

ANTHROPOLOGY

Radiocarbon chronology of Manot Cave, Israel and Upper Paleolithic dispersals

Bridget Alex,^{1*} Omry Barzilai,^{2*} Israel Hershkovitz,^{3,4} Ofer Marder,⁵ Francesco Berna,⁶ Valentina Caracuta,^{7,8} Talia Abulafia,⁵ Lauren Davis,⁵ Mae Goder-Goldberger,⁵ Ron Lavi,⁹ Eugenia Mintz,⁸ Lior Regev,⁸ Daniella Bar-Yosef Mayer,^{4,10,11} José-Miguel Tejero,^{12,13} Reuven Yeshurun,¹⁴ Avner Ayalon,¹⁵ Mira Bar-Matthews,¹⁵ Gal Yasur,¹⁵ Amos Frumkin,¹⁶ Bruce Latimer,^{17,18} Mark G. Hans,¹⁷ Elisabetta Boaretto^{8*}

Copyright © 2017
The Authors, some
rights reserved;
exclusive licensee
American Association
for the Advancement
of Science. No claim to
original U.S. Government
Works. Distributed
under a Creative
Commons Attribution
NonCommercial
License 4.0 (CC BY-NC).

The timing of archeological industries in the Levant is central for understanding the spread of modern humans with Upper Paleolithic traditions. We report a high-resolution radiocarbon chronology for Early Upper Paleolithic industries (Early Ahmarian and Levantine Aurignacian) from the newly excavated site of Manot Cave, Israel. The dates confirm that the Early Ahmarian industry was present by 46,000 calibrated years before the present (cal BP), and the Levantine Aurignacian occurred at least between 38,000 and 34,000 cal BP. This timing is consistent with proposed migrations or technological diffusions between the Near East and Europe. Specifically, the Ahmarian could have led to the development of the Protoaurignacian in Europe, and the Aurignacian in Europe could have spread back to the Near East as the Levantine Aurignacian.

INTRODUCTION

Although distinct populations of modern humans likely dispersed to Eurasia at different times, the group that successfully colonized Europe after ~50,000 years ago was associated with a suite of behavioral and technological innovations, broadly referred to as the Upper Paleolithic (1). Along the dispersal route, the Levant is a key region for understanding the origins and spread of Upper Paleolithic traditions and peoples (2, 3). During the temporal phase known as the Early Upper Paleolithic (EUP), there were two archeological cultures in the Levant attributed to modern humans, the Early Ahmarian and the Levantine Aurignacian (text S1) (4, 5). It has been proposed that the Early Ahmarian led to the Protoaurignacian in Europe (6) and that makers of the Aurignacian in Europe backmigrated to the Near East, producing the Levantine Aurignacian (7).

The likelihood of these hypotheses depends on the similarities between industries and their relative ages. This study focuses on the latter, adding new data to the Levantine EUP chronology to test pro-

posed relations between industries. Although chronology alone cannot prove these hypotheses, it can be consistent with them or it can refute them, if shown that a proposed descendant industry actually predated its alleged antecedent.

However, thus far, this test has been inconclusive for Levantine EUP industries because the regional chronology is not firmly established. Dates for Ahmarian assemblages differ by several millennia between sites, clustering into early appearance dates [~46 thousand calibrated years before the present (ka cal BP)] that allow for an Ahmarian-Protoaurignacian development (8) and late appearance dates (~40 ka cal BP) that refute this hypothesis (3, 9). Regarding the Levantine Aurignacian, the available dates are not precise enough to evaluate whether the industry could have derived from the Aurignacian in Europe (3). As it stands, the regional chronology is difficult to resolve because it includes chronometric samples collected from unclear contexts of old excavations and dates produced through analytical procedures that failed to demonstrate the removal of contaminants.

Here, we present a research program for radiocarbon dating, designed to ameliorate these issues through (i) the use of geochemical methods to characterize samples and their archeological contexts and (ii) experimentally determined pretreatment procedures, customized for the dated materials. The methodology is applied to newly excavated EUP assemblages from Manot Cave, Israel, resulting in a high-resolution chronology of 47 radiocarbon dates. Integrating the radiocarbon dates, geoarcheological analyses, and artifact analysis, the following minimum ranges are suggested for cultural phases at Manot: Early Ahmarian, from 46 to 42 ka cal BP; Levantine Aurignacian, from 38 to 34 ka cal BP; a post-Levantine Aurignacian industry, from 34 to 33 ka cal BP. These reliable dates provide a foundation for the Levantine EUP chronology, which is consistent with the hypotheses that the Ahmarian led to the Protoaurignacian in Europe and that the Aurignacian in Europe gave rise to the Levantine Aurignacian through the movement of people or ideas.

RESULTS

Site description and cultural-chronometric sequence

Excavated from 2010 to 2017, Manot is an active karstic cave in north-west Israel, about 10 km from the present-day Mediterranean (Fig. 1)

¹Department of Human Evolutionary Biology, Harvard University, Cambridge, MA 02138, USA. ²Archaeological Research Department, Israel Antiquities Authority, POB 586, Jerusalem 91004, Israel. ³Department of Anatomy and Anthropology, Dan David Center for Human Evolution and Biohistory Research, Shmunis Family Anthropology Institute, Sackler Faculty of Medicine, Tel Aviv University, Tel Aviv, Israel. ⁴The Steinhardt Museum of Natural History, Tel Aviv University, PO Box 39040, Tel Aviv 6997801, Israel. ⁵Department of Bible, Archaeology and the Ancient Near East, Ben-Gurion University of the Negev, PO Box 653, Beer-Sheva 8410501, Israel. ⁶Department of Archaeology, Simon Fraser University, 8888 University Drive, Burnaby, British Columbia V5A 1S6, Canada. ⁷Laboratory of Archaeobotany and Palaeoecology, University of Salento, Lecce 73100, Italy. ⁸Max Planck-Weizmann Center for Integrative Archaeology and Anthropology, DANGOOR Research Accelerator Mass Spectrometry Laboratory, Weizmann Institute of Science, Rehovot 7610001, Israel. ⁹8 Dan Street, Modi'in 7173161, Israel. ¹⁰Institute of Archaeology, Tel Aviv University, PO Box 39040, Tel Aviv 6997801, Israel. ¹¹Peabody Museum of Archaeology and Ethnology, Harvard University, Cambridge MA 02138, U.S.A. ¹²CNRS, UMR 7041, ArScAn équipe Ethnologie préhistorique, 92023 Nanterre, France. ¹³Seminari d'Estudis i Recerques Prehistòriques, Universitat de Barcelona, 08001 Barcelona, Spain. ¹⁴Zinman Institute of Archaeology, University of Haifa, Haifa 3498838, Israel. ¹⁵Geological Survey of Israel, 30 Malkhe Israel Street, Jerusalem 95501, Israel. ¹⁶Institute of Earth Sciences, Hebrew University of Jerusalem, Jerusalem 91904, Israel. ¹⁷Department of Orthodontics, Case Western Reserve University School of Dental Medicine, 10900 Euclid Avenue, Cleveland, OH 44106, USA. ¹⁸Department of Anatomy, Case Western Reserve University, Cleveland, OH 44106, USA.

*Corresponding author. Email: balex@fas.harvard.edu (B.A.); omry@isr antique.org.il (O.B.); elisabetta.boaretto@weizmann.ac.il (E.B.)

(10). A modern human calvaria, Manot 1, was recovered from the cave surface but was not associated with artifacts. It was uranium-thorium (U-Th)-dated to a minimum age of 54.7 ± 5.5 ka (11, 12). The site's archaeological finds constitute a stratified sequence of EUP industries (Table 1, text S2, figs. S1 and S4, and tables S1 and S2). The uppermost cultural phase, located by the cave entrance (area E), is classified as post-Levantine Aurignacian and contains endscrapers, burins, Dufour bladelets, and partially retouched twisted bladelets. It is underlain by a Levantine Aurignacian assemblage, characterized by endscrapers (carinated, nosed, and flat), carinated burins, blades with Aurignacian retouch, and Dufour bladelets. The Aurignacian finds also include bone awls, antler projectile points, shell beads, and a perforated red deer canine. Near the base of the cave (area C), another Aurignacian deposit overlays an Early Ahmarian assemblage, characterized by a technology of long, narrow blade/bladelets from uni- or bidirectional cores and a toolkit of endscrapers, burins, and el-Wad points. A small number of Initial Upper Paleolithic (IUP) and Middle Paleolithic (MP) artifacts have been found in the cave, but these industries have not yet been uncovered in stratigraphic sequence.

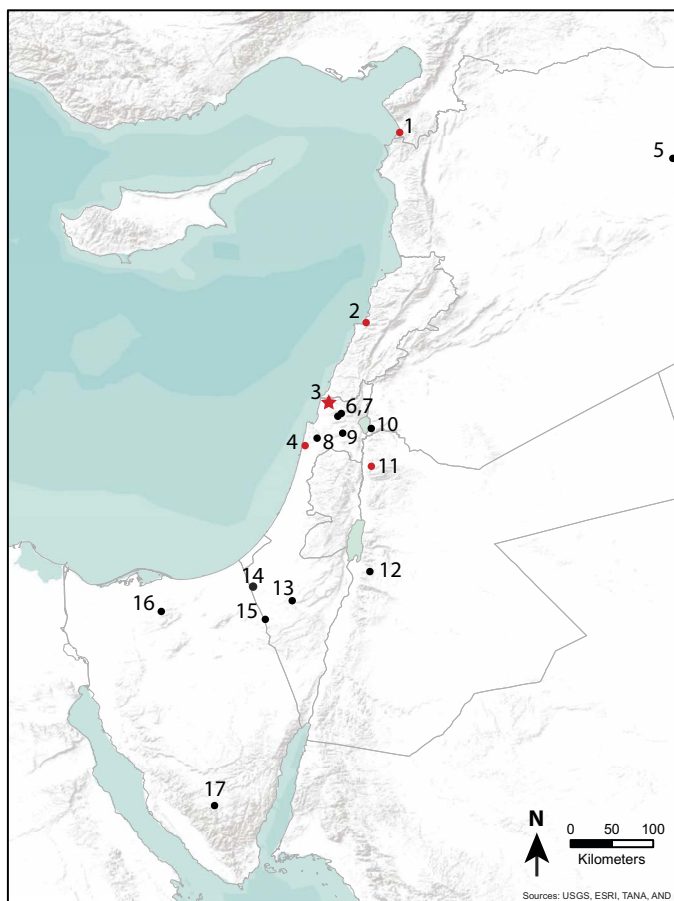


Fig. 1. Map of Levantine EUP sites mentioned in the text. Sites included in regional chronology are red. The Manot Cave is indicated by a star. 1, Üçağızlı; 2, Ksâr 'Akil; 3, Manot; 4, Kebara; 5, Wadi Kharar 16R; 6, Hayonim; 7, Meged; 8, Raqefet; 9, Qafzeh; 10, Nahal Ein-Gev I; 11, Mughr el-Hamamah; 12, Tor Sadaf; 13, Boker A/Boker Tachtit; 14, Nahal Nizzana XIII; 15, Qadesh Barnea; 16, Lagama VII; 17, Abu Noshra. USGS, U.S. Geological Survey; ESRI, Environmental Systems Research Institute; TANA, Telugu Association of North America; AND, Automotive Navigation Data.

Here, we report 47 radiocarbon dates used to establish the EUP chronology and to understand site formation processes at Manot (Fig. 2 and table S5). The dates were produced from 41 charcoal and 6 sediment samples, some of which were divided and subjected to different pretreatment procedures for a total of 86 accelerator mass spectrometry (AMS) measurements (texts S4 and S5 and tables S3 and S5). Radiocarbon dates in the text are reported as calibrated 68% probability density functions (PDFs). Dated samples came from the most intensively excavated areas, E and C (text S2 and fig. S1). By the current cave entrance at the top of the west talus, area E has preserved occupational surfaces indicated by semibrecciated sediment, concentrations of artifacts, and in situ hearths (fig. S2 and table S1). Dated charcoals were collected from hearths in area E ($n = 8$), associated with post-Levantine Aurignacian and Levantine Aurignacian artifacts (fig. S10).

Area C is near the bottom of the west talus, approximately 30 m southeast and 20 m below the current cave entrance (figs. S3 and S11). No clear-cut occupational surfaces were observed through excavation or geoarchaeological analyses. However, anthropogenic material seems to have been redeposited in sequence from primary contexts higher on the slope, resulting in a package of Aurignacian artifacts overlying a package of Ahmarian artifacts (fig. S4 and table S2). Isolated charcoals ($n = 23$), collected from a 1.5-m-long section, show increasing age with depth, dividing into a younger and older cluster. The younger cluster of 38 to 34 ka cal BP came from higher in the section (unit 4 and top of unit 5) associated with mostly Aurignacian artifacts. The older cluster of 46 to 42 ka cal BP came from lower in the section (unit 7 and bottom of unit 6), associated with mostly Ahmarian artifacts. Only three dates deviate from this pattern. The samples (RTD-7783A, RTD-7785, and RTD-7786) came from midway through the area C section and show reverse stratigraphy or decreasing age with depth. This 15-cm portion of the section ($z = 205.50$ to 205.35) is relatively rocky, suggesting stronger water activity, which could have led to mixed and missing deposits. We do not consider this area of the section representative of the cultural sequence and have excluded these dates in estimating the ages of cultural phases.

Radiocarbon pretreatment and statistical analysis

To remove contaminants from fossil charcoals before radiocarbon dating, laboratories routinely apply a number of pretreatment procedures,

Table 1. Excavation contexts and date ranges of cultural phases.

Cultural phase	Context dated	Date ranges cal BP 68.2% (sample number)
Post-Levantine Aurignacian	In situ occupational surfaces Area E, unit 2, layer I, loci 500 and 501	34,030–33,050 (6)
Levantine Aurignacian	In situ occupational surfaces Area E, unit 2, layer IV, locus 502	36,860–35,960 (2)
	Secondary talus deposit Area C, unit 4; area C, unit 5 above $z = 205.50$	38,260–34,050 (11)
Ahmarian	Secondary talus deposit Area C, unit 6 below $z =$ 205.35 ; area C, unit 7	45,940–41,560 (8) 49,440–41,600 (9)

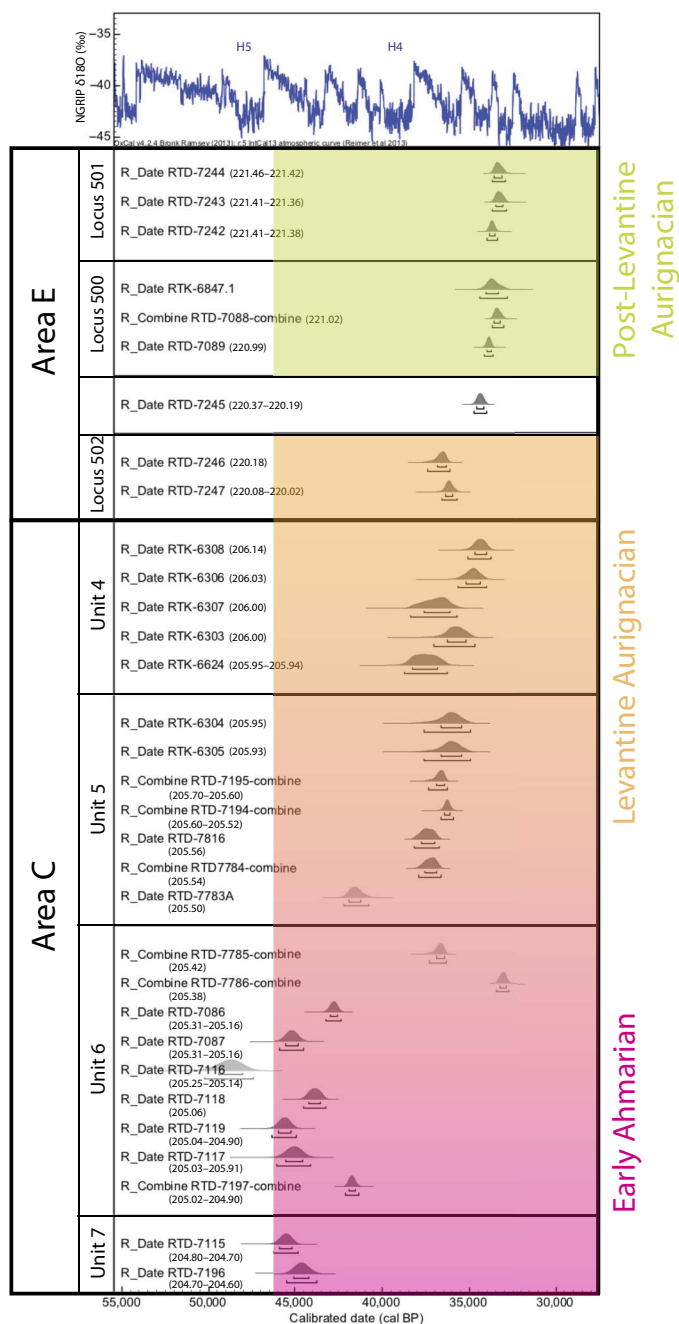


Fig. 2. Radiocarbon dates for archaeological chronology of Manot Cave. Samples from areas E and C. J squares are shown as PDFs calibrated with OxCal v4.2 (59) and IntCal13 (60). Dates are listed in stratigraphic sequence by laboratory code, followed by absolute elevation or the elevation range of the sample's excavation basket. The associated archaeological culture is indicated by color: post-Levantine Aurignacian, green; Levantine Aurignacian, orange; Early Ahmarian, pink. NGRIP, North Greenland Ice Core Project.

including the acid-base-acid (ABA) method, acid-base wet oxidation (ABOx) method, and stepped combustion. Controlled studies, comparing the effectiveness of different pretreatment procedures, have produced inconclusive results. Numerous studies have yielded older and more reliable dates with the harsher ABOx and stepped combustion methods (13, 14). However, studies of charcoals from certain Levan-

tine EUP sites found that ABA-treated fractions had better preservation parameters and older or statistically indistinguishable dates compared to their ABOx-treated pairs (text S4, fig. S8, and table S4) (8, 9, 15). These results indicate that the appropriate pretreatment method for fossil charcoal depends on the preservation state and depositional environment of the samples and thus should be experimentally determined for a given site (8, 16).

Here, experimental charcoals from Manot were separately divided into homogenized subsamples and treated with six different procedures: ABA, ABOx, and those methods, followed by stepped combustion to 630° or 900°C (text S4, fig. S6, and table S3). The fractions treated by ABA without stepped combustion produced the smallest percent modern carbon (pMC) values and Fourier transform infrared (FTIR) spectra, showing that sediment had been removed from samples (fig. S7). Radiocarbon dates of the total organic carbon in sediment were 16 to 10 ka younger than associated charcoals, so we expect any contamination from sediment to have made dates younger rather than older (text S5 and table S5). These combined results—smallest pMC values and demonstrated removal of younger-aged sediment—indicated that ABA without stepped combustion was the most effective method for charcoals from Manot. We recommend the methodology and parameters used to reach this conclusion (FTIR and pMC by different pretreatments) be used in future studies to determine the most effective method for samples from other sites, which may not be the same as Manot.

Bayesian models were produced that constrain dates based on stratigraphic information to test for outliers and estimate the span of cultural phases (text S6, fig. S12, and tables S7 to S9). However, our conclusions are based on the unmodeled ranges, which are less influenced by interpretations of stratigraphy and depositional history. The cultural span model (model 1) comprised three sequential phases of Ahmarian before Aurignacian before post-Levantine Aurignacian. It included dates from combustion features of area E and the sequence in area C (J squares with the exception of three dates described above that showed reverse stratigraphy). In this model, only 1 of 28 dates was identified as an outlier (fig. S12 and table S7). This was RTD-7116, a date of 49 to 48 ka cal BP that is significantly older than any other radiocarbon dates from Manot. Although the sample produced a finite radiocarbon age ($48,700 \pm 700$ ^{14}C years BP), it extends beyond the 50,000-year age limit of the calibration curve at 95.4% confidence and therefore may exceed the age limit of the radiocarbon method. The sample came from midway through unit 6 and could be the oldest Ahmarian date at Manot or represent an earlier phase because artifacts suggestive of the IUP and MP were recovered from the base of the sequence. The latter seems more likely, considering the tight spread of other Ahmarian-associated dates of 46 to 42 ka cal BP.

The modeled spans were the same as the unmodeled ranges, except that the Aurignacian was reduced to ~2000 years from an unmodeled range of 38 to 34 ka cal BP to a modeled span of 37 to 35 ka cal BP. The improved precision comes with the caveat that there is no continuous in situ stratigraphic boundary between the Ahmarian and Aurignacian sequences; rather, the boundary is inferred on the basis of artifact composition and clustering of dates in area C (text S6). In contrast, the end of the Aurignacian is bound stratigraphically by the overlying in situ post-Levantine Aurignacian layer in area E, dated to 34 to 33 ka cal BP. Moreover, the modeled range aligns with dates from the most secure Levantine Aurignacian context at Manot, the combustion feature in area E dated to 37 to 36 ka cal BP.

DISCUSSION

Implications for Levantine EUP chronology

In addition to Manot, there are four sites with large sequences of radiocarbon dates (>10) produced by modern analytical methods and associated with EUP assemblages (Figs. 1 and 3, text S7, and data set S1). Three of these are caves or rock shelters along the Mediterranean coast: Üçağızlı in Turkey (17), Ksâr ‘Akil in Lebanon (9, 18), and Kebara in Israel (8). The fourth is Mughr el-Hamamah in the Jordan Valley (19). Other sites in the southern arid zone, including Abu Noshra I and II, Boker A, Qadesh Barnea, and the Lagaman sites, have fewer dates, and those were mostly produced in the 1970s and early 1980s with less reliable methods (20, 21). Thus, as it stands, the Levantine EUP chronology is based on Mediterranean coastal sites, which underrepresent the assemblage variability of the region. Relations between coastal and arid sites are unclear, and the timing and character of industries may have differed between these zones.

The post-Levantine Aurignacian assemblage at Manot is tightly dated to 34 to 33 ka cal BP by charcoals from in situ combustion features. It is similar to assemblages, described as Atlitian, located in the

Mediterranean zone (text S2). The age of these assemblages has been estimated ~27 or 26 ka cal BP—younger than the Manot dates—but is considered problematic based on limited stratigraphic and chronometric data (22, 23). The secure Manot dates do align with the few dates from Atlitian layers at Ksâr ‘Akil (phase 6, level VI), approximately 35 to 32 ka cal BP (9, 18).

Dates included in the regional chronology for the Levantine Aurignacian, coming from Ksâr ‘Akil (*n* = 3) and Kebara (*n* = 7), have large uncertainties, which only constrain the timing of the phase to some time between 42 and 34 ka cal BP. The Manot data provide a relatively large sequence of high-precision dates for the industry (*n* = 13), which establishes a firm chronological peg for the Levantine Aurignacian at least between 38 and 34 ka cal BP and probably more precisely between 37 and 35 ka cal BP. The Levantine Aurignacian at Manot is also stratigraphically bound by the in situ post-Levantine Aurignacian surface dated to 34 to 33 ka cal BP. These chronostratigraphic data support views that the Levantine Aurignacian *sensu stricto* was a relatively short-lived archeological phenomenon (~2000 years), restricted to the Mediterranean vegetation belt (24).

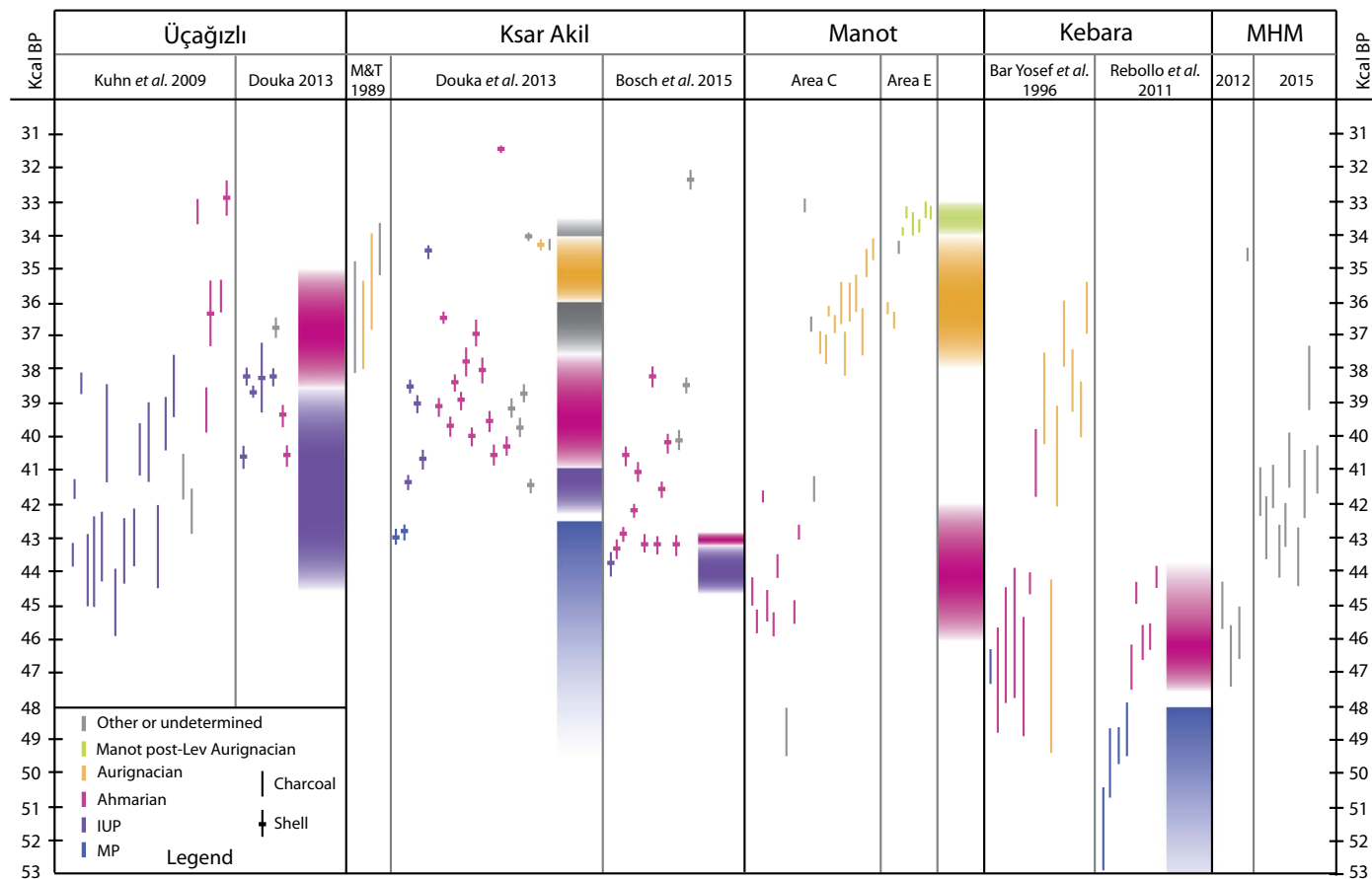


Fig. 3. Regional chronology of radiocarbon dates for stratified EUP sites between 50 and 30 ka cal BP. Vertical lines are charcoal dates, and crossed lines are shell dates. Dates are calibrated as 68.2% PDFs using the OxCal v4.2 software (59) and the IntCal-Marine13 calibration curve (60). Dates are color-coded by associated archeological industry and organized into columns by site and study. Within a given study, dates are ordered in stratigraphic sequence (from the lowest elevation or layer on the left to the highest on the right), as precisely as this information is known. The shaded blocks represent the phase ranges reported by particular studies. These ranges are the result of Bayesian models, with the exception of Manot, which shows the full unmodeled range. M&T, Mellars and Tixier (61); MHM, Mughr el-Hamamah. Dates assigned to “other or undetermined” do not necessarily represent the same industry between sites and strata. Site and date information is found in text S7 and data set S1.

The Early Ahmarian appears to have begun by 47.5 to 46 ka cal BP at Kebara (8) and Manot and then around 43 ka cal BP (18) or 40 ka cal BP (3) at Ksâr 'Akil and Üçağızlı. This 3000- to 7000-year difference may be because people at Manot and Kebara produced the Early Ahmarian several thousand years earlier than people at Ksâr 'Akil and Üçağızlı. The discrepancy may also result from mischaracterization of archeological assemblages or incorrect assumptions that named stone tool industries were made by socially related people. However, the relevant assemblages at Manot, Kebara, Ksâr 'Akil, and Üçağızlı show a high degree of technotypological similarity within a narrow geographic and stratigraphic range, corresponding to the "Northern Early Ahmarian" (25). The Early Ahmarian is thought to have developed locally from the IUP (26, 27). Although the more southern sites of Manot and Kebara do not have stratified IUP assemblages, the well-dated Early Ahmarian layers are earlier than or contemporaneous with the IUP at Ksâr 'Akil and Üçağızlı. In this case, the people of Ksâr 'Akil and Üçağızlı would have gradually developed an industry 3000 to 7000 years after it was fully developed less than 500 km to the south.

Alternatively, the disagreement could be explained by differences in the reliability of radiocarbon dates related to sample context, material, and pretreatment methods (text S7). Regarding the issue of context, radiocarbon samples from Manot were collected during recent excavations from combustion features and known stratigraphic positions, which were characterized by several geochemical methods (text S3). Radiocarbon samples from Ahmarian levels of Ksâr 'Akil were recovered in the 1930s to 1940s with outdated excavation methods, and in the decades since, some specimens likely became mislabeled in terms of provenience (9). Inaccurate proveniences may explain the large number of outliers in Bayesian models that constrain Ksâr 'Akil dates to stratigraphic position [9 of 39 dates in the study of Douka *et al.* (9) and 6 of 16 dates in the study of Bosch *et al.* (18)].

Next, late appearance dates for the Early Ahmarian from Ksâr 'Akil and Üçağızlı were produced primarily from shells, whereas the early appearance dates from Manot and Kebara were produced from charcoals. Evidence that contamination has been removed from samples should be based on independent analyses of the dated materials rather than the ages obtained. For charcoal, several such methods have been developed (28–30) and proven reliable in intercomparison studies between laboratories (8). For shell, it is difficult to detect and demonstrate the removal of diagenetic carbonate from the original biogenic carbonate (31).

Last, when disagreements arise between charcoal dates for a given event, the older dates are generally considered more reliable and the younger dates are thought to reflect contamination (32, 33). This is because a small amount of modern carbon (<1%) can make Late Pleistocene samples appear thousands of years younger (34). Our pretreatment experiments showed that for charcoals from Manot, the ABA method produced the smallest pMC values (and oldest dates) and purest FTIR spectra. The same pattern was found for charcoals from Kebara (8). We hypothesize that this is because harsher treatments (ABOX and stepped combustion) destroy more of the charcoals. Then, any surviving contaminant clay comprises a greater portion of the measured sample (28), and some of these contaminants (for example, siliceous aggregates) are reactive with atmospheric CO₂ (8). Because dated sediment at Manot is approximately 15 to 10 ka younger than associated charcoals, contamination from clay would make dates younger. Thus, we argue that the Ahmarian appeared in the Levant by at least 46 ka cal BP based on the early appearance dates from Kebara and Manot.

This age is also older than some dates for the Ahmarian from the southern arid zones of the Levant (Negev and Sinai) (20, 21). The arid zone dates should be viewed with caution because they include a small number of samples and were produced decades ago. However, they highlight a potentially interesting pattern for future research that the Ahmarian may have originated in the coastal Levant and then spread southward into the arid zones.

Implications for relations between the Near East and Europe

Here, we use the Manot chronology to evaluate proposals that the Ahmarian led to the Protoaurignacian in Europe and that the European Aurignacian led to the Levantine Aurignacian. These hypotheses are founded on the premise that archeological industries can be used to trace migrations and relations of past human groups. Although this approach is widely applied, it must be justified for each context (35). Assemblages should be systematically compared within a framework that considers artifact traits resulting from socially learned, idiosyncratic choices in material culture production to distinguish between hypotheses of independent invention and cultural transmission (36). Although this research is ongoing, it is also essential to test the conclusions against chronometric data. Accurate chronologies constrain hypotheses by refuting scenarios that do not accord with the timing of archeological industries.

It has been proposed that the Levantine Aurignacian was an intrusive industry, introduced by makers of the European Aurignacian (text S1) (7, 37–39). The view that the Levantine Aurignacian was nonlocal is supported by statistical comparison of technological and typological traits of lithics from Ksâr 'Akil, showing that Levantine Aurignacian traits (phase 5, levels VIII to VII) differ significantly from all other EUP layers (40). Regarding ties to the European Aurignacian, the broad similarities include thick scrapers made on flakes (nosed, carinated, and shouldered), Dufour bladelets, bone/antler points, and animal tooth pendants (40–43). Some of the shared features are characteristic of the Early Aurignacian [Aurignacian I (44–46)], such as Aurignacian re-touched blades, scrapers with scalar lateral retouch, and flat carinated items (7, 39). However, other features, including nosed and shouldered pieces, twisted Dufour bladelets, and simple-based antler points, resemble tools of the later Evolved Aurignacian [Aurignacian II and III (46, 47)]. Thus, linking the Levantine Aurignacian to a particular phase of the European sequence is an open question, which must be addressed through systematic comparisons of assemblages between regions. There have been few studies of this nature, although Tostevin (36) showed that blank production and toolkit morphology of lithics from Aurignacian layers of Kebara and Central Europe (Stránská skála, Czech Republic) are more similar to each other than to preceding strata at each site. In addition, Tejero *et al.* (47) demonstrated similarities between Aurignacian assemblages at Manot and Europe in the uses and production methods of osseous tools.

In terms of chronology, the secure Levantine Aurignacian dates from Manot are contemporaneous with or slightly later than the 39.5 to 35.5 ka cal BP modeled start dates of the Evolved Aurignacian in Southwest France/Northern Iberia at L'Arbreda, La Viña, and Abri Pataud and substantially later than Early Aurignacian assemblages, which begin between 43.5 and 40 ka cal BP across Europe at sites including Abri Pataud, Labeko Koba, and Willendorf II (48, 49). Thus, dates from Manot do not refute the hypothesis that the Levantine Aurignacian developed from a European Aurignacian precursor.

It is often claimed that the Ahmarian led to the European Protoaurignacian (1, 6) based on shared features of shell ornaments and

long, straight blades/bladelets produced by soft hammer reduction, possibly for projectile weapons (50). The Protoaurignacian appears to be intrusive in European sequences because it is typologically and technologically distinct from assemblages in preceding layers (51). However, systematic studies comparing Ahmarian and Protoaurignacian assemblages are lacking. The Ahmarian-Protoaurignacian hypothesis has been challenged because late appearance dates for the Ahmarian of ~40 ka cal BP from Ksar 'Akil and Üçağzılı (3) are younger than the earliest Protoaurignacian dates of 44 to 41 ka cal BP from sites including Isturitz, Riparo Mochi, L'Arbreda, and Fumane (48). In contrast, early appearance dates from Manot and Kebara begin the Ahmarian by 46 ka cal BP, securely before the earliest Protoaurignacian, and therefore allow for the hypothesis that the Ahmarian of the Levant gave rise to the Protoaurignacian of Europe.

Testing proposed affinities between the Ahmarian and Protoaurignacian, as well as the European Aurignacian and Levantine Aurignacian, will require more systematic comparisons of the material cultural remains (that is, lithic, shell, bone, and antler artifacts) from each region. However, these hypotheses cannot be evaluated without accurate, high-precision chronologies. The results from Manot Cave provide a chronological foundation, which is critical for understanding the spread of modern humans and Upper Paleolithic traditions.

MATERIALS AND METHODS

Radiocarbon dating

The archeological chronology was based on radiocarbon dates of charcoals (Fig. 2, Table 1, and table S5). In area E, the charcoal samples were selected from combustion features, whereas in area C, charcoals were chosen to cover as much of the sequence vertically as possible. Charcoal pieces were collected by hand during excavation or from exposed sections and wrapped in aluminum foil with associated sediment. Several charcoals were collected from micromorphology blocks, as the blocks were cut and removed. Charcoals were identified using a metallographic microscope (Nikon Eclipse LV150N). The vast majority of charcoals at Manot are *Amygdalus* sp. (almond), and all dated specimens were identified as belonging to this taxon. No bones yielded collagen. Approximately 40 bones were sampled, collected from all excavation areas, and in varying taphonomic states. Although dietary and ornamental marine shells were recovered, they were not dated because it is unclear whether diagenetic carbonate can be separated from original biogenic carbonate (31).

Samples were characterized and prepared for radiocarbon dating based on tailor-made procedures at the DANGOOR Research Accelerator Mass Spectrometry (D-REAMS) Laboratory (text S5) (8, 28, 52). Before and after pretreatment, samples were analyzed by FTIR spectrometry to test the purity of the material. Approximately 50 mg of each charcoal piece was cleaned of sediment with a scalpel and homogenized by crushing with an agate mortar and pestle. Most samples were then treated with the following ABA procedure: (i) acid treatment in 1 M HCl for 30 min, followed by rinsing with Nanopure water until it reached pH 6, (ii) base treatment of 0.1 M NaOH for 15 min, followed by rinsing until it reached pH 6, and (iii) acid treatment in 1 M HCl for 1 hour in a water bath of 80°C, followed by rinsing until it reached pH 6. Because of their small size, four charcoals included in the chronology were treated with a water-base-acid regime, which followed the same procedure except that the first acid treatment was replaced by a wash with Nanopure water.

Samples were dried overnight at ~60°C, combusted to CO₂ with ~200 mg of CuO at 900°C, and then reduced to graphite in a vacuum line. Four samples were divided and underwent graphitization on the standard vacuum line and on an ultraclean line, dedicated to samples over 30,000 ¹⁴C years BP. Samples with laboratory code RTD were measured by AMS at the D-REAMS Laboratory (53), whereas those with RTK were measured at the National Science Foundation (NSF)-Arizona AMS Facility, University of Arizona. Stable isotope measurements were conducted at the Geological Survey of Israel.

Radiocarbon dates were produced for sediment to evaluate how contaminant sediment would affect charcoal dates. Four sediment samples were directly removed from dated charcoal samples, and two additional sediment samples were collected from the section. The sediment samples were crushed, homogenized, and then dissolved in 1 M HCl, followed by three rinses with Nanopure water. The remaining fraction contained the total organic carbon (TOC) and was prepared to graphite, as described above. The sediment TOC dates were between 16,000 and 10,000 years younger than their associated charcoals (table S5).

Determination of radiocarbon pretreatment

To determine the best pretreatment method for charcoals from Manot, four charcoal samples from area C were separately homogenized, divided, and prepared by different procedures (text S4). These experimental charcoals were subjected to six procedures: ABA, ABOx, and both of those treatments followed by stepped combustion at 630° or 900°C. The ABOx procedure consisted of the following: (i) 6 M HCl for 1 hour, followed by rinsing with Nanopure water, (ii) 1 M NaOH for 1 hour, followed by rinsing with Nanopure water, and (iii) 0.1 M K₂Cr₂O₇ in 2 M H₂SO₄ at 60°C overnight. After rinsing with Nanopure water, samples were oven-dried at 105°C. The step combustion procedure followed (i) precombustion at 300°C in 750 torr O₂ for 30 min (this should remove the more recent contamination), (ii) combustion at 630°C with CuO for 2 hours in vacuum and collection of the CO₂, and (iii) combustion at 900°C with CuO for 3 hours and collection of the CO₂.

In total, 31 fractions were measured from the original four charcoals. The results are reported as pMC (fig. S6 and table S3). The same background correction of 0.263 ± 0.032 pMC was applied to all fractions, which reflects graphitization and AMS steps. The pretreatment background correction was not applied so that pMC values resulting from different procedures could be directly compared. In this way, the pMC values indicate the effectiveness of the specific pretreatments; however, a background correction reflecting graphitization, AMS, and pretreatment was applied in calculating the reported radiocarbon dates in table S5. The results show that the ABA treatment procedure without step combustion produced the smallest pMC measurements and oldest ages. Explanations for this pattern are discussed in text S4.

Geoarcheological analysis

In conjunction with other geoarcheological work at Manot Cave, focused mineralogical analyses were conducted to support radiocarbon sampling and interpretation. The analyses included micromorphology, loose sediment characterization, and experimental heating of local control sediment. For micromorphological study, intact sediment blocks were taken from throughout the vertical section of area C (fig. S3) and from specific features in area E. Air-dried blocks were impregnated with polyester/styrene resin, cured, cut with a rock saw,

and sent to Spectrum Petrographics, where they were prepared into 30- μm -thin sections. The thin sections were analyzed with a petrographic microscope and described using conventional criteria and terminology (54, 55). Loose sediment samples were collected from surfaces, from sections, and with radiocarbon samples and then analyzed by FTIR. For all FTIR measurements, a few milligrams of sample were ground and homogenized with an agate mortar and pestle. Approximately 0.2 mg of the sample was mixed with ~50 mg of KBr powder and pressed into a 7-mm pellet with a hand press (Qwik Handi-Press, Spectra-Tech Industries Corporation) or a manual hydraulic press (Specac). FTIR spectra were measured at a resolution of 4 cm^{-1} for 32 scans between 4000 and 400 cm^{-1} using a Nicolet 380 (Thermo Fisher Scientific) (56, 57). Spectra and photographs of thin sections are available upon request.

Control sediment was collected from the surface of the cave base (area A) for an experimental heating study (58). The sediment was heated to set temperatures and analyzed by FTIR to determine the temperature-related transformations of the clay minerals contained in the local sediment. This calibration was then used to estimate the temperatures reached by sediment associated with putative combustion features. Fifty grams of sediment was homogenized and separated into 10 samples (5 g each). The samples were placed in ceramic crucibles and heated to different temperatures (0°C and 200° to 1000°C at 100°C increments) for 4 hours in a muffle furnace (A. Mandel, T21 type coupled with a Eurotherm 3216 temperature programmer). After heating, the sediments were analyzed by FTIR, as described above.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/3/11/e1701450/DC1>

text S1. Levantine EUP
 text S2. Site description and archeological sequence
 text S3. Geoarcheological results
 text S4. Charcoal pretreatment: ABA, ABOx, and stepped combustion comparisons
 text S5. Charcoal preservation and radiocarbon results
 text S6. Bayesian modeling
 text S7. Regional chronology
 fig. S1. Top view and profile view of Manot Cave.
 fig. S2. Excavation area E with combustion features.
 fig. S3. Area C showing locations of radiocarbon samples and micromorphology blocks.
 fig. S4. Artifacts from Manot Cave.
 fig. S5. FTIR spectra of sediment exposed to different temperatures in experimental heating study.
 fig. S6. Radiocarbon measurements of Manot charcoal samples prepared by different pretreatments.
 fig. S7. FTIR spectra of charcoal sample before pretreatment, after ABA, and after ABOx.
 fig. S8. Comparison of ABA and ABOx charcoal dates from Levantine EUP sites.
 fig. S9. Characterization of *Amygdalus* sp. charcoal by scanning electron microscope and FTIR.
 fig. S10. Calibrated radiocarbon dates from area E plotted by absolute elevation.
 fig. S11. Calibrated radiocarbon dates from area C plotted by absolute elevation.
 fig. S12. Bayesian models and outlier analysis.
 table S1. Lithic assemblage in area E.
 table S2. Lithic assemblage in area C.
 table S3. Radiocarbon measurements of Manot charcoal samples prepared by different pretreatments.
 table S4. Comparison of ABA and ABOx charcoal dates from Levantine EUP sites.
 table S5. Radiocarbon samples and dates for Manot Cave.
 table S6. Excavation contexts with archeological classifications and date ranges.
 table S7. Outputs of Bayesian model 1 based on cultural phases.
 table S8. Cultural phase estimates for eight runs of model 1.
 table S9. Outputs of Bayesian model 2 based on lithostratigraphic units.
 data set S1. Published dates used to construct regional chronology.
 References (62–116)

REFERENCES AND NOTES

- J.-J. Hublin, The modern human colonization of western Eurasia: When and where? *Quat. Sci. Rev.* **118**, 194–210 (2015).
- A. N. Goring-Morris, A. Belfer-Cohen, *More Than Meets the Eye: Studies on Upper Palaeolithic Diversity in the Near East* (Oxbow Books, 2003).
- K. Douka, Exploring “the great wilderness of prehistory”: The chronology of the Middle to the Upper Paleolithic transition in the northern Levant. *Mitteilungen der Gesellschaft für Urgeschichte* **22**, 11–40 (2013).
- A. E. Marks, in *Préhistoire du Levant: Chronologie et organisation de l'espace depuis les origines jusqu'au VIe millénaire*, J. Cauvin, P. Sanlaville, Eds. (Éditions du CNRS, 1981), pp. 287–298.
- I. Gilead, in *Préhistoire du Levant: Chronologie et organisation de l'espace depuis les origines jusqu'au VIe millénaire*, J. Cauvin, P. Sanlaville, Eds. (Éditions du CNRS, 1981), pp. 331–333.
- P. Mellars, Archeology and the dispersal of modern humans in Europe: Deconstructing the “Aurignacian.” *Evol. Anthropol.* **15**, 167–182 (2006).
- N. Goring-Morris, A. Belfer-Cohen, in *Towards a Definition of the Aurignacian*, O. Bar-Yosef, J. Zilhão, Eds. (Instituto Portugues de Arqueologia, 2006), pp. 297–316.
- N. R. Rebollo, S. Weiner, F. Brock, L. Meignen, P. Goldberg, A. Belfer-Cohen, O. Bar-Yosef, E. Boaretto, New radiocarbon dating of the transition from the Middle to the Upper Paleolithic in Kebara Cave, Israel. *J. Archaeol. Sci.* **38**, 2424–2433 (2011).
- K. Douka, C. A. Bergman, R. E. M. Hedges, F. P. Wesselingh, T. F. G. Higham, Chronology of Ksar Akil (Lebanon) and implications for the colonization of Europe by anatomically modern humans. *PLOS ONE* **8**, e72931 (2013).
- O. Barzilai, I. Hershkovitz, O. Marder, The Early Upper Paleolithic Period at Manot Cave, Western Galilee, Israel. *J. Hum. Evol.* **31**, 85–100 (2016).
- I. Hershkovitz, O. Marder, A. Ayalon, M. Bar-Matthews, G. Yasur, E. Boaretto, V. Caracuta, B. Alex, A. Frumkin, M. Goder-Goldberger, P. Gunz, R. L. Holloway, B. Latimer, R. Lavi, A. Matthews, V. Slon, D. B.-Y. Mayer, F. Berna, G. Bar-Oz, R. Yeshurun, H. May, M. G. Hans, G. W. Weber, O. Barzilai, Levantine cranium from Manot Cave (Israel) foreshadows the first European modern humans. *Nature* **520**, 216–219 (2015).
- I. Hershkovitz, B. Latimer, O. Barzilai, O. Marder, Manot 1 calvaria and recent modern human evolution: An anthropological perspective. *BMSAP* **29**, 119–130 (2017).
- M. I. Bird, V. Levchenko, P. L. Ascough, W. Meredith, C. M. Wurster, A. Williams, E. L. Tilston, C. E. Snape, D. C. Apperley, The efficiency of charcoal decontamination for radiocarbon dating by three pre-treatments—ABOX, ABA and hypy. *Quat. Geochronol.* **22**, 25–32 (2014).
- R. E. Wood, K. Douka, P. Boscato, P. Haesaerts, A. Sinityn, T. F. G. Higham, Testing the ABOx-SC method: Dating known-age charcoals associated with the Campanian Ignimbrite. *Quat. Geochronol.* **9**, 16–26 (2012).
- F. Brock, T. F. G. Higham, AMS radiocarbon dating of Paleolithic-aged charcoal from Europe and the Mediterranean rim using ABOx-SC. *Radiocarbon* **51**, 839–846 (2009).
- M. I. Bird, P. L. Ascough, Isotopes in pyrogenic carbon: A review. *Org. Geochem.* **42**, 1529–1539 (2012).
- S. L. Kuhn, M. C. Stiner, E. Güleş, I. Özer, H. Yilmaz, I. Baykara, A. Açıkkol, P. Goldberg, K. M. Molina, E. Ünay, F. Suata-Alpaslan, The early Upper Paleolithic occupations at Üçağızlı Cave (Hatay, Turkey). *J. Hum. Evol.* **56**, 87–113 (2009).
- M. D. Bosch, M. A. Mannino, A. L. Prendergast, T. C. O'Connell, B. Demarchi, S. M. Taylor, L. Niven, J. van der Plicht, J.-J. Hublin, New chronology for Ksar Akil (Lebanon) supports Levantine route of modern human dispersal into Europe. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 7683–7688 (2015).
- A. J. Stutz, J. J. Shea, J. A. Rech, J. S. Pigati, J. Wilson, M. Belmaker, R. M. Albert, T. Arpin, D. Cabanes, J. L. Clark, G. Hartman, F. Hourani, C. E. White, L. Nilsson Stutz, Early upper Paleolithic chronology in the Levant: New ABOx-SC accelerator mass spectrometry results from the Mughr el-Hamamah site, Jordan. *J. Hum. Evol.* **85**, 157–173 (2015).
- J. L. Phillips, in *Late Quaternary Chronology and Paleoclimates of the Eastern Mediterranean*, O. Bar-Yosef, R. S. Kra, Eds. (Radiocarbon and American School of Prehistoric Research, 1994), pp. 169–176.
- A. N. Goring-Morris, A. Belfer-Cohen, Appendix: radiometric dates for the Upper Palaeolithic of the Levant, in *More than Meets the Eye: Studies on Upper Palaeolithic Diversity in the Near East*, A. N. Goring-Morris, A. Belfer-Cohen, Eds. (Oxbow Books, 2003), pp. 281–287.
- L. Copeland, The Middle and Upper Palaeolithic of Lebanon and Syria in the light of recent research, in *Problems in Prehistory: North African and the Levant*, F. Wendorf, A. E. Marks, Eds. (Southern Methodist Univ. Press, 1975), pp. 317–350.
- A. Belfer-Cohen, A. N. Goring-Morris, The Upper Palaeolithic in Cisjordan, in *Quaternary of the Levant: Environments, Climate Change, and Humans*, Y. Enzel, O. Bar-Yosef, Eds. (Cambridge Univ. Press, 2017), pp. 627–638.
- O. Bar-Yosef, A. Belfer-Cohen, The Levantine Upper Palaeolithic and Epipalaeolithic, in *South-Eastern Mediterranean Peoples Between 130,000 and 10,000 Years Ago*, E. A. Garcea, Ed. (Oxbow Books, 2010), pp. 144–167.
- S. Kadowaki, T. Omori, Y. Nishiaki, Variability in Early Ahmarian lithic technology and its implications for the model of a Levantine origin of the Protoaurignacian. *J. Hum. Evol.* **82**, 67–87 (2015).

26. S. L. Kuhn, Questions of complexity and scale in explanations for cultural transitions in the Pleistocene: A case study from the Early Upper Paleolithic. *J. Archaeol. Method Theory* **20**, 194–211 (2013).
27. A. E. Marks, The upper and middle palaeolithic of the Near East and the Nile Valley: The problem of cultural transformations, in *The Emergence of Modern Humans: An Archaeological Perspective*, P. Mellars, Ed. (Cornell Univ. Press, 1990), pp. 56–80.
28. M. Yizhaq, G. Mintz, I. Cohen, H. Khalilay, S. Weiner, E. Boaretto, Quality controlled radiocarbon dating of bones and charcoal from the early Pre-Pottery Neolithic B (PPNB) of Motza (Israel). *Radiocarbon* **47**, 193–206 (2005).
29. D. Alon, G. Mintz, I. Cohen, S. Weiner, E. Boaretto. The use of Raman spectroscopy to monitor the removal of humic substances from charcoal: Quality control for ^{14}C dating of charcoal. *Radiocarbon* **44**, 1–11 (2002).
30. N. R. Rebollo, I. Cohen-Ofri, R. Popovitz-Biro, O. Bar-Yosef, L. Meignen, P. Goldberg, S. Weiner, E. Boaretto, Structural characterization of charcoal exposed to high and low Ph: Implications for ^{14}C sample preparation and charcoal preservation. *Radiocarbon* **50**, 289–307 (2008).
31. F. S. Busschers, F. P. Wesselingh, R. H. Kars, M. Versluijs-Helder, J. Wallinga, J. H. A. Bosch, J. Timmer, K. G. J. Nierop, T. Meijer, F. P. M. Bunnik, H. De Wolf, Radiocarbon dating of Late Pleistocene marine shells from the Southern North Sea. *Radiocarbon* **56**, 1151–1166 (2014).
32. T. Higham, European Middle and Upper Palaeolithic radiocarbon dates are often older than they look: Problems with previous dates and some remedies. *Antiquity* **85**, 235–249 (2011).
33. R. Wood, From revolution to convention: The past, present and future of radiocarbon dating. *J. Archaeol. Sci.* **56**, 61–72 (2015).
34. C. Bronk Ramsey, Radiocarbon dating: Revolutions in understanding. *Archaeometry* **50**, 249–275 (2008).
35. O. Bar-Yosef, A. Belfer-Cohen, Following Pleistocene road signs of human dispersals across Eurasia. *Quat. Int.* **285**, 30–43 (2013).
36. G. B. Tostevin, *Seeing Lithics: A Middle-Range Theory for Testing for Cultural Transmission in the Pleistocene (American School of Prehistoric Research Monograph)* (Oxbow Books, 2013).
37. D. A. E. Garrod, The relations between Southwest Asia and Europe in the Later Palaeolithic Age. *J. World Hist.* **1**, 13–38 (1953).
38. A. Belfer-Cohen, O. Bar-Yosef, The levantine aurignacian: 60 years of research, in *Dorothy Garrod and the Progress of the Palaeolithic: Studies in the Prehistoric Archaeology of the Near East and Europe*, W. Davies, R. Charles, Eds. (Oxbow Books, 1999), pp. 118–134.
39. A. Belfer-Cohen, A. N. Goring-Morris, The earlier Upper Palaeolithic: A view from the Southern Levant, in *The Aurignacian of Yafteh Cave and its Context (2005–2008 Excavations)*, M. Otte, S. Shidrang, D. Flas, Eds. (ERAUL, 2012), pp. 127–136.
40. J. K. Williams, C. A. Bergman, Upper Paleolithic levels XIII–VI (A and B) from the 1937–1938 and 1947–1948 Boston college excavations and the Levantine Aurignacian at Ksar Akil, Lebanon. *Paléorient* **36**, 117–161 (2010).
41. J. J. Shea, *Stone Tools in the Paleolithic and Neolithic Near East: A Guide* (Cambridge Univ. Press, 2013).
42. A. Belfer-Cohen, O. Bar-Yosef, The Aurignacian at Hayonim Cave. *Paléorient* **7**, 19–42 (1981).
43. A. Belfer-Cohen, A. N. Goring-Morris, On the rebound—A Levantine view of Upper Palaeolithic dynamics, in *Modes de Contacts et de Déplacements au Paléolithique Eurasiatique*, M. Otte, F. Le Brun-Ricalens, Eds. (ERAUL, 2014), pp. 27–38.
44. J.-G. Borde, News from the West: A reevaluation of the classical Aurignacian sequence of the Périgord, in *Towards a Definition of the Aurignacian: Proceedings of the Symposium Held in Lisbon, Portugal, June 25–30, 2002*, O. Bar-Yosef, J. Zilhão, Eds. (Instituto Português de Arqueologia, 2006), pp. 147–172.
45. F. Bon, *L'Aurignacien entre Mer et Océan: Réflexion sur l'unité des phases anciennes de l'Aurignacien dans le sud de la France* (Société Préhistorique Française, 2002).
46. F. Bon, N. Teyssandier, J.-G. Borde, in *Les Aurignaciens (Civilisations et Cultures)*, M. Otte, Ed. (Errance, 2010), pp. 49–72.
47. J.-M. Tejero, R. Yeshurun, O. Barzilai, M. Goder-Goldberger, I. Hershkovitz, R. Lavi, N. Schneller-Pels, O. Marder, The osseous industry from Manot Cave (Western Galilee, Israel): Technical and conceptual behaviours of bone and antler exploitation in the Levantine Aurignacian. *Quat. Int.* **403**, 90–106 (2016).
48. R. E. Wood, A. Arrizabalaga, M. Camps, S. Fallon, M.-J. Iriarte-Chiapusso, R. Jones, J. Maroto, M. de la Rasilla, D. Santamaría, J. Soler, N. Soler, A. Villaluenga, T. F. G. Higham, The chronology of the earliest Upper Paleolithic in northern Iberia: New insights from L'Arbreda, Labeko Koba and La Viña. *J. Hum. Evol.* **69**, 91–109 (2014).
49. P. R. Nigst, P. Haesaerts, F. Dambon, C. Frank-Fellner, C. Mallol, B. Viola, M. Götzinger, L. Niven, G. Trnka, J.-J. Hublin, Early modern human settlement of Europe north of the Alps occurred 43,500 years ago in a cold steppe-type environment. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 14394–14399 (2014).
50. N. Teyssandier, F. Bon, J.-G. Borde, Within projectile range: Some thoughts on the appearance of the Aurignacian in Europe. *J. Anthropol. Res.* **66**, 209–229 (2010).
51. J. Riel-Salvatore, thesis, Arizona State University (2007).
52. E. Boaretto, X. Wu, J. Yuan, O. Bar-Yosef, V. Chu, Y. Pan, K. Liu, D. Cohen, T. Jiao, S. Li, H. Gu, P. Goldberg, S. Weiner, Radiocarbon dating of charcoal and bone collagen associated with early pottery at Yuchanyan Cave, Hunan Province, China. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 9595–9600 (2009).
53. L. Regev, E. M. Wild, W. Kutschera, E. Boaretto, D-REAMS: A new compact AMS system for radiocarbon measurements at the Weizmann Institute of Science, Rehovot, Israel. *Radiocarbon* **59**, 775–784 (2017).
54. P. Bullock, *Handbook for Soil Thin Section Description* (Waine Research Publications, 1985).
55. G. Stoops, *Guidelines for Analysis and Description of Soil and Regolith Thin Sections* (Soil Science Society of America, 2003).
56. S. Weiner, *Microarchaeology: Beyond the Visible Archaeological Record* (Cambridge Univ. Press, 2010).
57. M. Toffolo, A. M. Maeir, J. R. Chadwick, E. Boaretto, Characterization of contexts for radiocarbon dating: Results from the Early Iron Age at Tell Es-Safi/Gath, Israel. *Radiocarbon* **54**, 371–390 (2012).
58. F. Berna, A. Behar, R. Shahack-Gross, J. Berg, E. Boaretto, A. Gilboa, I. Sharon, S. Shalev, S. Shilstein, N. Yahalom-Mack, J. R. Zorn, S. Weiner, Sediments exposed to high temperatures: Reconstructing pyrotechnological processes in Late Bronze and Iron Age Strata at Tel Dor (Israel). *J. Archaeol. Sci.* **34**, 358–373 (2007).
59. C. Bronk Ramsey, Bayesian analysis of radiocarbon dates. *Radiocarbon* **51**, 337–360 (2009).
60. P. J. Reimer, E. Bard, A. Bayliss, J. Warren Beck, P. G. Blackwell, C. Bronk Ramsey, C. E. Buck, H. Cheng, R. Lawrence Edwards, M. Friedrich, P. M. Grootes, T. P. Guilderson, H. Hallidason, I. Hajdas, C. Hatté, T. J. Heaton, D. L. Hoffmann, A. G. Hogg, K. A. Hughen, K. Felix Kaiser, B. Kromer, S. W. Manning, M. Niu, R. W. Reimer, D. A. Richards, E. Marian Scott, J. R. Southon, R. A. Staff, C. S. M. Turney, J. van der Plicht, IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* **55**, 1869–1887 (2013).
61. P. Mellars, J. Tixier, Radiocarbon-accelerator dating of Ksar 'Aqil (Lebanon) and the chronology of the Upper Palaeolithic sequence in the Middle East. *Antiquity* **63**, 761–768 (1989).
62. A. Belfer-Cohen, A. N. Goring-Morris, Current issues in Levantine Upper Palaeolithic research, in *More Than Meets the Eye: Studies on Upper Paleolithic Diversity in the Near East*, A. N. Goring-Morris, A. Belfer-Cohen, Eds. (Oxbow Books, 2003), pp. 1–12.
63. L. Meignen, Levantine perspectives on the Middle to Upper Paleolithic “transition.” *Archaeol. Ethnol. Anthropol. Eurasia* **40**, 12–21 (2012).
64. A. E. Marks, Reflections on Levantine Upper Palaeolithic studies: Past and present, in *More than Meets the Eye: Studies on Upper Palaeolithic Diversity in the Near East*, N. Goring-Morris, A. Belfer-Cohen, Eds. (Oxbow Books, 2003), pp. 249–264.
65. M. H. Newcomer, Study and replication of bone tools from Ksar Akil (Lebanon). *Radiocarbon* **6**, 138–153 (1974).
66. I. Azoury, *Ksar Akil, Lebanon: A Technological and Typological Analysis of the Transitional and Early Upper Paleolithic levels at Ksar Akil and Abu Halka* (British Archaeological Reports, 1986), vol. 289.
67. K. Ohnuma, *Ksar Akil, Lebanon: A Technological Analysis of the Earlier Paleolithic Levels of Ksar Akil. Volume III: Levels XXV–XIV* (British Archaeological Reports, 1988), vol. 3.
68. O. Bar-Yosef, M. Arnold, N. Mercier, A. Belfer-Cohen, P. Goldberg, R. A. Housley, H. Laville, L. Meignen, J. C. Vogel, B. Vandermeersch, The dating of the Upper Paleolithic layers in Kebara Cave, Mt. Carmel. *J. Archaeol. Sci.* **23**, 297–306 (1996).
69. K. Monigal, Technology, economy and mobility at the beginning of the Levantine Upper Palaeolithic, in *More than Meets the Eye: Studies on Upper Palaeolithic Diversity in the Near East*, A. N. Goring-Morris, A. Belfer-Cohen, Eds. (Oxbow Books, 2003), pp. 118–133.
70. N. Goring-Morris, A. Davidzon, Straight to the point: Upper Paleolithic Ahmarian lithic technology in the Levant. *Anthropologie* **44**, 93–111 (2006).
71. J. L. Phillips, The Upper Paleolithic of the Wadi Feiran, Southern Sinai. *Paléorient* **14**, 183–200 (1988).
72. I. Gilead, O. Bar-Yosef, Early Upper Paleolithic sites in the Qadesh Barnea area, NE Sinai. *J. Field Archaeol.* **20**, 265–280 (1993).
73. O. Bar-Yosef, J. L. Phillips, *Prehistoric Investigations in the Gebel Maghara, Northern Sinai* (Institute of Archaeology, Hebrew Univ. of Jerusalem, 1977), vol. 7.
74. I. Gilead, Upper Palaeolithic occurrences in Sinai and the transition to the Epi-palaeolithic in the Southern Levant. *Paléorient* **9**, 39–53 (1983).
75. J. R. Fox, The Tor Sadaf lithic assemblages: A technological study of the Early Upper Palaeolithic in the Wadi al-Hasa, in *More than Meets the Eye: Studies on Upper Palaeolithic Diversity in the Near East*, A. N. Goring-Morris, A. Belfer-Cohen, Eds. (Oxbow Books, 2003), pp. 80–94.
76. C. B. Stringer, C. A. Bergman, Fifty years after: Egbert, an early Upper Palaeolithic juvenile from Ksar Akil, Lebanon. *Paléorient* **15**, 99–111 (1989).
77. J. Williams, An examination of Upper Paleolithic flake technologies in the marginal zone of the Levant, in *More than Meets the Eye: Studies on Upper Palaeolithic Diversity in the Near East*, A. N. Goring-Morris, A. Belfer-Cohen, Eds. (Oxbow Books, 2003), pp. 196–208.
78. O. Bar-Yosef, A. Belfer-Cohen, Another look at the Levantine Aurignacian, in *The Upper Paleolithic: Colloquia, XIII International Congress of Prehistoric and Protohistoric Sciences*, A. Montet-White, A. Palma di Cesnola, K. Valoch, Eds. (Abaco, 1996), pp. 139–150.
79. R. Shimelmitz, D. E. Friesem, J. L. Clark, I. Groman-Yaroslavski, L. Weissbrod, N. Porat, A. W. Kandel, The Upper Paleolithic and Epipaleolithic of Sefunim Cave, Israel. *Quat. Int.* 1–20 (2017).

80. A. E. Marks, The Middle to Upper Paleolithic transition in the Levant. *Adv. World Archaeol.* **2**, 51–98 (1983).
81. A. E. Marks, Ed. *Prehistory and Paleoenvironments in the Central Negev, Israel. Vol 1: The Avdat/Aqev Area, Part 1* (Southern Methodist Univ. Press, 1976).
82. A. Belfer-Cohen, L. Grosman, Tools or cores? And why does it matter: Carinated artifacts in Levantine Late Upper Palaeolithic assemblages, in *Tools versus Cores: Alternative Approaches to Stone Tool Analysis*, S. P. McPherron, Ed. (Cambridge Scholars Publishing, 2007), pp. 143–163.
83. M. Ofer, B. Alex, A. Ayalon, M. Bar-Matthews, G. Bar-Oz, D. Bar, Y. Mayer, F. Berna, E. Boaretto, V. Caracuta, A. Frumkin, M. Goder-Goldberger, I. Hershkovitz, B. Latimer, R. Lavi, A. Matthews, S. Weiner, U. Weiss, G. Yas'ur, O. Barzilai, The Upper Palaeolithic of Manot Cave, Western Galilee, Israel: The 2011–12 excavations. *Antiquity* **87** (2013).
84. O. Barzilai, I. Hershkovitz, O. Marder, A. Ayalon, M. Bar-Matthews, G. Bar-Oz, E. Boaretto, F. Berna, A. Frumkin, H. Khalaily, S. Weiner, R. Yeshurun, "Manot Cave, preliminary report," *Hadashot Arkheologiyot* (2012); www.hadashot-esi.org.il/report_detail_eng.asp?id=2183&mag_id=119.
85. O. Barzilai, O. Marder, I. Hershkovitz, "Manot Cave, Seasons 2011–2012, preliminary report," *Hadashot Arkheologiyot* (2014); www.hadashot-esi.org.il/Report_Detail_eng.asp?print=all&id=6470&mag_id=121.
86. R. Yeshurun, J.-M. Tejero, O. Barzilai, I. Hershkovitz, O. Marder, Upper Palaeolithic bone retouchers from Manot Cave (Israel): A preliminary analysis of a (yet) rare phenomenon in the Levant, in *The Origins of Bone Tool Technologies*, J. H. Hutson, S. Gaudzinski-Windheuser, Eds. (Römisch-Germanisches Zentralmuseums, 2017), pp. 1–9.
87. A. L. Kuhn, A. Belfer-Cohen, O. Barzilai, M. C. Stiner, K. W. Kerry, N. Munro, D. B.-Y. Mayer, The last glacial maximum at Meged Rockshelter, Upper Galilee, Israel. *J. Israel Prehist. Soc.* **34**, 5–47 (2004).
88. A. Belfer-Cohen, A. Davidzon, A. N. Goring-Morris, D. Lieberman, M. Spiers, Nahal Ein Gev I: A Late Upper Palaeolithic site by the sea of Galilee, Israel. *Paléorient* **30**, 25–45 (2004).
89. C. A. Bergman, *Ksar Akil, Lebanon: A Technological and Typological Analysis of the Later Palaeolithic Levels of Ksar Akil. Volume II: Levels XIII-VI* (British Archaeological Reports, 1987).
90. M. Vanhaeren, F. d'Errico, Aurignacian ethno-linguistic geography of Europe revealed by personal ornaments. *J. Archaeol. Sci.* **33**, 1105–1128 (2006).
91. R. White, Systems of personal ornamentation in the Early Upper Palaeolithic: Methodological challenges and new observations, in *Rethinking the Human Revolution: New Behavioural and Biological Perspectives on the Origin and Dispersal of Modern Humans*, P. Mellars, K. Boyle, O. Bar-Yosef, C. Stringer, Eds. (McDonald Institute for Archaeological Research, 2007), pp. 287–302.
92. G. Lengyel, *Upper Palaeolithic and Epipalaeolithic Lithic Technologies at Raqefet Cave, Mount Carmel East, Israel* (British Archaeological Reports, 2007).
93. O. Bar-Yosef, A. Belfer-Cohen, The Qafzeh Upper Palaeolithic assemblages: 70 years late. *Eurasian Prehist.* **2**, 145–180 (2004).
94. L. Regev, K. M. Poduska, L. Addadi, S. Weiner, E. Boaretto, Distinguishing between calcites formed by different mechanisms using infrared spectrometry: Archaeological applications. *J. Archaeol. Sci.* **37**, 3022–3029 (2010).
95. K. Douka, T. Higham, A. Sinitsyn, The influence of pretreatment chemistry on the radiocarbon dating of Campanian Ignimbrite-aged charcoal from Kostenki 14 (Russia). *Quat. Res.* **73**, 583–587 (2010).
96. J. S. Pigati, J. Quade, J. Wilson, A. J. T. Jull, N. A. Lifton, Development of low-background vacuum extraction and graphitization systems for ¹⁴C dating of old (40–60 ka) samples. *Quat. Int.* **166**, 4–14 (2007).
97. M. I. Bird, L. K. Ayliffe, L. K. Fifield, C. S. M. Turney, R. G. Cresswell, T. T. Barrows, B. David, Radiocarbon dating of "old" charcoal using a wet oxidation, stepped-combustion procedure. *Radiocarbon* **41**, 127–140 (1999).
98. I. Cohen-Ofri, L. Weiner, E. Boaretto, G. Mintz, S. Weiner, Modern and fossil charcoal: Aspects of structure and diagenesis. *J. Archaeol. Sci.* **33**, 428–439 (2006).
99. F. Braadbaart, I. Poole, Morphological, chemical and physical changes during charcoalification of wood and its relevance to archaeological contexts. *J. Archaeol. Sci.* **35**, 2434–2445 (2008).
100. C. Bronk Ramsey, Dealing with outliers and offsets in radiocarbon dating. *Radiocarbon* **51**, 1023–1045 (2009).
101. K. Douka, T. F. G. Higham, C. A. Bergman, Statistical and archaeological errors invalidate the proposed chronology for the site of Ksar Akil. *Proc. Natl. Acad. Sci. U.S.A.* **112**, E7034 (2015).
102. P. J. Reimer, F. G. McCormac, Marine radiocarbon reservoir corrections for the Mediterranean and Aegean Seas. *Radiocarbon* **44**, 159–166 (2002).
103. P. J. Reimer, M. G. L. Baillie, E. Bard, A. Bayliss, J. W. Beck, P. G. Blackwell, C. Bronk Ramsey, C. E. Buck, G. S. Burr, R. L. Edwards, M. Friedrich, P. M. Grootes, T. P. Guilderson, I. Hajdas, T. J. Heaton, A. G. Hogg, K. A. Hughen, K. F. Kaiser, B. Kromer, F. G. McCormac, S. W. Manning, R. W. Reimer, D. A. Richards, J. R. Southon, S. Talamo, C. S. M. Turney, J. van der Plicht, C. E. Weyhenmeyer, IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* **51**, 1111–1150 (2009).
104. S. L. Kuhn, From initial Upper Paleolithic to Ahmarian at Üçağizli cave, Turkey. *Anthropologie* **42**, 249–262 (2004).
105. S. L. Kuhn, M. C. Stiner, K. W. Kerry, E. Güleç, The early Upper Paleolithic at Üçağizli Cave (Hatay, Turkey): Preliminary results, in *More than Meets the Eye: Studies on Upper Palaeolithic Diversity in the Near East*, A. N. Goring-Morris, A. Belfer-Cohen, Eds. (Oxbow Books, 2003), pp. 106–117.
106. J. F. Ewing, Preliminary note on the excavations at the Palaeolithic site of Ksar 'Akil, Republic of Lebanon. *Antiquity* **21**, 186–196 (1947).
107. J. Tixier, Fouille à Ksar 'Aqil, Liban (1969–1974). *Paléorient* **2**, 183–185 (1974).
108. A. E. Marks, P. Volkman, The Mousterian of Ksar Akil: Levels XXVIA through XXVIII. *Paléorient* **12**, 5–20 (1986).
109. C. A. Bergman, Ksar Akil and the Upper Palaeolithic of the Levant. *Paléorient* **14**, 201–210 (1988).
110. J. F. Ewing, A probable neanderthaloid from Ksar 'Akil, Lebanon. *Am. J. Phys. Anthropol.* **21**, 101–104 (1963).
111. M. D. Bosch, M. A. Mannino, A. L. Prendergast, T. C. O'Connell, B. Demarchi, S. M. Taylor, L. Niven, J. van der Plicht, J.-J. Hublin, Reply to Douka et al.: Critical evaluation of the Ksar 'Akil chronologies. *Proc. Natl. Acad. Sci. U.S.A.* **112**, E7035 (2015).
112. O. Bar-Yosef, B. Vandermeersch, B. Arensburg, A. Belfer-Cohen, P. Goldberg, H. Laville, L. Meignen, Y. Rak, J. D. Speth, E. Tchernov, A.-M. Tillier, S. Weiner, G. A. Clark, A. Garrard, D. O. Henry, F. Hole, D. Roe, K. R. Rosenberg, L. A. Schepartz, J. J. Shea, F. H. Smith, E. Trinkaus, N. M. Whalen, L. Wilson, The excavations in Kebara Cave, Mt. Carmel [and comments and replies]. *Curr. Anthropol.* **33**, 497–550 (1992).
113. H. Valladas, J. L. Joron, G. Valladas, B. Arensburg, O. Bar-Yosef, A. Belfer-Cohen, P. Goldberg, H. Laville, L. Meignen, Y. Rak, E. Tchernov, A. M. Tillier, B. Vandermeersch, Thermoluminescence dates for the Neanderthal burial site at Kebara in Israel. *Nature* **330**, 159–160 (1987).
114. S. L. Kuhn, N. Zwyns, Rethinking the initial Upper Paleolithic. *Quat. Int.* **347**, 29–38 (2014).
115. A. J. Stutz, L. Nilsson-Stutz, T. Arpin, J. L. Clark, J. Rech, J. Robinson, Mughr el-Hamamah. *Am. J. Archaeol.* **116**, 697–699 (2012).
116. B. Weninger, O. Jöris, A ¹⁴C age calibration curve for the last 60 ka: The Greenland-Hulu U/Th timescale and its impact on understanding the Middle to Upper Paleolithic transition in Western Eurasia. *J. Hum. Evol.* **55**, 772–781 (2008).

Acknowledgments: We thank S. Weiner and M. Thibodeau for the microarchaeology work; C. Klöcker, J. Kakayuk, and P. Sathyanarayan for carrying out the sediment heating experiment; and three anonymous reviewers as well as D. Pilbeam, O. Bar-Yosef, and C. Tryon for their comments on this paper. **Funding:** Analytical work was funded by NSF Doctoral Dissertation Improvement Grant (1334615), Fulbright Student Scholarship from the U.S.-Israel Educational Foundation, and NSF Graduate Research Fellowship Program Award (DGE-1144152) to B.A. Radiocarbon dates were funded by the Exilarch's Foundation, D-REAMS, and the Max Planck-Weizmann Center for Integrative Archaeology and Anthropology awards to E.B. Paleobotanical analysis was supported by the Ministry of Science, Technology and Space, Israel, and the Ministry of Foreign Affairs and International Cooperation General Directorate for Political Affairs & Security, Italian Republic (IMOS 3-13329) awards to E.B. and V.C. Manot Cave excavation is funded by the Dan David Foundation, the Israel Antiquities Authority, Case Western Reserve University, the Leakey Foundation, the Irene Levi Sala CARE Archaeological Foundation, the Keren Kayemet L'Israel, and the Binational Science Foundation (2015303) to I.H., B.L., O.B., and O.M. and by the the Israel Science Foundation (338/14) to I.H., O.M., and O.B. Geoaerchological work was supported by awards to F.B. from the Social Sciences and Humanities Research Council of Canada (award no. 430-2013-000546) and the Bertha and Louis Weinstein Research Fund, and research was supported by the Kimmel Center for Archaeological Science. **Author contributions:** B.A. and E.B. designed the radiocarbon sample collection, characterization, and dating protocols. B.A., O.B., O.M., and E.B. designed the paper. B.A. and E.B. wrote the manuscript with contributions from O.M., O.B., T.A., L.D., F.B., and M.G.-G., and all co-authors assisted in revisions. B.A. and O.M. conducted the regional review. O.B., I.H., and O.M. directed the Manot Cave research project. E.B. directed the radiocarbon dating laboratory. F.B. and B.A. conducted the geoaerchological work. V.C. conducted the anthracological analysis. O.B., O.M., T.A., and L.D. analyzed the lithic artifacts. M.G.-G. and R.L. led the excavation and stratigraphic interpretations of areas C and E, respectively. B.A., E.B., E.M., and L.R. performed the radiocarbon analyses. D.B.-Y.M., J.-M.T., and R.Y. studied the faunal remains and artifacts. A.A., M.B.-M., and G.Y. performed the U-Th dating. A.F. conducted the geological study of the cave. I.H., B.L., and M.G.H. studied the human remains. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 11 May 2017

Accepted 23 October 2017

Published 15 November 2017

10.1126/sciadv.1701450

Citation: B. Alex, O. Barzilai, I. Hershkovitz, O. Marder, F. Berna, V. Caracuta, T. Abulafia, L. Davis, M. Goder-Goldberger, R. Lavi, E. Mintz, L. Regev, D. Bar-Yosef Mayer, J.-M. Tejero, R. Yeshurun, A. Ayalon, M. Bar-Matthews, G. Yasur, A. Frumkin, B. Latimer, M. G. Hans, E. Boaretto, Radiocarbon chronology of Manot Cave, Israel and Upper Paleolithic dispersals. *Sci. Adv.* **3**, e1701450 (2017).

Radiocarbon chronology of Manot Cave, Israel and Upper Paleolithic dispersals

Bridget Alex, Omry Barzilai, Israel Hershkovitz, Ofer Marder, Francesco Berna, Valentina Caracuta, Talia Abulafia, Lauren Davis, Mae Goder-Goldberger, Ron Lavi, Eugenia Mintz, Lior Regev, Daniella Bar-Yosef Mayer, José-Miguel Tejero, Reuven Yeshurun, Avner Ayalon, Mira Bar-Matthews, Gal Yasur, Amos Frumkin, Bruce Latimer, Mark G. Hans and Elisabetta Boaretto

Sci Adv 3 (11), e1701450.
DOI: 10.1126/sciadv.1701450

ARTICLE TOOLS	http://advances.sciencemag.org/content/3/11/e1701450
SUPPLEMENTARY MATERIALS	http://advances.sciencemag.org/content/suppl/2017/11/13/3.11.e1701450.DC1
REFERENCES	This article cites 74 articles, 5 of which you can access for free http://advances.sciencemag.org/content/3/11/e1701450#BIBL
PERMISSIONS	http://www.sciencemag.org/help/reprints-and-permissions

Use of this article is subject to the [Terms of Service](#)