undertook an extensive radiocarbon dating program on mammal bone which allows us to propose a chronological framework of five distinct phases dating from the Mousterian to the Early Aurignacian at this site. We found that the Mousterian and Châtelperronian industries are separated from the overlying Protoaurignacian by a gap of approximately 1000 calendar years. Based on a comparison with Upper Paleolithic sites in Europe we see an overlap in the ages of Châtelperronian industries and Aurignacian lithic assemblages, which are usually associated with Anatomical Modern Humans, which is consistent with an acculturation at distance model for these late Neanderthals. The Proto and Early Aurignacian appear contemporaneous indicating that this transition was rapid in this region. Anatomically Modern Humans was present at the site of Les Cottés at least at 39,500 cal BP roughly coincident with the onset of the cold phase Heinrich 4.

1. Introduction

The nature of the Middle to Upper Palaeolithic transition (MUP) in Western Europe is one of the key ongoing debates in Palaeoanthropology, and it is an area where accurate chronology is essential. Central to this debate is the biological nature of the makers of the different lithic assemblages (Neanderthals and modern humans), and contradictory models have been proposed to explain the cultural evolution of these hominins (Hublin et al., 1996). Although two sites have yielded Neanderthal remains in association with Châtelperronian lithics (Bailey and Hublin, 2006; Lévêque and Vandermeersch, 1980), this association has been recently challenged (Bar-Yosef and Bordes, 2010; Higham et al., 2010). Similarly, although the assignment of later Aurignacian assemblages to modern humans is generally widely accepted (Bailey et al., 2009; Klein, 1999), doubts have been raised about the biological identity of the makers of the earliest phases of this industry (Conard et al., 2004). It is, however, generally accepted that the "Protoaurignacian" is the initial stage of the Aurignacian in Europe (Bon, 2006; Laplace, 1966; Mellars, 2006). Bon (2006) recently changed the perception of the Middle to Upper Paleolithic transition in Europe by identifying, based on detailed technological analysis, two techno-complexes within the first phase of the Aurignacian, the Protoaurignacian, and Early Aurignacian.

Sites which have a complete sequence covering this period and have been excavated using modern excavation techniques are few. The site of Les Cottés is one of these rare sites where each of the cultural phases occur in the stratigraphy: Mousterian, Châtelperronian, Protoaurignacian and Early Aurignacian, hence the complete sequence of industries have been identified and recently analyzed. Due to several sterile layers between these phases we cannot consider the site of Les Cottés a continuous site across time but a well preserved site with a clear and complete sequence during the period of the Middle to Upper Palaeolithic transition (Soressi et al., 2010).

Refinement of AMS ^{14}C bone dating methods, including ultrafiltration, a new calibration curve (IntCal09, (Reimer et al., 2009)) and advanced calibration programs (OxCal 4.1, (Bronk Ramsey, 2009)) allow us to apply radiocarbon dating to bones from late Middle and Upper Palaeolithic sites in Europe to provide more accurate chronologies for these industries. We, therefore, obtained

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a series of radiocarbon dates on bone from the main stratigraphic units at Les Cottés.

2. Overview of Les Cottés

Les Cottés is a cave located at the southwestern margins of the Parisian basin, close to the Aquitaine basin (Fig. 1). The site is on the northern limit of the known distribution of the Châtelperronian industry (Pelegrin and Soressi, 2007). Les Cottés was discovered at the end of the nineteenth century, and during the first excavation led by Rochebrune (1881a,b), anatomically modern human remains were found in an Aurignacian layer at the entrance of the cave. Pradel (1961) later defined a sequence of Mousterian, Châtelperronian, Early Aurignacian and Gravettian layers at the site. Les Cottés is best known for its well preserved Aurignacian industry with split-based points and as the type site for "Les Cottés point" lithics from the so-called "evolved" variant of the Châtelperronian (Pradel, 1963). During Pradel's research, conventional radiocarbon dates were obtained on teeth and bone from the site (Evin et al., 1985; Pradel, 1967; Vogel and Waterbolk, 1967). However, the teeth and bone used for dating had been coated in a turpentine solution saturated with beeswax which likely influenced the obtained ages (Evin et al., 1985; Vogel and Waterbolk, 1967) which are listed in Table 1.

In 2006, a new excavation program was started at this site using a multidisciplinary approach including micromorphological, taphonomic, faunal and lithic studies, and dating by OSL, which is in progress, and radiocarbon dating (Soressi et al., 2010).

2.1. Stratigraphy and cultural sequence

The 2006–2009 excavation focused on the 13 m long contiguous section (north, east and south sections) left by Pradel in the 1950s from his original approximately 20 m^2 excavation area (Fig. 2).

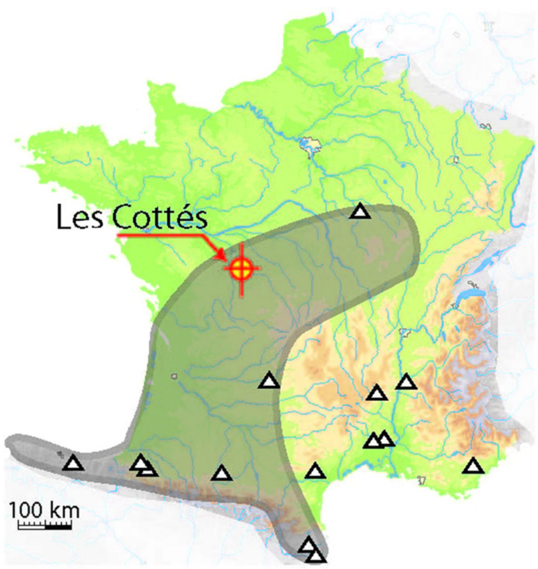

Fig. 1. Map of Les Cottés and of Châtelperronian as well as Protoaurignacian sites in France and north of Spain (map drawn by Soressi and Roussel).

Table 1
Radiometric ^{14}C ages of Les Cottés obtained between 1965 and 1985 (Evin et al., 1985; Pradel, 1967; Vogel and Waterbolk, 1967).

Culture facies	Lab code	^{14}C Age	Err
Gravettian	Ly-2752	23,420	710
Early Aurignacian	Grn-4258	30,800	500
Early Aurignacian	Grn-4296	31,000	320
Early Aurignacian	Grn-4509 teeth	31,200	410
Châtelperronian	Grn-4510	31,900	430
Châtelperronian	Grn-4333 teeth	33,300	500
Mousterian Quina	Grn-4334	32,300	400
Mousterian Quina	Grn-4421	37,600	700

The excavation extended down to the Mousterian levels (Unit 08). The sequence had been preserved by small blocks and gravels fallen from the limestone walls in a clayish sand matrix transported by run-off during the formation of the more recent unit (Unit 02) (Texier, in Soressi et al., 2010), and by run-off but also probably debris-flow for unit 04 and 06 (Liard, unpublished data). The Châtelperronian (Unit 06) is separated from the preceding Mousterian by a 12–15 cm sterile unit. The Protoaurignacian (Unit 04 lower) is separated from the Châtelperronian by a sterile deposit of up to 12 cm in thickness. A small sterile level separates the Protoaurignacian from the overlying Early Aurignacian (Unit 04 upper) in squares 4 and 5 on the north section, although the two stratigraphic units come into contact in the south section. Unit 02 is separated from Unit 04 upper by Unit 03 which is a low density layer.

The formation processes of the sterile layers are, for now, not understood, and will be the focus of future investigations. Flint artefacts show no patination and there are no lithics with natural edge damage except for a few pieces from the Châtelperronian (Soressi et al., 2010). Site formation processes certainly modified the spatial organization of artifacts, but each unit can be considered to be homogenous because of the combination of three types of observations: sterile layers occur between these units, the flint artifacts at the site are well preserved, and the composition of each unit is different.

2.2. Cultural sequence

The large sample size of 3-D plotted artifacts ($n = 13,296$) allowed us to determine a precise chrono-cultural attribution for each layer. The specific type of Mousterian present in Unit 08 cannot yet be precisely determined as the number of artifacts is small ($n = 350$: among which only one third are larger than 3 cm, Table 2). In Pradel's publications this Mousterian assemblage has been characterized as a "Moustérien sans biface" even if though one biface was recovered during the excavation in the 1950's (Pradel, 1961). This layer has also been characterized as a Quina Mousterian, even if the reasons for making this attribution was not clearly explained but is likely due to the high proportion of scrapers (Lévêque, 1993). Further work at the site will allow us to increase our sample of Mousterian artifacts and to then determine the specific type of Mousterian.

Châtelperronian retouched tools are mostly backed pieces ("Châtelperron" points as well as "Les Cottés" points). Backed pieces represent 36% of the 83 retouched tools from Unit 06. Blades with a continuous marginally retouch are also well represented (17% of the 83 retouched tools). The production (2273 numbered lithics, Table 2) is orientated towards the production of rectilinear blades. Among the 23 Châtelperronian cores, none of them show an organized flake production and instead they all show blade production characteristic of the Châtelperronian (Connet, 2002;

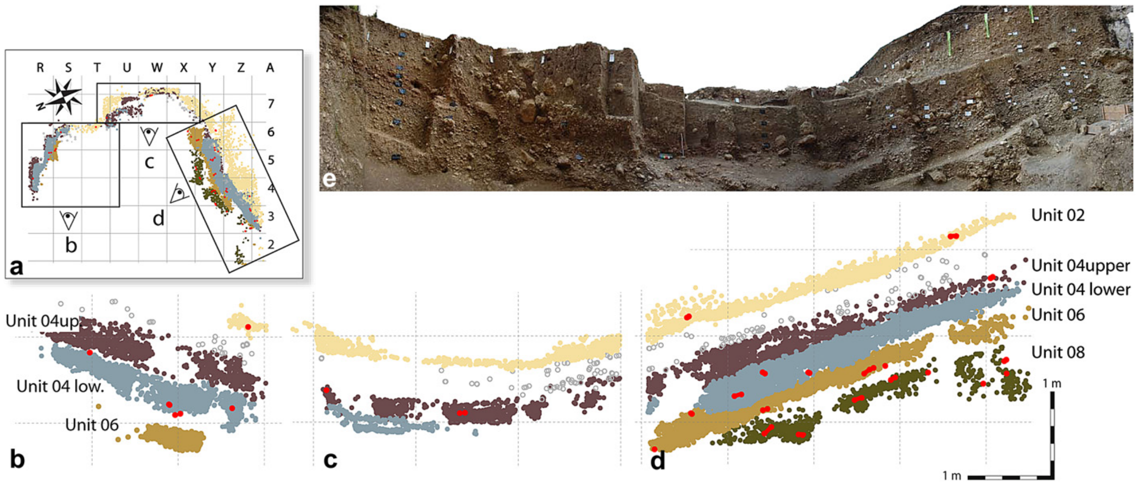

Fig. 2. Top pane: distribution of all archaeological finds on a plan view of numbered lithics and bones. Cultural phases are indicated by color (see legend). Bottom pane: section view of excavation, samples selected are marked in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Pelegrin, 1995). Blades are unipolarly removed by sequential series, on both narrow and wide surfaces (Roussel, 2011).

The Châtelperronian blade cores show a triangular or a rectangular section which is different from the hemi-conical section of Aurignacian cores (Roussel, 2011). The definition of "evolved" Châtelperronian proposed by Pradel (Pradel, 1961, 1963) for this layer cannot for now be accepted or rejected. Comparison with other Châtelperronian layers preserved in a same stratigraphical sequence, such as Quinçay (46 km West of Les Cottés) (Roussel, 2011; Roussel and Soressi, 2010) would help to better evaluate this chrono-cultural attribution.

The Protoaurignacian (Unit 04 lower) lithic production (6466 numbered lithics, Table 2) was aimed towards the production of slightly curved and large bladelets. Bladelet cores (62% of 47 cores) are more numerous than blade cores (32% of 47 cores), which were used to produce a few blades only. Bladelet cores are made out of flakes or out of blocks; bladelet cores are of prismatic or pyramidal morphology. The size of the bladelet cores as well as the absence of blade scars on them may indicate that these bladelet cores are not reduced blade cores (Bon, 2002). Independent bladelet production has been described in the Protoaurignacian of the Grotte du Renne, level VII (Bon and Bodu, 2002), of Isturitz, level C4dIII (Normand, 2006) of l'Observatoire (Porraz et al., 2010,) and of Mandrin (Slimak et al., 2006). Retouched tools are mainly retouched bladelets which are almost always Dufour sub-type Dufour (44% of the 195 retouched tools). These characteristics are typical of the Protoaurignacian from France, Spain and Italy (Arrizabalaga and Altuna, 2000; Bartolomei et al., 1994; Bazile, 2006; Bon and Bodu, 2002; Bordes, 2006; Kuhn and Stiner, 1998; Laplace, 1966; Onoratini, 1986; Slimak et al., 2006).

Table 2
Cultural attribution of the different stratigraphical units (major units are in bold font).

Units	Cultural attribution	Numbered lithics 2006–2009
01	non applicable (n.a.)	45
02	**Final Early Aurignacian**	**1183**
03 top	na	2
03 bottom	Early Aurignacian	116
04upper	**Early Aurignacian**	**2840**
04lower	**Protoaurignacian**	**6466**
05	na	15
06	**Châtelperronian**	**2273**
07	na	6
08	Mousterian	350

Bladelets from the Early Aurignacian (Unit 04 upper) are not morphologically different from the Protoaurignacian, although they are retouched much less often. Bladelets are mostly produced from large carinated endscrapers or from "rabots". Blades from Unit 04 upper are wider, thicker and also more robust (in the width to thickness ratio) than in Unit 04 lower. Retouched tools ($n = 112$) are mostly retouched blades, among which one in five is a blade with Aurignacian retouch. Blades with Aurignacian retouch do not exist in the Unit 04 lower. Simple endscrapers account for 25% of the retouched tools, while they are less numerous in the Protoaurignacian, Unit 04lower (8%). Also, retouched bladelets are much less numerous (13%) than in the Protoaurignacian where they composed 47% of the 195 retouched tools. These features are characteristic of the classic Early Aurignacian (Bon, 2002; Sonneville-Bordes, 1960).

The final assemblage (Unit 02) preserved at the top of the sequence is currently attributed to a final Early Aurignacian. Unit 02 bladelets are smaller than in older levels, most of the time they are curved, and they are never retouched including bladelets found in the systematically sorted 2 mm screen. These small bladelets could have been produced from carinated endscrapers, which are rare, but present, in this layer. Blades are wider than in the oldest levels, and some of them are intentionally fractured. Simple endscrapers are the more numerous retouched tools in this final level (49% of 35 retouched tools), and blades with Aurignacian retouch are present (6% of 35 retouched tools).

2.3. Faunal remains

Faunal remains (3337 bigger than 2.5 cm) are relatively well preserved and rounding and weathering is infrequent (Rendu, in Soressi et al., 2010). Reindeer is the most abundant species (it counts for up to 96% of the 716 identified bones in Unit 02) except

Table 3
Isotopic data, %Collagen, %C and %N and C:N for the samples taken during the 2007 and 2008 field campaigns. Radiocarbon results of Les Cottés: CPh = Culture phases, EA = Early Aurignacian, PA = Protoaurignacian, C = Châtelperronian and M = Mousterian.

S-EVA	US	Square Nr	CPh	%Coll.	$\delta^{13}C$	$\delta^{15}N$	%C	%N	C:N	EVA Code	^{14}C Age Graphite MPI dated at ORAU	1σ Err	MAMS Code	^{14}C Age Collagen MAMS	1σ Err	OxA Code	^{14}C Age Collagen OxA	1σ Err
9717	02.1	T6-61	EA	0.8	−19.6	7.4	35.2	12.7	3.2							OxA-V-2381-46	31,750	280
9718	02.1	Z3-3	EA	2.5	−19.3	8.6	40.6	13.6	3.5	EVA-2	32,150	160	MAMS-10810	31,470	180	OxA-V-2381-47	31,640	260
[a]9719	02.1	Y6-321	EA	2.3	−19.2	8.2	43.2	14.5	3.5	EVA-3	32,530	170	MAMS-10811	32,940	220	OxA-V-2381-48	32,590	280
[a]9706	04	A3-218	EA	1.4	−20.2	7.2	42.2	14.3	3.4	EVA-9	34,330	210				OxA-V-2381-44	34,050	350
9711	04.0r	T7-109	EA	1.6	−19.2	7.4	40.3	14.6	3.2	EVA-8	33,050	250	MAMS-10807	33,240	230	OxA-V-2384-10	33,340	390
9709	04.1r	W7-206	EA	3.1	−20.5	7.5	42.2	14.4	3.4	EVA-10	34,350	190	MAMS-10805	35,160	280	OxA-V-2381-45	34,650	340
[a]9720	04.2r	R4-271	EA	1.5	−19.0	6.8	44.0	14.6	3.5	EVA-22	33,750	250	MAMS-10812	33,960	280	OxA-V-2381-49	33,920	320
9713	04.4b	S6-363	PA	2.9	−19.7	5.2	33.6	11.4	3.4				MAMS-10808	35,150	280			
[a]13671	04.4	Y5-1083	PA	1.6	−19.1	4.5	39.2	14.2	3.2				MAMS-10826	33,710	230			
[a]13672	04.9	Y6-1681	PA	1.3	−19.6	7.7	38.8	14.1	3.2				MAMS-10827	34,080	250			
[a]13663	04,6	Y5-1225	PA	0.7	−19.6	7.1	36.9	13.4	3.2				MAMS-10814	33,080	230			
[a]13665	04.5 BJ	S6-557	PA	2.2	−19.2	8.5	38.9	14.1	3.2	EVA-7	34,380	210	MAMS-10816	35,250	280	OxA-V-2381-52	34,220	400
[a]13669	04.5 BJ	R5-785	PA	2.7	−19.3	6.4	38.7	14.1	3.2	EVA-14	34,250	220				OxA-V-2382-47	34,870	340
9695	06 rc	Z4-1258	C	3.4	−20.4	5.3	45.9	15.6	3.4				MAMS-10803	38,540	270			
[a]13662	06	Y6-979	C	1.7	−20.4	5.3	37.5	13.7	3.2	EVA-21	41,280	340				OxA-V-2381-50	40,280	650
[a]13664	06	Y5-2785	C	1	−18.9	6.8	37.4	13.6	3.2	EVA-5	42,410	400				OxA-V-2381-51	42,090	900
[a]13666	06	X6-205	C	2.1	−19.1	4.2	41.9	15.2	3.2	EVA-11	36,180	240				OxA-V-2381-53	36,410	450
[d]13667	06	Z4-3286	C	1.9	−21.6	6.3	38.3	14.0	3.2	EVA-12	36,720	320	MAMS-10823	38,430	420	OxA-V-2382-45	37,400	500
13668	06	Z4-3368	C	3.3	−19.9	5.2	42.7	15.6	3.2	EVA-13	38,150	290	MAMS-10824	38,210	420	OxA-V-2382-46	37,850	450
[a]13673	08	Y4-625	M	1	−20.2	7.9	20.7	7.5	3.2	EVA-15						OxA-V-2384-11	39,760	1600
[a]13674	08	Y5-1575	M	1	−20.1	4.8	24.7	9.0	3.2	EVA-16	34,390	250				OxA-V-2384-12	35,330	900
[c]13675	08	Z3-362	M	3.4	−19.8	7.6	39.6	14.4	3.2	EVA-17	41,730	330	MAMS-10828	40,800	530	OxA-V-2382-48	42,870	750
[b]13676	08	Y5-1654	M	3.6	−20.1	4.9	41.6	15.2	3.2	EVA-18	42,200	350	MAMS-10829	41,780	600	OxA-V-2382-49	42,690	750
[c]13677	08	Z3-356	M	6.8	−20.4	7.7	43.1	15.7	3.2	EVA-19	38,650	260	MAMS-10830	40,710	510	OxA-V-2382-50	40,280	550
[c]13678	08.rc	Z3-289	M	3.8	−20.3	6.8	40.7	14.8	3.2				MAMS-10831	38,970	440			
[a]13679	08.rc	Y4-311	M	3.2	−19.5	7.7	39.0	14.1	3.2				MAMS-10832	39,390	470			
[a]13680	08.rc	Z3-308	M	1	−18.4	6.8	34.9	12.6	3.2	EVA-20	37,640	270				OxA-V-2384-13	38,970	900

[a] bone with cut marks.
[b] retouchoir.
[c] digested bone.
[d] carnivore bite marks.

for in the Mousterian levels, where bovids are more abundant than reindeer (Soressi et al., 2010). In the Mousterian layer (Unit 08), 15.5% of the 220 numbered bones were modified by carnivores, and about an other 17% show evidence of human activity, suggesting the contribution of two different accumulators. Although the human impact on the material increase significantly with the Châtelperronian (24% of Unit 06 bones show human impact), the carnivore ratio stays the same as with the Mousterian. Carnivore action almost disappear with the Protoaurignacian and the Early Aurignacian. Less than 2% of the total number of bone show evidence of carnivore action in Unit 04 lower, Unit 04 upper and Unit 02. Within these top layers, up to 31% of bones show human modifications (Rendu, unpublished data).

3. Radiocarbon dating

3.1. Samples selection and pretreatment

At Les Cottés we selected bone samples for dating from all of the layers excavated during the 2007 and 2008 seasons (Fig. 2 and Table 3). To date the human presence in a site it is important to select bones which document human activity (Higham et al., 2011) and at the same time it is important to find out if processes like intrusion, mixing, taphonomic reworking, cryoturbation, bioturbation occurred. In the case of Les Cottés we selected 27 mammal bones, 15 with cut marks, one retouchoir, 6 without any marks and 5 which document the presence of carnivores.

Bone samples were pretreated at the Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology (MPI-EVA), Leipzig, Germany, using the following method (Talamo and Richards, 2011): the outer surface of the bone samples are first cleaned by a shot blaster and then 500 mg of bone powder is taken. The samples are then decalcified in 0.5 M HCl at room temperature until no CO_2 effervescence is observed, usually for about 4 h 0.1 M NaOH is added for 30 min to remove humics. The NaOH step is followed by a final 0.5 M HCl step for 15 min. The resulting solid is gelatinized following Longin (1971) at pH3 in a heater block at 75 °C for 20 h. The gelatin is then filtered in an Eeze-Filter™ (Elkay Laboratory Products (UK) Ltd.) to remove small (<8 μm) particles. The gelatin is then ultrafiltered with Sartorius "Vivaspin 15" 30 kDa ultrafilters (Brown et al., 1988). Prior to use the filter is cleaned to remove carbon containing humectants (Higham et al., 2006). The samples are lyophilized for 48 h.

In the past we sometimes observed discordant results for test samples in the Middle and Upper Palaeolithic time ranges between different AMS labs (Talamo and Richards, 2011). We therefore designed an extended dating procedure. Samples which gave sufficient collagen were separated into three aliquots; one was then sent to the Klaus-Tschira-AMS facility of the Curt-Engelhorn Centre, Mannheim, Germany, one was sent to the Oxford Radiocarbon Accelerator Unit (ORAU) and the last one was graphitized at the MPI-EVA and the graphite was dated at the ORAU. Samples with low amounts of collagen were sent to one of these two AMS labs. The crucial step is the collagen preparation, hence the replication of dates provided by the choice of two AMS facilities does not provide checks on the bone pretreatment itself, but instead provides a check on the dates produces by the different laboratories, and also improves the precision of the radiocarbon ages.

Table 4
Combined radiocarbon results of Les Cottés.

S-EVA	SquareNr	CPh	EVA Code	MAMS Code	OxA Code	Weighted Mean	1σ Err
9717	T6-61	EA			OxA-V-2381-46	31,750	280
9718	Z3-3	EA	EVA-2	MAMS-10810	OxA-V-2381-47	31,810	[a]250
9719	Y6-321	EA	EVA-3	MAMS-10811	OxA-V-2381-48	32,670	120
9706	A3-218	EA	EVA-9		OxA-V-2381-44	34,260	180
9711	T7-109	EA	EVA-8	MAMS-10807	OxA-V-2384-10	33,180	160
9709	W7-206	EA	EVA-10	MAMS-10805	OxA-V-2381-45	34,610	140
9720	R4-271	EA	EVA-22	MAMS-10812	OxA-V-2381-49	33,860	160
9713	S6-363	EA		MAMS-10808		35,150	280
13671	Y5-1083	PA		MAMS-10826		33,710	230
13672	Y6-1681	PA		MAMS-10827		34,080	250
13663	Y5-1225	PA		MAMS-10814		33,080	230
13665	S6-557	PA	EVA-7	MAMS-10816	OxA-V-2381-52	34,620	[a]390
13669	R5-785	PA	EVA-14		OxA-V-2382-47	34,430	180
9695	Z4-1258	C		MAMS-10803		38,540	270
13662	Y6-979	C	EVA-21		OxA-V-2381-50	41,070	300
13664	Y5-2785	C	EVA-5		OxA-V-2381-51	42,360	370
13666	X6-205	C	EVA-11		OxA-V-2381-53	36,230	210
13667	Z4-3286	C	EVA-12	MAMS-10823	OxA-V-2382-45	37,360	[a]610
13668	Z4-3368	C	EVA-13	MAMS-10824	OxA-V-2382-46	38,100	210
13673	Y4-625	M	EVA-15		OxA-V-2384-11	39,760	1600
13674	Y5-1575	M	EVA-16		OxA-V-2384-12	34,460	240
13675	Z3-362	M	EVA-17	MAMS-10828	OxA-V-2382-48	41,640	260
13676	Y5-1654	M	EVA-18	MAMS-10829	OxA-V-2382-49	42,180	280
13677	Z3-356	M	EVA-19	MAMS-10830	OxA-V-2382-50	39,260	[a]770
13678	Z3-289	M		MAMS-10831		38,970	440
13679	Y4-311	M		MAMS-10832		39,390	470
13680	Z3-308	M	EVA-20		OxA-V-2384-13	37,750	260

CPh = Culture phases EA = Early Aurignacian; PA = Protoaurignacian; CP = Châtelperronian; M = Mousterian.
[a] standard deviation of the aliquot.

3.2. Collagen quality control

As an indicator of contamination and/or degradation of collagen, C:N ratios, %C, %N, collagen yield and $\delta^{13}C$ and $\delta^{15}N$ values are measured (Ambrose, 1990; DeNiro, 1985; Harbeck and Grupe, 2009; Hedges, 2002; Schoeninger et al., 1989; Strydonck et al., 2004, van Klinken, 1999), and it is assumed that contamination has occurred when the atomic C:N ratio falls outside the range observed for modern animals and humans (2.9–3.6). $\delta^{13}C$ and $\delta^{15}N$ values in bone collagen depend on diet and can be used to distinguish herbivores from carnivores and marine and terrestrial diets. The full range of these parameters needs to be considered to decide if collagen extracted from bone is of sufficient quality (Lee-Thorp, 2008; Richards and Hedges, 1999, 2003; Richards et al., 2005, 2000, 2008). Another simple but important criterion is the quantity of collagen that can be recovered. Usually a limit of 1% weight is considered as a necessary minimum condition (Hedges and Van Klinken, 1992), and samples of lower yield are potentially problematic, although the use of an ultrafilter to extract high quality collagen means that this lower limit is not necessarily valid for ultrafiltered samples (Brock et al., 2007; Higham et al., 2006). For Les Cottés the isotopic results, C:N ratios and collagen yields are given in Table 3. The C:N ratios of all samples are well within acceptable ranges, and the collagen yield is mostly above 1%.

4. Results

4.1. ^{14}C results

The radiocarbon results from the Mannheim AMS laboratory (Lab code: MAMS), the Oxford laboratory (Lab code: OxA-V) and the MPI-EVA laboratory (Lab code: EVA) are listed in Table 3. All dates were corrected for a residual preparation background estimated from pretreated ^{14}C free bone samples, kindly provided by the ORAU. Radiocarbon dates are available for all layers, from the Aurignacian to the Mousterian.

For the majority of the samples we have results on aliquots from two AMS facilities (Oxford and Mannheim) and for two stages of the preparation (collagen and graphite). Hence we can perform consistency checks on these three types of results, using the R_Combine function of OxCal (Bronk Ramsey, 2009). Of 18 pairs or triplets, 14 pass the agreement test, and the four results flagged as outliers do not show a systematic pattern according to lab or sample type. Therefore we combine the radiocarbon results of each sample using the weighted mean of AMS labs and type and the error of the mean, except for the four flagged samples where the error is the scaled standard deviation of the ^{14}C results (Table 4, Fig. 3).

The uncalibrated radiocarbon dates of all Aurignacian layers range from 31,750 to 35,150 radiocarbon years BP. The Early Aurignacian (US 04 upper) and Protoaurignacian (US04 lower) units cannot be separated in age by radiocarbon dating. Six dates come from the Châtelperronian layer and these range from 36,230 to 42,360 radiocarbon years BP. The Mousterian samples are surprisingly well preserved, with collagen yields of up to 7%. The ^{14}C dates range from 34,460 to 42,180 radiocarbon years BP.

Generally the radiocarbon results of each stratigraphic unit agree with their stratigraphic position, but some samples are observed with ages apparently inconsistent with their stratigraphic location. The obvious case is between Mousterian and Châtelperronian, with one extremely young Mousterian date (S-EVA13674, ^{14}C Age 34,460 ± 240 BP) and two Châtelperronian dates (S-EVA13662, ^{14}C Age 41,070 ± 300 BP; S-EVA13664, ^{14}C Age 42,360 ± 370 BP) which would be considered of Mousterian age. At the present stage of the excavation potential causes of this overlap cannot be determined; vertical mixing appears improbable because of the presence of a sterile layer (US07) between these two phases. These dates cannot be explained at present time and are considered outliers. They are reported here for completeness, but are excluded

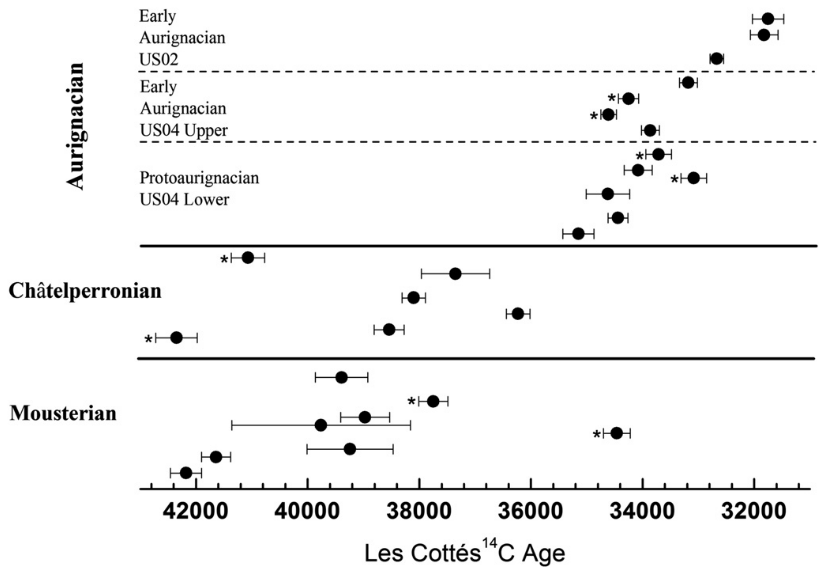

Fig. 3. Radiocarbon ages of the weighted means of Les Cottés. The dates are arranged according to the archaeological layer; within each layer they are sorted by depth. The bars indicate 1σ error. The asterisks indicate the outliers for the Bayesian analysis.

from the subsequent discussion. More samples are expected from future excavation in the northern part of this area.

Compared to the earlier radiometric ^{14}C dates (Table 1), our results, older by 500–5000 radiocarbon years (Table 4, Fig. 3), demonstrate the importance of the advanced pretreatment techniques of bone, made possible by the low amount of carbon required for AMS and ultrafiltration. Moreover, the design of the study with age determination of sample aliquots by two independent AMS facilities allows additional checks of the credibility of the dating.

4.2. Calibrated results

Radiocarbon calibration for dates older than 25,000 years BP was controversial until recently. In 2009 radiocarbon calibration saw substantial progress through the publication of the calibration curve IntCal09 (Reimer et al., 2009). Earlier discrepancies between various ^{14}C datasets were largely resolved; especially the apparent ^{14}C excursions between 30,000 and 40,000 ^{14}C BP were shown not to be real. Consequently, the IntCal working group constructed a new calibration curve back to 50,000 cal BP (Reimer et al., 2009).

The weighted means of the radiocarbon dates we produced (Fig. 3) were calibrated using OxCal 4.1 (Bronk Ramsey, 2009) and IntCal09 (Reimer et al., 2009). Within each layer the dates are arranged according to the stratigraphic level. Bayesian analysis, which is a powerful tool to detect outliers in stratified datasets, was used to build a model which includes a sequence of 5 sequential (non-overlapping) phases. Mainly due to the temporal overlap between the dates of the distinct layers (Fig. 3), OxCal finds no agreement between the full set of dates and stratigraphy. However, we obtained an agreement of 82% (A_overall = 60% indicates good agreement) if 8 dates, marked by asterisks in Fig. 3 (S-EVA13674 ^{14}C age 34,460 ± 240 BP and S-EVA13680 ^{14}C age 37,750 ± 260 BP from Mousterian levels, S-EVA13662 ^{14}C age 41,070 ± 300 BP and S-EVA13664 ^{14}C age 42,360 ± 370 BP from Châtelperronian levels, S-EVA13671 ^{14}C age 33,710 ± 230 BP and S-EVA13663 ^{14}C age 33,080 ± 230 BP from the Protoaurignacian US 04 lower level, and S-EVA9706 ^{14}C age 34,260 ± 180 BP and S-EVA9709 ^{14}C age 34,610 ± 140 BP from the Early Aurignacian US 04 upper level), were removed from the dataset (Fig. 4). There is no clear indication as to the reason of the removal of a sample, e.g. cut marks, % of collagen, isotope ratios or faunal distinction. It is difficult to accept mixing as explanation because as discussed above all sequences are clearly separated in the excavation, and there are even sterile layers between them.

5. Discussion

The Châtelperronian and the Protoaurignacian (US 04 lower) are separated by a gap of about 1000 calendar years, calculated from the difference in the respective boundaries in the OxCal model.

The interpretation of the Châtelperronian as resulting from an acculturation at a distance of late Neanderthals who observed modern human Aurignacian technology (Hublin et al., 1996) clearly depends on the temporal relation between the Châtelperronian and Aurignacian. At Les Cottés the two phases are well separated but a comparison shows that the Châtelperronian of Les Cottés is contemporaneous to the Aurignacian (Proto and Early) of other sites in Europe (Haesaerts et al., 1996; Higham et al., 2009; Hoffecker et al., 2008; Nigst et al., 2008; Sirakov et al., 2007; Szmidt et al., 2010). Potentially the most important site in the region is the Grotte du Renne at Arcy-sur-Cure, which has a complete but shorter sequence and which is almost (there is no Early Aurignacian at Arcy-sur-Cure) analogous to Les Cottés, but a recent re-assessment showed doubts about the validity of the stratigraphy (Higham et al., 2010).

Reconsidering the full dataset of ^{14}C ages between Protoaurignacian US 04 lower and Early Aurignacian US 04 upper (Fig. 3), in which 6 out of 10 dates overlap, indicating that one tradition very quickly replaced the other in this region.

At the top of the sequence at Les Cottés the final Early Aurignacian US 02 is distinctly different from the underlying phases,

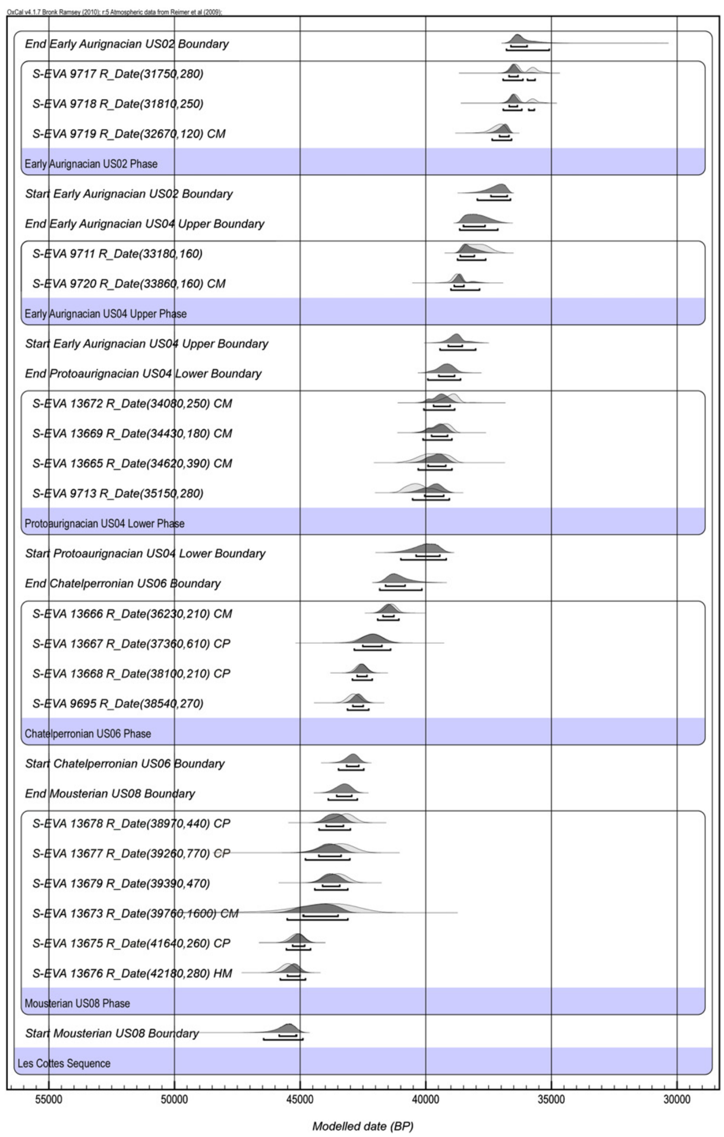

Fig. 4. Bayesian model build using OxCal 4.1 (Bronk Ramsey, 2009) and IntCal09 (Reimer et al., 2009) from the radiocarbon weighted means of Les Cottés. CP = Carnivore Presence, CM = Cut Marks and HM = Human Modification (Retouchoir).

and has the youngest dates for this type of assemblage in Europe (Haesaerts et al., 1996; Higham et al., 2009; Hoffecker et al., 2008; Nigst et al., 2008; Sirakov et al., 2007; Szmidt et al., 2010).

5.1. Comparison to climatic data

It is useful to place cultural changes as indicated by lithic industries in the context of well documented events of rapid climate change in the glacial era (Müller et al., 2011; Tzedakis et al., 2007). Several warm Dansgaard-Oeschger (DO events 12 to 8) and one cold Heinrich Event (HE4) occurred in the Les Cottés time interval as shown in Fig. 5 (Chronology of the climate sequence taken from (Fleitmann et al., 2009).

The shading of the DO bars indicates the rapid initial warming (less than 50 years) of 11 °C–16 °C in Greenland (Wolff et al., 2010), whereas the cooling is gradual. A discussion of links to the decadal scale warming phase of DO events is limited by the unresolved question of synchroneity between Greenland climate markers and mid-latitude ecological response to climate change (Blaauw et al., 2010; Wohlfarth et al., 2008) and because of the error range of the radiocarbon dates in the chronology. HE4, on the other hand, lasted for more than 1500 years, therefore the age distribution

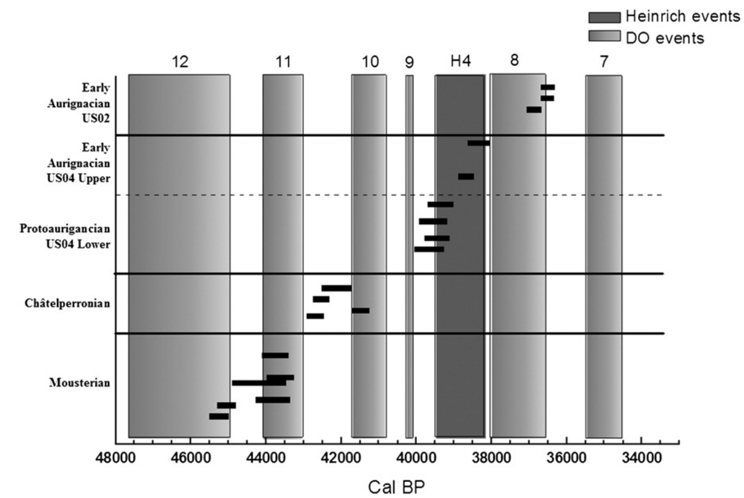

Fig. 5. Temporal relation of the archaeological phases of Les Cottés compared to the rapid climate changes as defined by several climate archives in the northern hemisphere (Fleitmann et al., 2009); for France see also Genty et al. (2003).

in our chronology should document if the area of Les Cottés was less populated during this cold phase.

The ages obtained on Les Cottés Protoaurignacian confirm that the Anatomically Modern Humans associated with this industry entered this part of Europe with the onset of HE4 and that they populated this area even during this phase, as observed also for Eastern Europe (Hoffecker, 2011, 2009).

6. Conclusion

Les Cottés is one of the few sites with a complete and well defined sequence covering the Middle to Early Upper Palaeolithic periods in Europe. We obtained radiocarbon dates on 27 bone samples from each archaeological level at this site. We created a chronological framework of five phases from the Mousterian to Early Aurignacian periods. The Mousterian and Châtelperronian are separated from the overlying Protoaurignacian level by a gap of approximately 1000 calendar years. The internal temporal relation between the Mousterian and Châtelperronian is not fully resolved by our dates, this aspect will be addressed by future work at the site. The fact that a substantial part of the Proto and Early Aurignacian appear contemporaneous, within the resolution of ^{14}C dating, indicates that this transition was rapid in this region. Anatomically Modern Humans are presents at the site of Les Cottés at least at 39,500 cal BP roughly coincident with the onset of the strong cold phase Heinrich 4.

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