TECHNICAL RESPONSE

PALEOANTHROPOLOGY

Response to Comment on "U-Th dating of carbonate crusts reveals Neandertal origin of Iberian cave art"

D. L. Hoffmann[1], C. D. Standish[2], M. García-Diez[3], P. B. Pettitt[4], J. A. Milton[5], J. Zilhão[6,7,8], J. J. Alcolea-González[9], P. Cantalejo-Duarte[10], H. Collado[11], R. de Balbín[9], M. Lorblanchet[12], J. Ramos-Muñoz[13], G.-Ch. Weniger[14,15], A. W. G. Pike[2]*

Slimak *et al*. challenge the reliability of our oldest (>65,000 years) U-Th dates on carbonates associated with cave paintings in Spain. They cite a supposed lack of parietal art for the 25,000 years following this date, along with potential methodological issues relating to open-system behavior and corrections to detrital or source water ^{230}Th. We show that their criticisms are unfounded.

Slimak *et al.*'s (*1*) supposed ~25,000-year (25-ka) hiatus in the production of parietal art comes from a misunderstanding of the logic of working with minimum ages. Our results (*2*) cannot be taken to imply the existence of such a hiatus. The minimum age of 45.9 ka for Ardales ARD16 and the minimum-maximum pair of 32.1 and 63.7 ka for ARD08, 09, and 06 bound painting episodes that could fall within Slimak *et al.*'s "hiatus," as could the El Castillo red disk dated to before 40.8 ka ago (*3*). Indeed, if dates older than 65 ka are excluded, the hundreds of minimum ages we have obtained are all consistent with dates in the 40- to 65-ka interval for the stratigraphically associated paintings. The origin of the red pigment at Ardales is also questioned, but its anthropogenic nature is backed by more than a century of research (*4*–*6*), and with careful inspection it is even possible to recognize technical characters linked to the execution processes used.

Slimak *et al.*'s methodological objections relate to (i) open-system behavior, (ii) nonradiogenic ^{230}Th in source water, and (iii) detrital contamination corrections. These topics have formed the focus of discussion in previous publications (*7*, *8*) and are thoroughly assessed in (*2*).

As Slimak *et al*. acknowledge, we use a sequential sampling methodology to test for open-system behavior. When dates for subsamples are in correct stratigraphic order (i.e., from younger to older systematically from the "outside" of a crust inward toward the pigment), we can be confident that the carbonate has remained a closed system. In an open system, preservation of the chronological order of subsamples is highly unlikely. We have published multiple sequences of three or more subsamples with ages in the expected stratigraphic order, including examples from all three caves under consideration; open-system behavior is not an issue here.

Concerning nonradiogenic ^{230}Th entering the carbonates from the source water, we have dated samples from all three sites to the very recent

[1]Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology, 04103 Leipzig, Germany. [2]Department of Archaeology, University of Southampton, Avenue Campus, Southampton SO17 1BF, UK. [3]Faculty of Humanities and Social Sciences, University of Isabel I, 09003 Burgos, Spain. [4]Department of Archaeology, Durham University, Durham DH1 3LE, UK. [5]Ocean and Earth Science, University of Southampton Waterfront Campus, National Oceanography Centre Southampton, Southampton SO14 3ZH, UK. [6]Departament d'Història i Arqueologia (SERP), University of Barcelona, 08001 Barcelona, Spain. [7]Institució Catalana de Recerca i Estudis Avançats (ICREA), 08010 Barcelona, Spain. [8]Centro de Arqueologia da Universidade de Lisboa (UNIARQ), Faculdade de Letras, Campo Grande, 1600-214 Lisbon, Portugal. [9]Prehistory Section, University of Alcalá de Henares, 28801 Alcalá de Henares, Madrid, Spain. [10]Centro de la Prehistoria/Cueva de Ardales, 29550 Ardales (Málaga), Spain. [11]Quaternary-Prehistory Research Group, I-PAT Research Group, D.G. Bibliotecas, Museos y Patrimonio Cultural, Junta de Extremadura, Spain. [12]CNRS-Retraité, Roc des Monges, 46200 St. Sozy, France. [13]Departamento de Historia, Geografía y Filosofia, Universidad de Cádiz, Cádiz, Spain. [14]Neanderthal Museum, 40822 Mettmann, Germany. [15]Institute of Prehistory, University of Cologne, Cologne, Germany.
*Corresponding author. Email: a.w.pike@soton.ac.uk

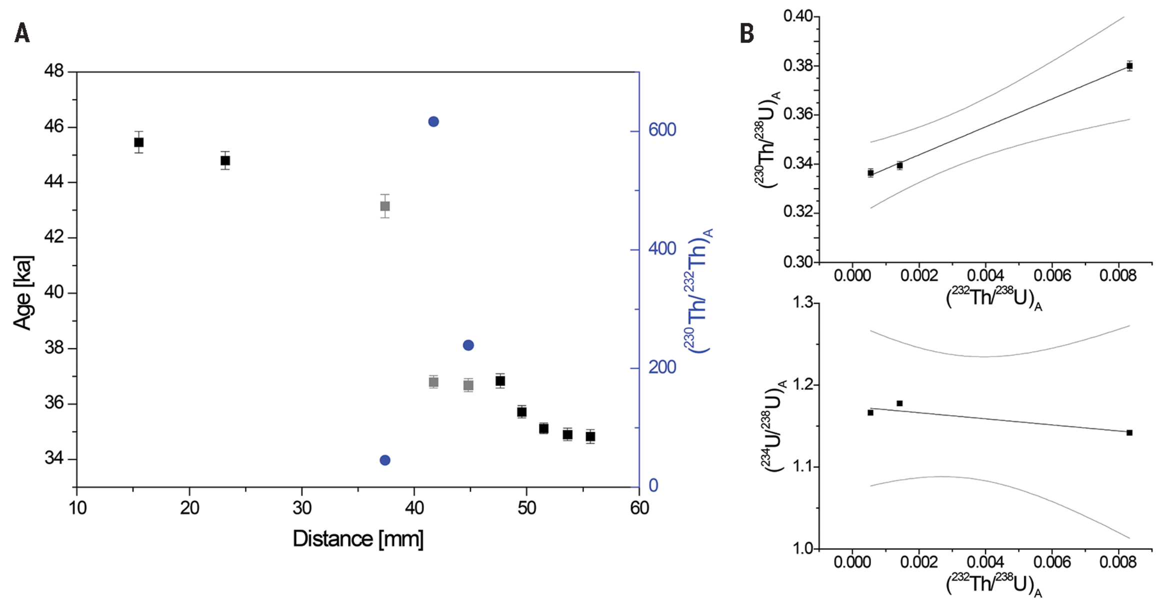

Fig. 1. A hypothetical example of erroneous isochron dating. (**A**) U-Th dating results across a 5-cm section of a flowstone (where distance is measured from the base). The results clearly reveal a 6-ka-long growth arrest at 40 mm. Dating results before and after the arrest are supported by the full dataset. (**B**) The three gray data points in (A) are used to obtain an Osmond-type pseudo-isochron, as done for PAS34a, -b, and -c by Slimak *et al*. The isochron gives an age of 36 ± 3 ka, which is clearly too young. Error bars denote 2 SD.

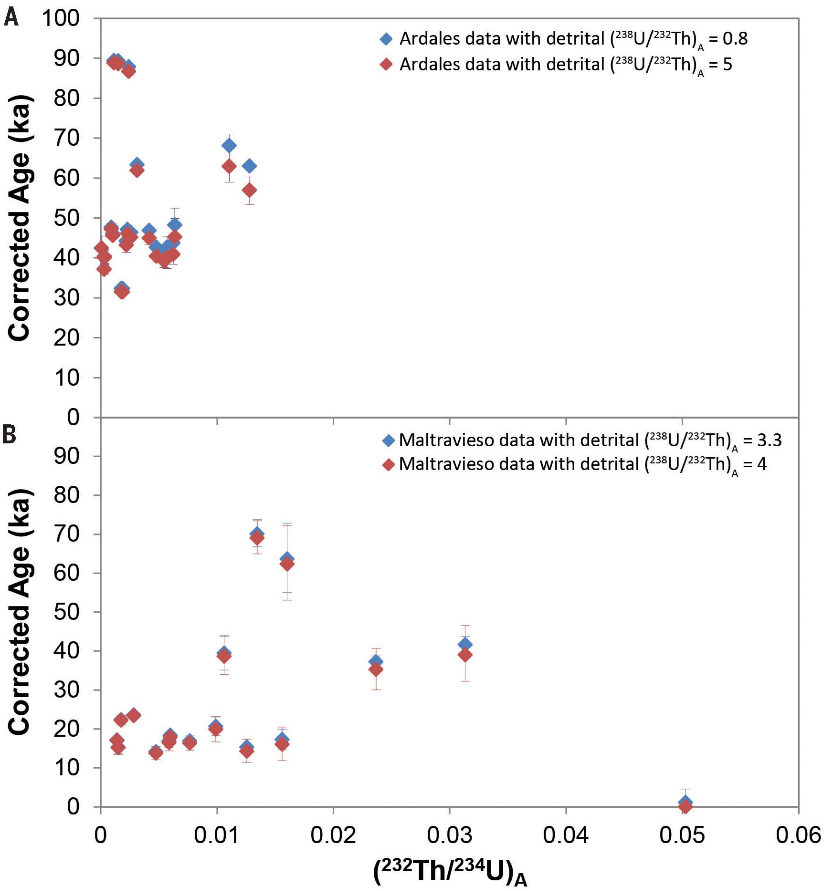

Fig. 2. Corrected ages and $(^{232}Th/^{234}U)_A$ for carbonate samples associated with art (i.e., as maximum or minimum ages). (**A**) Ardales cave; (**B**) panel GS3b in Maltravieso cave (*2*). Error bars denote 2 SD.

past, i.e., ~1 ka (e.g., PAS35a and -c) (*2*). This is entirely inconsistent with the hypothesis of high ^{230}Th drip water; dates as young as ~1 ka cannot be obtained by U-Th if the drip water has a high ^{230}Th content.

When considering detrital contamination corrections, it is true that La Pasiega PAS34c has large uncertainties due to the detrital Th correction; this was discussed at length in the supplementary materials of (*2*). There, we demonstrated that the chosen correction factor is appropriate by looking at the $^{234}U/^{238}U$ activity ratio, $(^{234}U/^{238}U)_A$, which is also affected by the detrital correction. A higher detrital $(^{238}U/^{232}Th)_A$ yields an initial $(^{234}U/^{238}U)_A$ for PAS34c inconsistent with all other samples from this cave. Slimak *et al.* propose using such an elevated detrital value, yet make no attempt to explain the effect this would have on the $(^{234}U/^{238}U)_A$. Furthermore, even if PAS34c is disregarded, PAS34a and PAS34b provide a minimum age of 53.0 ka, which still implies pre–Upper Paleolithic painting activity.

Slimak *et al.* argue for a younger minimum age for PAS34 based on an isochron derived from our results. However, deriving an isochron from three data points is not scientifically sound; a minimum of five would be needed. Furthermore, the assumption that these types of crust form within a short time is unsupported by previous results (*2*, *7*). A hypothetical example for flowstone dated sequentially by U-Th shows how misleading Slimak *et al.*'s pseudo-isochron is (Fig. 1A). The suite of dating results shows a 6-ka-long hiatus in growth at 40 mm, and the sample just below the hiatus is more contaminated than the two above. If we follow the same approach as Slimak *et al.* and use only three data points, one just below the hiatus and two above, to derive an "isochron" (i.e., assuming that all are of similar age and that the difference in detritus is the reason for the age difference), then we obtain an age of 36 ± 3 ka and a detrital $(^{238}U/^{232}Th)_A$ of 5.7 ± 0.5 (Fig. 1B). This age is clearly wrong for the sample below the hiatus, and the very high detrital correction is largely a result of the faulty assumption that the samples are coeval. The pseudo-isochron is biased by the pair of younger samples, which coincidentally are less contaminated, exactly as is the case for PAS34. Unless Slimak *et al.* can demonstrate that PAS34a, -b, and -c are contemporary, their approach is inappropriate.

All carbonate samples will be contaminated by detrital Th to some degree, and the threshold of reliability based on measured $(^{232}Th/^{238}U)_A$ or $(^{232}Th/^{234}U)_A$ that Slimak *et al.* suggest is entirely arbitrary. Of more importance is the sensitivity to the applied correction of the resulting corrected age. Figure 2 shows corrected ages and $(^{232}Th/^{234}U)_A$ for all the published Ardales and Maltravieso data (*2*) using our detrital $(^{238}U/^{232}Th)_A$ values and elevated ones. It is apparent that there is no clear positive correlation between age and $(^{232}Th/^{234}U)_A$ for either site, and the dates are relatively insensitive to the detrital correction. Critically, this means the shift in the two sets of corrected ages is not critical to our conclusion that some of the art is Neanderthal.

For Ardales (Fig. 2A), even with an unrealistic $(^{238}U/^{232}Th)_A$ value of 5, ARD13b still gives a minimum age of 59.0 ka. A highly unrealistic detrital $(^{238}U/^{232}Th)_A$ value of ≥11 is required before the corrected age of this sample is on the order of the ~47 ka that Slimak *et al.* prefer. When applying detrital Th corrections to relatively clean samples such as those from Ardales, using the bulk-earth value of $(^{238}U/^{232}Th)_A$ with a conservative error is adequate, and our applied detrital corrections are robust.

The samples from Maltravieso are characterized by higher detrital Th; thus, extra effort was made to characterize the detrital component directly. Sediment from the cave was collected and analyzed as a proxy for the samples' detrital fraction. A speleothem column was also sampled and a series of six growth layers dated to provide a control for this sediment-derived correction (*2*). In Fig. 2B, two detrital $(^{238}U/^{232}Th)_A$ values are used: 3.3 ± 0.2 (i.e., the sediment-derived correction) and an elevated value of 4 ± 2. Detrital $(^{238}U/^{232}Th)_A$ values of ≥4 are not possible, as beyond this limit the equivalent measured $(^{230}Th/^{232}Th)_A$ of one of the samples is exceeded. Shifting the detrital $(^{238}U/^{232}Th)_A$ to 4 ± 2 has very little effect on the corrected ages, giving, for example, a minimum age of 64.9 ka (instead of 66.7 ka) for MAL13a. This sample does contain a notable detrital component, but not enough to critically affect the corrected age. Finally, Slimak *et al.* cast further doubt by incorrectly claiming that the proposed Middle Paleolithic age of the Maltravieso hand stencil is based on a single sample. On the contrary, it is supported by a second sample, MAL17d ($63.6^{+9.6}_{-8.4}$ ka).

On the basis of present evidence, the most likely scenario is that in Europe, parietal art emerged prior to 65 ka ago and continued, perhaps episodically, throughout the remainder of the Paleolithic. Slimak *et al.*'s speculation that two technocomplexes dated to ~50 ka ago—the Bohunician and the Neronian—are possibly associated with modern humans sheds light on their willingness to accept a minimum age of 47 ka but not older. Their speculation is groundless. The earliest remains of modern humans in Europe, the Oase fossils from Romania, date to ~40 ka ago, and Neanderthal remains directly dated as recently as 40 to 50 ka are known across all of the then-inhabited Europe, east to west and north to south (*9*). There is no escaping the conclusion that these temporal patterns imply Neanderthal authorship of Europe's earliest cave art.

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