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Timelines for human evolution and dispersals

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Abstract

Luminescence dating has been instrumental in constraining the age of archaeological and human skeletal remains. Thermoluminescence dating was applied originally to heated pottery and burnt flint, and optical dating was developed subsequently to estimate the depositional age of sun-bleached sediments associated with artefacts and fossils. These methods have helped establish numerical timelines for human evolution and dispersals over the last half million years, including the earliest evidence for modern humans in Africa, Asia and Australia, and the comings and goings of archaic humans in Eurasia and Indonesia. Here, we recount the major role that luminescence dating has played recently in enriching our understanding of global human history.

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Timelines for Human Evolution and Dispersals

Richard G. Roberts¹ and Zenobia Jacobs¹

ABSTRACT

Luminescence dating has been instrumental in constraining the age of archaeological and human skeletal remains. Thermoluminescence dating was applied originally to heated pottery and burnt flint, and optical dating was developed subsequently to estimate the depositional age of sun-bleached sediments associated with artefacts and fossils. These methods have helped establish numerical timelines for human evolution and dispersals over the last half million years, including the earliest evidence for modern humans in Africa, Asia and Australia, and the comings and goings of archaic humans in Eurasia and Indonesia. Here, we recount the major role that luminescence dating has played in enriching our understanding of global human history.

KEYWORDS: modern humans, archaic humans, Neanderthals, Denisovans, thermoluminescence dating, optical dating

INTRODUCTION

“A journey of a thousand miles begins with a single step” (from the *Tao Te Ching*, attributed to Lao Tzu, ~ 604–531 BCE).

We humans are great travellers. Our species, *Homo sapiens*, can be found today on every continent on Earth. Our early ancestors were similarly possessed by wanderlust, fanning out from our African homeland into Asia, Australia, Europe, the Americas and the islands of the Pacific Ocean—in the process encountering Neanderthals (*Homo neanderthalensis*, our closest evolutionary relative) and their enigmatic cousins, the Denisovans, who were

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present in parts of Europe and Asia. Other hominins (primates more closely related to humans than to chimpanzees) (FIG. 1) had also migrated into Asia long before the first appearance of *Homo sapiens* in Africa—species such as *Homo erectus* and *Homo floresiensis*, both first described originally from fossils found in Indonesia.

What has been the history of colonisation of this planet by these different hominins? When did these dispersals take place, and what migration routes did these trailblazers take? When and where did modern humans first acquire DNA from Neanderthals and Denisovans, and did our ancestral pioneers ever interact with lingering populations of other hominins? To answer such questions requires that robust chronologies be developed, tested and replicated across multiple sites containing cultural, skeletal and genetic traces of human occupation—preferably using a variety of numerical dating techniques to minimize the shortcomings inherent in every dating method and to compare ages on a calendar-year timescale.

In this article, we take readers on a virtual journey through humanity's past, focussing on those chapters of our story that have been illuminated by thermoluminescence (TL) and optical dating techniques—the latter including optically stimulated luminescence (OSL); thermally transferred OSL (TT-OSL) dating of quartz; and both the infrared stimulated luminescence (IRSL) and post-infrared IRSL (pIRIR) dating of potassium-rich feldspars (see Smedley 2018 this issue). These techniques can be applied to mineral grains that have been heated to a high temperature or exposed to sunlight (bleached) within the last few hundred thousand years, a time span that encompasses the entire history of our species and several others in the genus *Homo* (FIG. 1). We have selected some recent studies to highlight current findings and emerging trends in this interdisciplinary field.

We start our story in Africa, where luminescence techniques have been used to date the earliest known traces of modern humans and the subsequent technological and behavioural innovations.

AFRICAN ORIGINS

When and where in Africa did our species first emerge? These questions are much debated, not only because fossils of our early ancestors are hard to find, but also because the most durable vestiges of human activity—stone artefacts—cannot be linked indisputably to a particular species of toolmaker. Nevertheless, the dates obtained from such artefacts and the sediments they are found in can be used to track the timing of hominid migration.

Early Modern Humans

The period associated with the origin of our species is known as the Middle Stone Age (MSA). Various ages have been proposed for origin of our species, and hence the start of the MSA, with luminescence dating contributing some of the oldest estimates for northern and southern Africa. At the open-air site of Kathu Pan (South Africa), a minimum age of 291 ± 45 thousand years (ka) was obtained for the early MSA from OSL dating of quartz grains in deposits containing reworked MSA artefacts (Porat et al. 2010). The underlying Fauresmith assemblage, which marks the transition between the Early Stone Age (attributed to pre-modern hominins) and the MSA in southern Africa, was dated to 464 ± 47 ka. This age may also be an underestimate, which would be consistent with the coupled electron-spin resonance (ESR) and uranium-series (U-series) age of ~ 540 ka for an animal tooth in the same layer, because the OSL signal was close to saturation (as defined in Smedley 2018 this issue).

In East Africa, chronologies for modern human origins and the MSA are based mostly on $^{40}\text{Ar}/^{39}\text{Ar}$ dating of volcanic tuffs deposited below and above the artefact- and fossil-bearing deposits. These indicate ages of ~ 280 ka for the dawn of the MSA, which is much older than the earliest skeletal remains of *Homo sapiens* known from East Africa (195 ± 5 ka). But hominin fossils and stone artefacts discovered recently in North Africa now suggest that anatomically modern humans and the MSA technologies both emerged before or around 300 ka (Richter et al. 2017). This new benchmark is based on coupled ESR/U-series dating of a *Homo sapiens* tooth and TL dating of heated flint artefacts at the site of Jebel Irhoud in Morocco. An unusually large proportion of artefacts ($\sim 37\%$) showed visible signs of heating, so sufficient specimens could be selected for TL dating. Two alternative

models for U-uptake by the hominin tooth yielded coupled ESR/U-series ages of ~ 281 ka (continuous uptake) and ~ 286 ka (fast uptake), both of which are compatible with the weighted mean TL age of 315 ± 34 ka for six heated flints. Together with the earliest recorded MSA in South and East Africa, these new finds in North Africa suggest that modern humans and the MSA technologies had spread across the continent by ~ 300 ka ago.

Innovations and Expansions

The techniques of TL and OSL dating have been widely used throughout Africa to investigate the timing of key events during the MSA, including the antiquity of artefacts suggestive of complex human cognition. These include decorative items, such as pierced shell beads found in rockshelters on the north and south coasts of Africa; engraved ochres and ostrich eggshells; ochre-processing toolkits; and advanced stone-working technology, all of which are widespread across southern Africa. Dating by TL of heated artefacts has contributed mainly to the chronology of northwest Africa and South Africa, but most luminescence ages for the MSA have been obtained from OSL dating of quartz grains and, in particular, individual sand-sized grains (Wintle 2014).

The measurement of equivalent dose (D_e) values for individual grains is particularly advantageous at archaeological sites where human activities or bioturbation has resulted in sediment disturbance after deposition (Roberts et al. 2015). Single-grain OSL dating has been used extensively in southern Africa to provide a timeline for two widespread MSA industries (i.e. two different classifications of stone tools): those of Still Bay and Howieson's Poort (both South Africa). Both these industries exhibit a range of early technological and behavioural innovations. Jacobs and Roberts (2017) dated ten sites spread across two million square kilometres of South Africa, Lesotho and Namibia. They found that the Still Bay flourished ~ 72 ka, followed by the Howieson's Poort from around 67 ka to 58 ka, although alternative ages for these two industries have been proposed for one of these sites (the Diepkloof Rockshelter).

As chronological precision must be matched by accuracy, many luminescence studies include comparisons with available independent age controls. Cross-checks are also made

between optical ages for quartz and feldspar grains and TL ages for heated artefacts, if these minerals and materials are available. At Haua Fteah in Libya, for example, the single-grain OSL chronology compares favourably with feldspar pIRIR ages and with radiocarbon (^{14}C), ESR/U-series and independently determined ages for three tephras (Douka et al. 2014).

OUT OF AFRICA

Gene flow from Neanderthals into modern humans outside Africa occurred between about 65 ka and 50 ka, soon after the rapid expansion within Africa of the ancestral mitochondrial DNA lineage of all non-African modern humans. Genetic studies have also revealed traces of a modern human presence outside Africa as early as the Last Interglacial (beginning ~130,000 years ago), when environmental conditions in the Sahara and Arabia were more conducive to human dispersals through these now-arid regions.

Over the past decade, optical dating has played a major role in developing a numerical timeline for the human occupation of Eurasia, and for the peopling of Australia. As in Africa, many of the key sites lie beyond the reliable limit of ^{14}C dating (~50 ka) and some are also too old for conventional OSL dating, due to signal saturation. In these instances, luminescence signals that can grow to higher doses before reaching saturation have been used instead, such as TT-OSL and 'pre-dose' pIRIR dating procedures (Roberts et al. 2015). We start our journey in South Asia, where some of the earliest archaeological traces of modern humans outside of Africa have been found buried in sediments amenable to OSL and TT-OSL dating.

Arabia and India

There are two routes out of Africa into Asia: north through the Sinai into the Levant (roughly equivalent to the Eastern Mediterranean today), and south across the narrow Bab al Mandab Straits into Arabia. Thirty years ago, TL dating of burnt flints from the sites of Kebara (a cave in northern Israel) and Qafzeh (a rockshelter in Israel) surprised many archaeologists by showing that modern humans were present in the Levant as early as ~100 ka, and that Neanderthals survived in this region until at least ~60 ka. Dating by TL

of heated artefacts has since been conducted at many other hominin sites in the Levant, extending the start of Neanderthal occupation of this region to at least ~ 220 ka.

Establishing the history of human dispersals through Arabia has proven especially challenging due to the paucity of hominin skeletal remains and the scarcity of Middle Palaeolithic artefacts in primary stratigraphic context (the Middle Palaeolithic outside Africa is broadly synonymous with the MSA inside Africa). But progress has recently been made, mostly using single-grain OSL techniques. The oldest artefacts attributed to modern humans in Arabia are those discovered in deposits dated to as early as 127 ± 16 ka at Jebel Faya, a rockshelter in the United Arab Emirates (Armitage et al. 2011). Other archaeological sites of Last Interglacial age also occur in the region, such as the stone artefacts reminiscent of a distinctive African MSA tools recovered from deposits in southwest Oman dated to 106 ± 9 ka (Rose et al. 2011). In Saudi Arabia, ancient lakeshore deposits containing Middle Palaeolithic artefacts have yielded single-grain OSL ages extending back to about 80–100 ka, when the interior of Arabia was much wetter than at present and was favourable for human dispersals (Groucutt et al. 2015). In some studies, TT-OSL procedures have also been used to address the possibility of age underestimation due to saturation of the OSL signal in Arabian quartz.

Further east, OSL dating has been applied to open-air sites in India that contain Middle Palaeolithic and Late Acheulean stone artefacts (Petruglia et al. 2012). Middle Palaeolithic tools were found buried beneath a layer of volcanic ash that was deposited by the Toba eruption of ~ 74 ka and above sediments dated by OSL to 77 ± 6 ka. For the Late Acheulean artefacts—attributed to pre-modern hominins—the single-grain OSL ages of ~ 130 ka suggest that the transition between archaic and modern humans may have taken place towards the start of the Last Interglacial, perhaps as a result of the spread of modern humans into India during this relatively humid period. However, the species of hominin responsible for the Acheulean and Middle Palaeolithic artefacts in Arabia and India will remain an open question in the absence of associated skeletal remains or traces of human DNA in the sediments.

Homo neanderthalensis

Since the discovery in 1856 of their fossils in a limestone quarry in Germany, skeletal remains of Neanderthals and the Middle Palaeolithic artefacts attributed to this species have been found across Eurasia. Research continues to reveal more on the dawn of the Neanderthals, their subsequent activities and their final demise—including the timing and nature of their interactions with modern humans. It is mostly in the last decade that scientists (and the public) have realised that Neanderthal DNA comprises a few percent of the genomes of *all* present-day people outside Africa.

Optical dating has contributed to establishing a numerical chronology for the early evolution of Neanderthals through its application to cave deposits at Atapuerca (northern Spain) where thousands of Neanderthal remains have been recovered from the Sima de los Huesos (the 'Pit of Bones'). Analyses of individual quartz grains by TT-OSL and measurements of feldspar grains using pIRIR resulted in a calculated age of 427 ± 12 ka for the sediments overlying the hominin-bearing deposits (Arnold et al. 2014). These same techniques have been applied to other Middle Pleistocene deposits at Atapuerca, placing the first archaeological evidence of hominins (i.e. Acheulean stone tools) at 313 ± 14 ka (Demuro et al. 2014). When cave fills are dated using luminescence methods, it is important to consider the likely extent to which the grains were bleached before entering the cave, especially when using TT-OSL and pIRIR signals which are less rapidly or completely bleached than their OSL and IRSL counterparts. An additional concern is whether grains were reworked subsequently in the darkness of the cave, so it is advisable to make some independent age cross-checks. At Atapuerca, the TT-OSL and pIRIR ages are in agreement with ESR and U-series ages obtained on associated materials.

Both the OSL and pIRIR dating methods have also been applied to sites containing human and cultural remains from the later stages of Neanderthal occupation of Eurasia, and to sites that span the Middle to Upper Palaeolithic transition, an interval that marks the replacement of Neanderthals by *Homo sapiens*. Pech de l'Azé I has been studied for more than 150 years, and is one of many rockshelters in the Dordogne region of France. The deposits at this site and at two nearby excavations (Pech de l'Azé II and IV) have recently

been dated using single-grain OSL methods for quartz (Jacobs et al. 2016), yielding ages for the Middle Palaeolithic layers of between 105 ± 7 and 49 ± 3 ka (Figs. 2A and 2B). It is from Pech de l'Azé that the oldest specialized bone tool in Europe was found in the ~51 ka layer. The OSL chronology for these sites agrees with the TL ages for burnt flint artefacts, ESR and coupled ESR/U-series ages for animal teeth, and ^{14}C ages for bones younger than ~50 ka.

Comparisons between ^{14}C , OSL and pIRIR ages have been made at other sites in France that contain evidence of some of the last surviving Neanderthals and the earliest modern human arrivals in western Europe. At La Ferrassie, where Neanderthal remains were first discovered more than a century ago, the artefact-bearing sediments were dated using OSL and pIRIR techniques (Guérin et al. 2015). The feldspar pIRIR signal was incompletely bleached, but OSL dating of single grains of quartz from a layer containing artefacts typical of the early modern human Châtelperronian industry, which lies at the Middle to Upper Palaeolithic transition, gave an age of ~42 ka. This age is consistent with the ^{14}C age of an associated animal bone.

A similar age for the Châtelperronian industry was obtained at another French site, Les Cottés, where a longer sequence of OSL, pIRIR and ^{14}C ages spans the Middle to Upper Palaeolithic transition (Jacobs et al. 2015) (Figs. 2C and 2D). Here, the pIRIR and single-grain OSL chronologies are in agreement. Given the differing bleaching rates of these signals and the consistency of their ages with those obtained from ^{14}C dating of bones in layers younger than ~50 ka, this suggests that the sediments were well bleached when deposited at the cave mouth.

EASTERN TRAILBLAZERS

How far east did Neanderthals spread and what other archaic lineages are known from Asia and the islands of Southeast Asia? And when did modern humans first set foot on the shores of Australia? Luminescence dating has recently shed new light on these shadowy chapters in the story of human evolution.

East Across Asia

Neanderthals spread east at least as far as southern Siberia, based on skeletal remains and fragments of DNA recovered from cave deposits in the Altai Mountains of southeast Asia (Slon et al. 2017). At Chagyrskaya Cave (Russia), the single-grain pIRIR chronology indicates that Neanderthals occupied the site ~60–50 ka, consistent with ^{14}C ages of >49 ka for associated bison bones and using interpretations drawn from pollen records and large mammal remains. At nearby Denisova Cave (southwest Siberia, Russia), DNA extracted from fossils of Neanderthals and Denisovans (and from cave sediments) has revealed a complex history of human interactions in the region extending back beyond the Last Interglacial. Both OSL and pIRIR were used on individual sand-sized grains of quartz and feldspar to directly date the time of deposition and the stratigraphic integrity of the DNA-bearing sediments.

Further east, in China, the time of transition between the Lower and Middle Palaeolithic—associated with archaic and modern humans, respectively—is disputed, as is the duration of the Middle Palaeolithic. This is because the Chinese stone tools cannot be grouped into distinctive technological industries. Ages of up to ~140 ka have been claimed for the oldest fossils of *Homo sapiens* (based on U-series dating of cave speleothems) but questions persist about the stratigraphic association of the fossils and speleothems. The attribution of Middle Palaeolithic artefacts to a particular species of hominin has become further complicated since the discovery in eastern China of two skulls with some Neanderthal features, excavated from deposits dated to ~110–95 ka using pIRIR and OSL methods (Li et al. 2017).

The Nihewan Basin in northeast China has a rich record of ancient human occupation. The Middle Palaeolithic deposits are challenging for conventional OSL dating because of saturation of the quartz signal. So, Guo et al. (2016) dated feldspar grains instead. For the two oldest sites, a ‘pre-dose’ pIRIR procedure was required to measure the large D_e values (~1,000 Gy). The ages of 268 ± 13 ka and 315 ± 13 ka obtained for the cultural layers raise questions about the validity of assigning the artefacts to the Middle Palaeolithic rather than the Lower Palaeolithic. In the future, TT-OSL dating of quartz could also be applied at such

sites to establish a dual-mineral chronology for early humans in East Asia: this has been done for the Dali hominin site in central China (Sun et al. 2017). In South Korea, TT-OSL procedures for quartz were used to date the oldest cultural layer at the archaeological site of Jeongokri to 195 ± 12 ka (Kim et al. 2010).

Astride Wallace's Line

When did modern humans first disperse through mainland Southeast Asia and cross Wallace's Line (which delineates Australian from Southeast Asian fauna) into the biogeographical region of Wallacea (a biogeographical region comprising a group of mostly Indonesian islands separated from the Australian and Asian continental shelves by deep-water straits)? This question has only recently begun to be addressed using luminescence dating techniques. Traces of archaic hominins have also been found in eastern Indonesia, where attention has focussed on optical and TL dating of the associated sediments.

The earliest skeletal remains of modern humans in mainland Southeast Asia are the skull and mandible discovered at Tam Pa Ling in Laos (Demeter et al. 2015). These fossils are thought to have been redeposited at the back of the cave, from which the sediments were dated to 46 ± 4 ka and 50 ± 12 ka using, respectively, single-grain OSL and TL dating procedures for quartz. The TL signal is much less easily bleached than the OSL signal, so the concordant ages suggests that the sediments were well bleached when deposited. These ages for final burial of the fossils are also consistent with the minimum ages of about 63 ka and 44 ka obtained from direct U-series dating of the skull and mandible, respectively.

In island Southeast Asia, pIRIR dating has been used to determine burial ages for artefacts made by archaic hominins. At Trinil (Java, Indonesia), a minimum age of 429 ± 46 ka was obtained for sediments contained inside a shell engraved with a geometric pattern of grooves attributed to *Homo erectus* (Joordens et al. 2015). While east of Wallace's Line, in southwest Sulawesi (Indonesia), stone tools made by an unknown hominin—probably either *Homo erectus*, the Denisovans or *Homo floresiensis*—were recovered from deposits dated by pIRIR to more than 156 ± 19 ka (van den Bergh et al. 2016).

Homo floresiensis is a diminutive species of archaic hominin—dubbed the ‘Hobbit’—identified from skeletal remains discovered at Liang Bua on the Indonesian island of Flores, ~300 km south of Sulawesi. The deposits containing these remains have been dated using pIRIR and TL methods to between about 100 ka and 60 ka, and Hobbit-made stone artefacts to between about 190 ka and 50 ka (Sutikna et al. 2016). The luminescence chronology is confirmed by a variety of independent dating methods, and begs the question: if Hobbits survived until ~50 ka or later, did they encounter other archaic hominins or modern humans dispersing through Wallacea to Australia? The answer depends in part on when people first reached Australia.

The First Australians

Australia’s oldest human remains are of two modern humans discovered almost 50 years ago eroding from the dunes that border Lake Mungo in the southeast of the continent. The deposits containing these burials have been dated by quartz OSL to 40 ± 2 ka, with stone artefacts in the stratigraphically underlying deposits indicating an even earlier human presence, extending back to ~51 ka (Fitzsimmons et al. 2014).

These events lie close to the reliable limit of ^{14}C dating, so OSL dating of sediments has formed the basis for constructing a timeline for the initial human colonisation of Australia. Indeed, the single-aliquot regenerative dose procedures now in common use were developed originally using quartz from Australian archaeological sites. Single-grain OSL measurements, in particular, have helped illuminate the early history of human settlement of Australia. At Riwi rockshelter in northwest Australia, for example, a sequence of discrete hearth features is preserved in quartz-rich sediments. The ^{14}C and single-grain OSL ages obtained for these deposits were evaluated within a Bayesian model and show good consistency throughout the sequence, with human occupation starting ~45 ka (Wood et al. 2016).

One of the first sites to be investigated using single-grain OSL dating was Madjedbebe, a rockshelter in northern Australia (FIGS. 3A–C). It is Australia’s oldest known human occupation site, with a TL age of 61 ± 10 ka obtained for the stratigraphically lowest level containing stone artefacts and ochres. The same sample was later dated to 56 ± 8 ka using

nascent single-grain procedures. These two ages are consistent, which suggests that the grains were well bleached when deposited, but the OSL age is based on D_e values for just seven grains. New excavations, combined with single-grain OSL dating of more than 50 sediment samples, has revised the time of human arrival at Madjedbebe to 65 ± 3 ka (Clarkson et al. 2017). The improved precision on this estimate reflects the greater number of samples analysed and D_e values obtained, coupled with the application of a Bayesian model to the sequence of ages (FIG. 3D). The single-grain OSL chronology is supported by a series of ^{14}C ages and sets a new benchmark for the antiquity of the first Australians.

OUTLOOK

Luminescence dating will continue to play a key role in the study of human evolution and dispersal, not only for deposits beyond the range of ^{14}C dating but also at sites where suitable materials are not available for ^{14}C and other numerical dating methods. Many potential pre- and post-depositional complications can be addressed using single-grain optically stimulated luminescence (OSL), thermally transferred OSL (TT-OSL) and both the infrared stimulated luminescence (IRSL) and post-infrared IRSL (pIRIR) techniques. But they are not a panacea. Ultimately, sample context is paramount, as with all dating methods. There remains much fertile ground that optical dating could explore to enrich our knowledge of human history. This includes the measurement of intact sediment samples, to gain new insights into processes of site formation and disturbance and the concomitant implications for the stratigraphic integrity of artefacts, fossils and DNA in the sediments; the discovery of new dating signals that can extend deeper into the Quaternary; and improvements to the accuracy and precision of luminescence chronologies to help resolve the timing of the critical events in humanity's past.

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FIGURE CAPTIONS

FIGURE 1 A simplified schematic of the time ranges of hominin taxa currently recognized. Those discussed in this article are highlighted along the top; other species in our genus (*Homo*) are also indicated. The double-headed arrow near the top of the time (y) axis indicates the approximate interval over which reliable luminescence ages can typically be obtained, with the dotted portion applicable only when circumstances are optimal. The bottoms and tops of the filled columns represent the published first and last appearances ages, respectively; the non-continuous bars indicate the extent of uncertainty associated with these time estimates. ADAPTED FROM WOOD AND BOYLE (2016)

FIGURE 2 Age comparisons Pech-de-l’Azé IV (**A, B**) and Les Cottés (**C, D**) in France. Single-grain optical stimulated luminescence ages (SG-OSL) are shown as filled red circles, together with post-infrared infrared stimulated luminescence (pIRIR) ages for potassium-rich feldspars, thermoluminescence (TL) ages for burnt flints, electron-spin resonance (ESR) ages for tooth enamel (EU, early uranium uptake; LU, linear uranium uptake) and ^{14}C ages for bone. Indicated are the associated artefact industries: Mousterian of Acheulian Tradition (MTA), Mousterian, Aurignacian (Upper Early, Early, and Proto-), and Châtelperronian. AGE DISPLAY ADAPTED FROM ROBERTS ET AL. 2015; PHOTO CREDITS TO (**B**) SHANNON MCPHERRON AND (**D**) MARIE SORESSI/STEFFEN SCHATZ.

FIGURE 2 (A) Image of the Pech-de-l’Aze IV archaeological dig site in France where Neanderthals resided during the Paleolithic. **(B)** Image of the Les Cottés archaeological dig site in France where Neanderthals, and later anatomically modern humans, resided. **(C)** Age comparison of the artefact-bearing layers at Pech-de-l’Azé IV. Typical Neandertal Mousterian and Mousterian of Acheulian Tradition (MTA) industries have been found at this location. **(D)** Age comparison of the artefact-bearing layers at Les Cottés. Neandertal industries (Mousterian) and early modern human industries (Aurignacian, Châtelperronian) have been found at this site. The following dating methods were used to date the artefact layers: filled red circles = single-grain optical stimulated luminescence (SG-OSL), open circles = post-infrared infrared stimulated luminescence (pIRIR) ages for potassium-rich feldspars, triangles = thermoluminescence (TL) ages for burnt flints,

filled/open squares = electron-spin resonance (ESR) ages for tooth enamel (EU, early uranium uptake; LU, linear uranium uptake), black bar = ^{14}C ages for bone. AGE DISPLAY ADAPTED FROM ROBERTS ET AL. 2015; PHOTO CREDITS TO (A) SHANNON MCPHERRON AND (B) MARIE SORESSI/STEFFEN SCHATZ.

FIGURE 3 (A-B) The archaeological Madjedbebe rockshelter lies at the foot of a sandstone escarpment in northern Australia. **(C)** Photograph of the excavated Madjedbebe rockshelter. **(D)** A Bayesian model was applied to the sequence of 53 single-grain OSL ages for the recently excavated deposits to estimate the start and end ages of the three dense bands of artefacts (Phases 2, 4 and 6). The modelled ages (at 95.4% probability, random errors only) are shown in red text. Pale and dark grey probability distributions represent the measured and modelled ages, respectively; blue distributions are OSL ages for four replicate samples measured at an independent laboratory; and green distributions are two OSL ages published in 1998. AGE MODEL ADAPTED FROM CLARKSON ET AL. (2017); PHOTOS: RICHARD ROBERTS.