doi:10.1038/nature13422

Pleistocene cave art from Sulawesi, Indonesia

M. Aubert[1,2]*, A. Brumm[1]†*, M. Ramli[3], T. Sutikna[1,4], E. W. Saptomo[4], B. Hakim[5], M. J. Morwood‡, G. D. van den Bergh[1], L. Kinsley[6] & A. Dosseto[7,8]

Archaeologists have long been puzzled by the appearance in Europe ∼40–35 thousand years (kyr) ago of a rich corpus of sophisticated artworks, including parietal art (that is, paintings, drawings and engravings on immobile rock surfaces)[1,2] and portable art (for example, carved figurines)[3,4], and the absence or scarcity of equivalent, well-dated evidence elsewhere, especially along early human migration routes in South Asia and the Far East, including Wallacea and Australia[5–8], where modern humans (*Homo sapiens*) were established by 50 kyr ago[9,10]. Here, using uranium-series dating of coralloid speleothems directly associated with 12 human hand stencils and two figurative animal depictions from seven cave sites in the Maros karsts of Sulawesi, we show that rock art traditions on this Indonesian island are at least compatible in age with the oldest European art[11]. The earliest dated image from Maros, with a minimum age of 39.9 kyr, is now the oldest known hand stencil in the world. In addition, a painting of a babirusa ('pig-deer') made at least 35.4 kyr ago is among the earliest dated figurative depictions worldwide, if not the earliest one. Among the implications, it can now be demonstrated that humans were producing rock art by ∼40 kyr ago at opposite ends of the Pleistocene Eurasian world.

Sulawesi is the world's eleventh largest island and the biggest and probably oldest in Wallacea, the zone of oceanic islands between continental Asia and Australia. The Eocene to middle Miocene limestones of the Maros and Pangkep regions lie between 4° 7′ S and 5° 1′ S and cover an area of $\sim$450 km^2 parallel to the west coast of the island's southwestern peninsula[12] (Fig. 1). Rivers draining the volcanic highlands to the east cut down into the basal limestone, forming clusters of plateau-like karst towers that rise abruptly from the surrounding alluvial plains[12]. Extensive networks of footcaves were formed around the tower bases and now harbour abundant evidence of prehistoric human occupation[13]. Cemented breccia banks containing archaeological material occur on the rear walls of many caves and rockshelters[14,15], and at least 90 rock art sites are recorded. While multiple cave and shelter sites have been excavated since the 1930s (ref. 16), only two with Pleistocene sequences—Leang Burung 2 (ref. 13) and Leang Sakapao 1 (ref. 17)—have so far been reported (Fig. 1). The oldest, Leang Burung 2, a cliff-foot shelter with a minimum age for the excavated deposits of 31,260 ± 320 radiocarbon years BP (35,248 ± 420 calendar years BP)[13], previously provided the earliest dated evidence for humans on Sulawesi. The Pleistocene deposits from both sites yielded evidence of pigment use in the form of faceted haematite nodules[13] and ochre-smeared stone tools[17].

The Maros–Pangkep rock art was first recorded in the 1950s (ref. 15) and has been extensively studied by Indonesian researchers, although few detailed reports have been published. On the basis of superimposition, two broad periods of prehistoric art production are defined[18]. The earliest of these is characterized by human hand stencils (made by spraying wet pigment around hands pressed against rock surfaces) and, less commonly, large naturalistic paintings of endemic Sulawesian land mammals, including the dwarfed bovid anoa (*Anoa* sp.), Celebes warty pig (*Sus celebensis*) and the 'pig-deer' babirusa (*Babyrousa* sp.). These wild animal species are most commonly depicted in profile as irregularly infilled outlines[18].

The later rock art phase in the Maros–Pangkep karsts lacks images of this nature. It is instead typified by small depictions of zoomorphs (including dogs and other domesticated species), anthropomorphs and a wide range of geometric signs, most commonly drawn onto rock surfaces using black pigment (possibly charcoal)[18]. This art can plausibly be attributed to early Austronesian immigrants on the basis of stylistic elements[19], and is thus at most a few thousand years old[20].

The red and mulberry-coloured motifs of the earlier phase typically occur on high roofs, elevated parts of rock walls or other difficult-to-access areas in caves and shelters[18]. They are located both close to site entrances

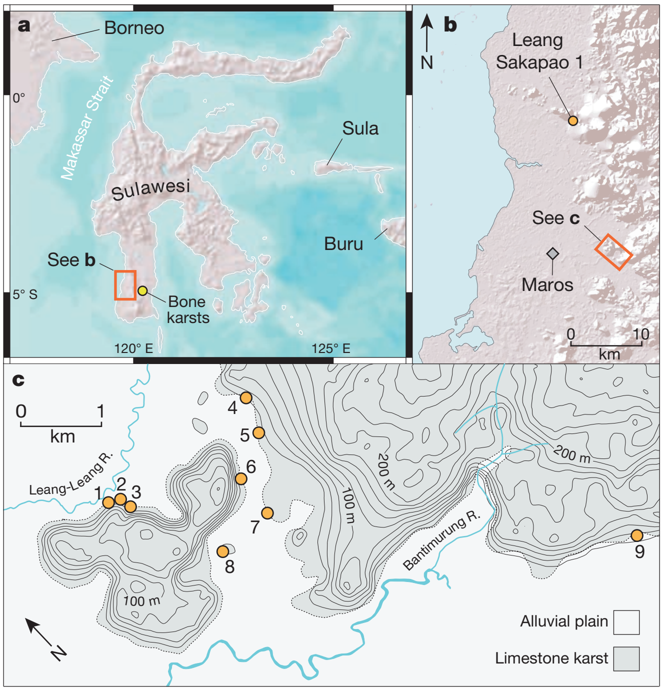


Figure 1 | Location of the study area. **a**, Sulawesi is situated east of Borneo in the Wallacean archipelago. **b**, The location of the Maros–Pangkep karsts (the area of high relief) near the town of Maros on Sulawesi's southwestern peninsula. The separate karst region of Bone is further east. **c**, The locations of the archaeological sites included in this study: 1, Leang Barugayya 2; 2, Leang Barugayya 1; 3, Gua Jing; 4, Leang Bulu Bettue; 5, Leang Sampeang; 6, Leang Timpuseng; 7, Leang Burung 2; 8, Leang Lompoa; and 9, Leang Jarie. Gua Jing and Leang Barugayya 1 and 2 are separate cave sites interconnected by a system of phreatic passages. Map data: copyright ESRI (2008).

---

[1]Centre for Archaeological Science, University of Wollongong, Wollongong, New South Wales 2522, Australia. [2]Place, Evolution and Rock Art Heritage Unit (PERAHU), Griffith University, Gold Coast, Queensland 4222, Australia. [3]Balai Pelestarian Peninggalan Purbakala, Makassar 90111, Indonesia. [4]National Centre for Archaeology (ARKENAS), Jakarta 12001, Indonesia. [5]Balai Arkeologi Makassar, Makassar 90242, Indonesia. [6]Research School of Earth Sciences, The Australian National University, Canberra, Australian Capital Territory 0200, Australia. [7]Wollongong Isotope Geochronology Laboratory, University of Wollongong, Wollongong, New South Wales 2522, Australia. [8]GeoQuEST Research Centre, University of Wollongong, Wollongong, New South Wales 2522, Australia. †Present address: Environmental Futures Research Institute, Griffith University, Brisbane, Queensland 4111, Australia.
‡Deceased.
*These authors contributed equally to this work.

and within deep, dark chambers and passages. In most cases the art is poorly preserved, surviving only as weathered patches of pigment on exfoliated rock surfaces. At some sites, better-preserved art is partly or almost completely obscured by dense clusters of small coralloid speleothems ('cave popcorn') up to ~10 mm thick, which form when thin films of water precipitate on rock surfaces[21]. At one Maros cave site, Leang Bulu Bettue (Fig. 1), we observed Austronesian style drawings on a 'fresh' limestone ceiling formed by shedding of an earlier surface containing faded hand stencils (Extended Data Fig. 1), suggesting that even in recent prehistoric times this art was in an advanced state of deterioration. Despite this, local custodians report that the loss of the art has accelerated in recent decades.

To determine the age of the earliest rock art in the Maros karsts we undertook an extensive program of uranium-series dating of coralloid speleothems directly associated with the motifs. The sampled materials all comprise static coralloids that formed directly on top of clearly discernible motifs, offering the possibility to obtain minimum ages for the underlying rock art. In some cases, hand stencils and paintings were made over coralloids that then continued to grow, providing an opportunity to obtain both minimum and maximum ages for the art.

We collected a total of 19 coralloid samples associated with 14 individual motifs (12 hand stencils and 2 figurative animal depictions) (Figs 2 and 3 and Extended Data Figs 2–9) at seven cave sites in the Maros karsts (Fig. 1). Six of these sites are located within a ~1-km radius in the

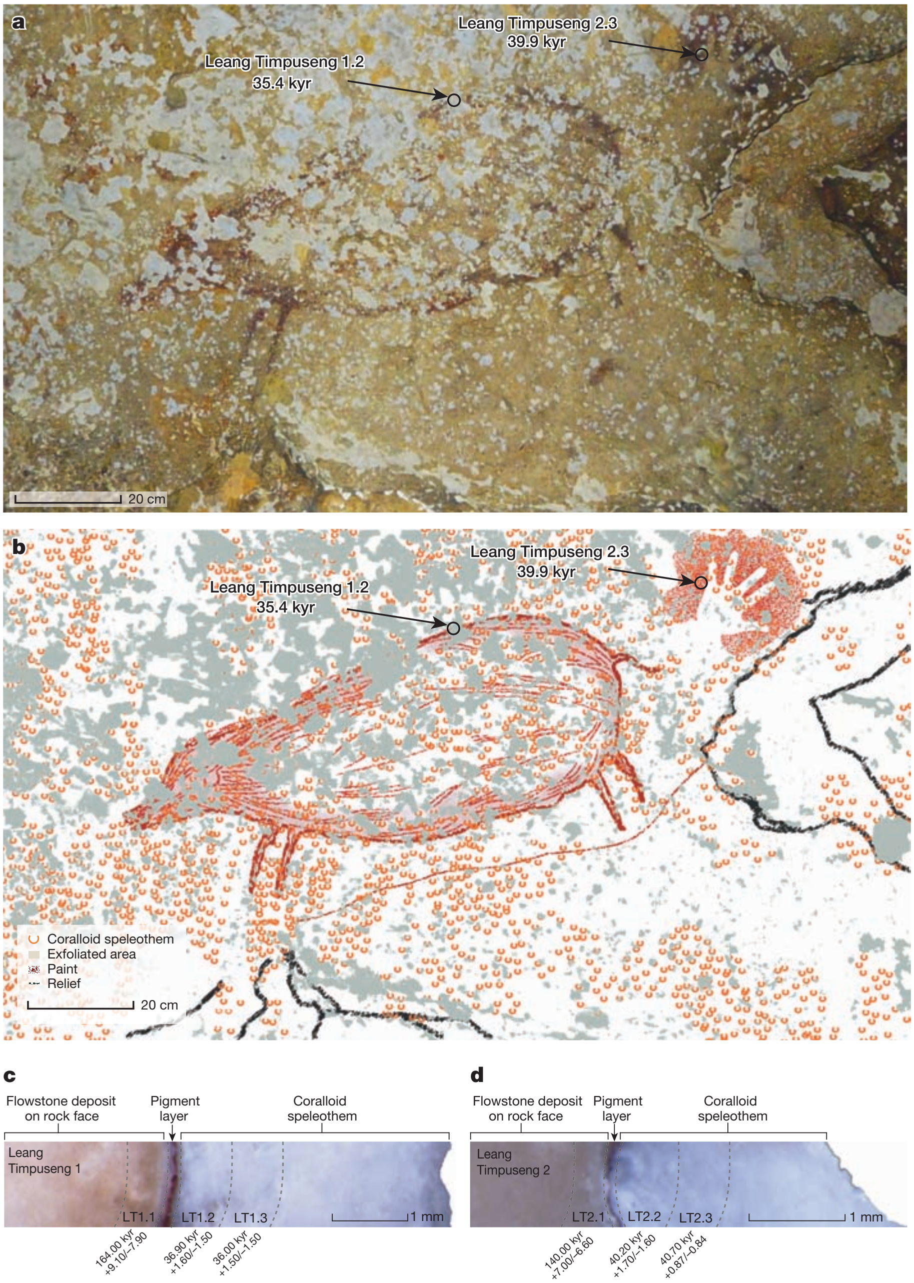


Figure 2 | Dated rock art from Leang Timpuseng. **a**, **b**, Photograph (**a**) and tracing (**b**) showing the locations of the dated coralloid speleothems and associated paintings: a hand stencil and a large naturalistic depiction of an animal shown in profile. Although the animal figure is badly deteriorated and obscured by coralloids, we interpret it as a female babirusa. A painted red line below the babirusa (not clearly visible in **a**, but illustrated in **b**) seems to represent the ground surface on which the animal is standing or walking. The rock art panel is located on the ceiling about 8 m from the cave entrance and 4 m above the current cave floor. **c**, **d**, Profiles of the coralloid speleothems showing the microexcavated subsamples bracketing the age of the paintings. We interpret the similar ages for the overlying aliquots as a result of fast-growing speleothems. Tracing credit: Leslie Refine 'Graph & Co' (France).

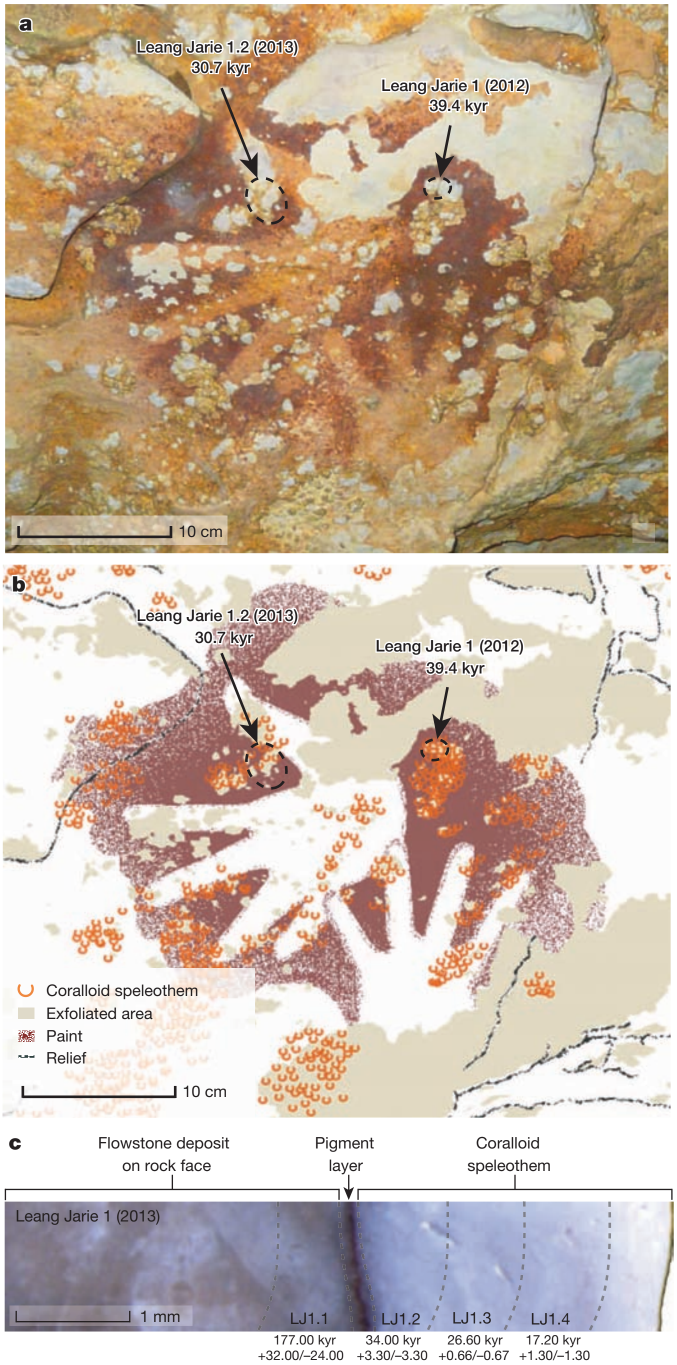


Figure 3 | Dated rock art from Leang Jarie. **a**, **b**, Photograph (**a**) and tracing (**b**) showing the locations of the dated coralloid speleothems and associated hand stencils. The hand stencils are part of a 4-m-long art panel located in a dark recess along the eastern wall of the cave, about 5 m from the entrance and 1.5 m above the floor. **c**, Profile of the coralloid speleothem (Leang Jarie 1 (2013)) showing the microexcavated subsamples bracketing the age of the paintings. The Leang Jarie 1 (2012) sample is from above the pigment layer and so only provides a minimum age for the underlying hand stencils. Tracing credit: Leslie Refine 'Graph & Co' (France).

Bantimurung region, close to Leang Burung 2. Four of the Bantimurung sites (Gua Jing, Leang Barugayya 1 and 2, and Leang Timpuseng) are situated in a large limestone outlier roughly 2 km in diameter and 180 m high[12]. Leang Sampeang is located in an elevated niche on tall limestone cliffs ~500 m east of the outlier, whereas Leang Lompoa occurs at the base of an adjacent karst inselberg. The seventh cave site, Leang Jarie, is in the Simbang district southeast of Bantimurung (Fig. 1).

To provide an internal check of the microstratigraphic order of ages we took a minimum of three (and up to six) aliquots from every sample (except for Samples Leang Jarie 1 and 2 (2012)), one from under the pigment layer and two or more from above it, giving a total of 55 uranium-series age determinations (Supplementary Information). In addition, at Leang Jarie (Fig. 3), Leang Barugayya 2 (Extended Data Fig. 6) and Leang Sampeang (Extended Data Fig. 9) we dated two coralloids that had formed over the same motif. At Leang Lompoa (Extended Data Fig. 3) and Leang Jarie (Extended Data Fig. 2) we also dated two samples taken from different parts of the same coralloid. Dating results for these five sets of paired samples are internally consistent (Supplementary Information), demonstrating the robustness of the ages for the associated motifs.

Minimum ages for the Maros rock art motifs ($n = 14$) span the time range between 39.9 and 17.4 kyr ago, with the majority dating to more than 25 kyr ago (Table 1 and Supplementary Information). The oldest dated motif is a hand stencil from Leang Timpuseng, which has a minimum age of 39.9 kyr (Fig. 2) and is now the earliest evidence for humans on Sulawesi, as well as the oldest known example of this widespread art form. This motif is located on a 4-m-high ceiling next to a large irregularly infilled painting of a female babirusa, which has a minimum age of 35.4 kyr (Fig. 2). At nearby Leang Barugayya 2, a large painting of an indeterminate animal (probably a pig) has a minimum age of 35.7 kyr (Extended Data Fig. 6). The next oldest motif in our assemblage is another hand stencil at Leang Jarie, which dates to at least 39.4 kyr ago (Fig. 3).

With the Leang Timpuseng hand stencil, and for many other motifs in our sample, subsamples taken from below the pigment layer were more than 100 kyr in age (Supplementary Information). These early dates represent calcium carbonate deposits (flowstone layers) present on the rock face before the art was produced. At Gua Jing we dated two distinct hand stencils, one of which yielded minimum and maximum ages of 22.9 and 27.2 kyr, respectively (Extended Data Fig. 8). Thus, given that the Leang Timpuseng hand stencil has a minimum age of 39.9 kyr, we can infer the existence in the Maros karsts of an artistic culture with a duration of at least ~13 kyr.

The discovery of rock art dating back at least 40 kyr ago on Sulawesi has implications for our understanding of the time-depth of early symbolic traditions in the region, about which little is currently known. For instance, rock art complexes that are focused on hand stencils and large animal paintings occur in the Bone karsts ~35 km east of Maros (Fig. 1), as well as west of Sulawesi in Kalimantan (Borneo)[22,23] and further afield in mainland Southeast Asia[24]. The northern Australian rock art provinces of Arnhem Land[25] and the Kimberley[26] also display early art phases (based on order of superimposition) characterized by hand stencils and large irregularly infilled paintings of animals, including apparent images of extinct megafauna[25,26], that are markedly similar in style to the Maros art. Given that the deepest excavated deposits in northern Australia (dated to ~50–40 kyr ago) contain use-worn haematite crayons and other evidence of ochre processing and use[9,10,27], it is possible that an extensive archive of rock art may yet survive from the initial modern human colonization of Australia and Southeast Asia.

There are also implications for current thinking about the origins of Palaeolithic rock art, which is invariably dominated by European data and for which there are two widely debated models[11,28]. The first of these is that rock art originated in Europe and developed gradually over thousands of years, beginning with abstract, non-figurative imagery (for example geometric patterns) and culminating in sophisticated naturalistic representations of animals, such as those in Altamira and Lascaux dated to ~20 kyr ago[11,28,29] and other late Upper Palaeolithic cave sites in western Europe. This long-standing notion is given new impetus by recent uranium-series dating of rock art motifs from 11 caves in northern Spain, which suggests that Europe's earliest cave art was non-figurative in nature and that animal paintings did not appear until considerably later[11,28]. Currently, the oldest dated rock art motif in Europe (and the world) is from El Castillo, where a single thin calcite deposit overlying a red 'disk' yielded a minimum uranium-series age of 40.8 kyr[11]. The alternative model is that cave art first appeared in Europe in fully developed form, as implied

Table 1 | Results of uranium-series disequilibrium dating showing the minimum age of each dated rock art motif

Sample	Site	Description	^{230}Th/^{238}U	^{234}U/^{238}U	^{230}Th/^{232}Th	Uncorrected age (kyr)	$+2\sigma$ (kyr)	-2σ (kyr)	Corrected age (kyr)	$+2\sigma$ (kyr)	-2σ (kyr)	Initial ^{234}U/^{238}U
LL3.2	Leang Lompoa	Overlies hand stencil	0.1525 ± 0.0022	1.0067 ± 0.0014	137	17.87	0.27	0.28	17.77	0.42	0.42	1.0070 ± 0.0014
LB2.3	Leang Barugayya 1	Overlies hand stencil	0.1624 ± 0.0077	0.9812 ± 0.0027	858	20.00	1.00	1.00	19.70	1.00	1.00	0.9801 ± 0.0028
LB3.3	Leang Barugayya 1	Overlies hand stencil	0.2004 ± 0.0214	0.9799 ± 0.0025	428	24.90	2.90	2.90	24.90	3.10	3.00	0.9784 ± 0.0026
GJ2.2	Gua Jing	Overlies hand stencil	0.1996 ± 0.0044	0.9943 ± 0.0009	50	24.40	0.60	0.59	24.00	1.10	1.10	0.9939 ± 0.0009
LB1.2	Leang Barugayya 1	Overlies hand stencil	0.2308 ± 0.0211	0.9831 ± 0.0025	360	29.10	3.00	2.90	29.10	3.20	3.10	0.9817 ± 0.0028
LL1.3	Leang Lompoa	Overlies hand stencil	0.2322 ± 0.0030	1.0128 ± 0.0024	121	28.31	0.44	0.43	28.10	0.66	0.67	1.0138 ± 0.0025
LL2.2	Leang Lompoa	Overlies hand stencil	0.2391 ± 0.0064	1.0065 ± 0.0007	133	29.50	0.92	0.89	29.30	1.20	1.10	1.0070 ± 0.0008
GJ1.3	Gua Jing	Sequence of aliquots	0.2525 ± 0.0048	0.9998 ± 0.0010	31	31.70	0.69	0.69	30.90	1.70	1.80	0.9998 ± 0.0011
LS1.2	Leang Sampeang	Overlies hand stencil	0.2549 ± 0.0044	0.9823 ± 0.0007	324	32.70	0.66	0.65	32.60	0.76	0.76	0.9806 ± 0.0007
LJ2	Leang Jarie	Overlies hand stencil	0.2738 ± 0.0022	0.9942 ± 0.0010	422	35.04	0.32	0.32	34.98	0.41	0.41	0.9935 ± 0.0011
LT1.2	Leang Timpuseng	Overlies babirusa painting	0.2927 ± 0.0100	1.0163 ± 0.0023	682	37.00	1.50	1.50	36.90	1.60	1.50	1.0181 ± 0.0025
LB4.2	Leang Barugayya 2	Overlies undetermined animal figure	0.3481 ± 0.0385	1.0080 ± 0.0042	18	46.00	6.40	6.20	44.00	9.10	8.30	1.0091 ± 0.0046
LJ1	Leang Jarie	Overlies hand stencil	0.3006 ± 0.0018	0.9839 ± 0.0014	1,474	39.69	0.29	0.30	39.67	0.32	0.32	0.9820 ± 0.0015
LT2.3	Leang Timpuseng	Overlies hand stencil	0.3177 ± 0.0055	1.0156 ± 0.0011	2,845	40.80	0.83	0.83	40.70	0.87	0.84	1.0175 ± 0.0013

by the great antiquity of the elaborate animal paintings from Chauvet Cave in southern France[29]. Although the early chronology for this art is disputed[30], the oldest animal image from Chauvet Cave is attributed an age of 32,410 ± 720 radiocarbon years BP (~35,000 calendar years BP) on the basis of ^{14}C-dating of charcoal pigment[29].

Our dating results from Sulawesi suggest that figurative art was already part of the cultural repertoire of the first modern human populations to reach this region more than 40 kyr ago. It is possible that rock art emerged independently at around the same time and at roughly both ends of the spatial distribution of early modern humans. An alternative scenario, however, is that cave painting was widely practised by the first *H. sapiens* to leave Africa tens of thousands of years earlier, and thus naturalistic animal art from Leang Timpuseng and Leang Barugayya 2, as well as Chauvet Cave in France, may well have much deeper origins outside both western Europe and Sulawesi. If so, we can expect future discoveries of depictions of human hands, figurative art and other forms of image-making dating to the earliest period of the global dispersal of our species.

METHODS SUMMARY

A small segment (~100–200 mm^2) of each coralloid was removed from the rock art panels using a battery-operated rotary tool equipped with a diamond saw blade. Each coralloid sample was sawn *in situ* so as to produce a continuous microstratigraphic profile extending from the outer surface of the coralloid through the pigment layer and into the underlying rock face. The only exceptions were Leang Jarie 1 and 2 (2012), which were sawn *in situ* but not through the pigment layer. All of the sampled coralloids comprised multiple layers of dense and non-porous calcite. The identification of a pigment layer overlain by an extensive accumulation of calcite laminations within each coralloid (except for Leang Jarie 1 and 2 (2012)) demonstrates unambiguously that the sampled speleothems formed over the motifs (see Figs 2 and 3 and Extended Data Figs 2–9). In the laboratory, the samples were micro-excavated in arbitrary 'spits' over the entire surface of the coralloids, creating a series of aliquots less than 1 mm thick. The pigment layer was visible across the entire length of the sample (except for Leang Jarie 1 and 2 (2012)). In total, we obtained 55 uranium-series age determinations (a further two samples failed to produce enough signal for age determination) (Table 1 and Supplementary Information). The uranium-series isotopes were measured on a ThermoFinnigan Neptune Plus Multi-Collector inductively coupled plasma mass spectrometer at the Research School of Earth Sciences, Australian National University. Calculation of ages and initial ^{234}U/^{238}U ratios was done with Isoplot 3.75. Corrections for detrital components were calculated assuming a bulk Earth ^{232}Th/^{238}U concentration ratio of the upper crust of 3.8 ± 50% and secular equilibrium for ^{230}Th, ^{234}U and ^{238}U. In the text, minimum ages are quoted as measured age minus 2σ and maximum ages as measured age plus 2σ rounded to one decimal place.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

Received 24 February; accepted 30 April 2014.

1. Lewis-Williams, D. J. *The Mind in the Cave: Consciousness and the Origins Of Art* (Thames & Hudson, 2002).
2. White, R. *et al.* Context and dating of Aurignacian vulvar representations from Abri Castanet, France. *Proc. Natl Acad. Sci. USA* **109,** 8450–8455 (2012).
3. Conard, N. J. Palaeolithic ivory sculptures from southwestern Germany and the origins of figurative art. *Nature* **426,** 830–832 (2003).
4. Dowson, T. A. & Porr, M. in *The Archaeology of Shamanism* (ed. Price, N.) 165–177 (Routledge, 2001).
5. Aubert, M. A review of rock art dating in the Kimberley, Western Australia. *J. Archaeol. Sci.* **39,** 573–577 (2012).
6. Brumm, A. & Moore, M. W. Symbolic revolutions and the Australian archaeological record. *Camb. Archaeol. J.* **15,** 157–175 (2005).
7. Langley, M. C., Clarkson, C. & Ulm, S. From small holes to grand narratives: the impact of taphonomy and sample size on the modernity debate in Australia and New Guinea. *J. Hum. Evol.* **61,** 197–208 (2011).
8. Mellars, P. Going east: new genetic and archaeological perspectives on the modern human colonization of Eurasia. *Science* **313,** 796–800 (2006).
9. Roberts, R. G., Jones, R. & Smith, M. Thermoluminescence dating of a 50,000-year-old human occupation site in northern Australia. *Nature* **345,** 153–156 (1990).
10. Roberts, R. G. *et al.* The human colonisation of Australia: optical dates of 53,000 and 60,000 years bracket human arrival at Deaf Adder Gorge, Northern Territory. *Quat. Sci. Rev.* **13,** 575–583 (1994).
11. Pike, A. W. G. *et al.* U-series dating of Paleolithic art in 11 caves in Spain. *Science* **336,** 1409–1413 (2012).
12. McDonald, R. C. Limestone morphology in South Sulawesi, Indonesia. *Z. Geomorphol.* **26** (suppl.), 79–91 (1976).
13. Glover, I. C. Leang Burung 2: an Upper Palaeolithic rock shelter in south Sulawesi, Indonesia. *Mod. Quat. Res. SE Asia* **6,** 1–38 (1981).
14. Glover, I. C. The effects of sink action on archaeological deposits in caves: an Indonesian example. *World Archaeol.* **10,** 302–317 (1979).
15. van Heekeren, H. R. Rock-paintings and other prehistoric discoveries near Maros (South West Celebes). *Laporan Tahunan Dinas Purbakala* **1950,** 22–35 (1952).
16. Bulbeck, D., Pasqua, M. & Di Lello, A. Culture history of the Toalean of South Sulawesi, Indonesia. *Asian Perspect.* **39,** 71–108 (2000).

17. Bulbeck, D., Sumantri, I. & Hiscock, P. Leang Sakapao 1, a second dated Pleistocene site from South Sulawesi, Indonesia. *Mod. Quat. Res. SE Asia* **18,** 111–128 (2004).
18. Eriawati, Y. *Lukisan di Gua-Gua Karst Maros–Pangkep, Sulawesi Selatan: Gambaran Penghuni dan Matapencahariannya* (Indonesian Ministry of Cultural Media Development, 2003).
19. O'Connor, S. Nine new painted rock art sites from East Timor in the context of the Western Pacific region. *Asian Perspect.* **42,** 96–128 (2003).
20. Simanjuntak, T. *Austronesian in Sulawesi* (Center for Prehistoric and Austronesian Studies, 2008).
21. Hill, C. A. & Forti, P. *Cave Minerals of the World* (National Speleological Society, 1997).
22. Fage, L. H. & Chazine, J. M. *Bornéo la Mémoire des Grottes* (Fage éditions, 2009).
23. Plagnes, V. *et al.* Cross dating (Th/U–^{14}C) of calcite covering prehistoric paintings in Borneo. *Quat. Res.* **60,** 172–179 (2003).
24. Taçon, P. S. C. & Tan, N. H. in *Rock Art News of the World 4* (eds Bahn, P., Franklin, N. & Strecker, M.) 207–214 (Oxbow Books, 2012).
25. Chaloupka, G. *Journey in Time, the World's Longest Continuing Art Tradition: The 50,000-year Story of the Australian Aboriginal Rock Art of Arnhem Land* (Reed, 1993).
26. Morwood, M. J. *Visions from the Past: The Archaeology of Australian Aboriginal Art* (Allen & Unwin, 2002).
27. David, B. *et al.* How old are Australia's pictographs? A review of rock art dating. *J. Archaeol. Sci.* **40,** 3–10 (2013).
28. García-Diez, M. *et al.* Uranium series dating reveals a long sequence of rock art at Altamira Cave (Santillana del Mar, Cantabria). *J. Archaeol. Sci.* **40,** 4098–4106 (2013).
29. Valladas, H. *et al.* Bilan des datations carbone 14 effectuées sur des charbons de bois de la grotte Chauvet. *Bull. Soc. Préhist. Fr.* **102,** 109–113 (2005).
30. Combier, J. & Jouve, G. Nouvelles recherches sur l'identité culturelle et stylistique de la grotte Chauvet et sur sa datation par la méthode du ^{14}C. *L'anthropologie* **118,** 115–151 (2014).

Supplementary Information is available in the online version of the paper.

Acknowledgements The fieldwork was authorized by the director of the Makassar Heritage Department (BPPP), M. Said, and the director of the National Centre for Archaeology in Jakarta (ARKENAS), B. Sulistyanto. We further acknowledge Balai Arkeologi Makassar, the Indonesian State Ministry of Research and Technology, and the Geological Survey Institute in Bandung, for facilitating the research. We thank the University of Wollongong's Deputy Vice Chancellor (Research), J. Raper, for additional project support. Field assistants included M. Andi Pampang and A. A. Oktaviana. Technical laboratory assistance involved G. Mortimer, H. Price, L. Sweetman and L. Yu., and C. Owers provided map data. We thank P. Taçon and M. W. Moore for critical feedback on the manuscript. This research was supported by grants from the Australian Research Council to M.A. (DP110102898/DE140100254) and A.B. (DP0879624/DE130101560) and the Centre for Archaeological Science (CAS), University of Wollongong.

Author Contributions A.B. and T.S. conceived the study with M.A., as part of a wider project led by M.R., E.W.S. and B.H., in collaboration with A.B., M.J.M. and G.v.d.B. M.A. and A.B. identified the samples. M.A. collected the samples and conducted the uranium-series dating with A.D. M.A. and A.B. wrote the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to M.A. (m.aubert@griffith.edu.au).

METHODS

Coralloid speleothems form from thin films of water precipitation on cave surfaces, resulting in concentric growth rings, and can be nodular, globular, botryoidal or coral-like in morphology[21]. When precipitated from saturated solutions, calcium carbonate usually contains small amounts of soluble uranium (^{238}U and ^{234}U), which eventually decay to ^{230}Th. The latter is essentially insoluble in cave waters and will not precipitate with the calcium carbonate. This produces disequilibrium in the decay chain where all isotopes in the series are no longer decaying at the same rate. Subsequently, ^{238}U and ^{234}U decay to ^{230}Th until secular equilibrium is reached. Because the decay rates are known, the precise measurement of these isotopes allows calculation of the age of the carbonate formation[31].

It is also common for secondary calcium carbonate to be contaminated by detrital materials, such as wind-blown or waterborne sediments, and as such can lead to uranium-series ages that are erroneously older than the true age of the sample. This is because the detrital fraction will contribute to the overall amount of uranium-series nuclides so that the sample does not reflect a radioactive disequilibrium related to the time of carbonate formation. The effects of detrital contamination can be identified and often corrected for by measuring the activity of ^{232}Th that is solely present in the detrital fraction but which plays no part in the decay chain of uranium. An indication of the degree of detrital contamination is expressed as ^{230}Th/^{232}Th activity, with high values ($>$20) indicating little or no effect on the calculated age and low values ($<$20) indicating that the correction on the age will be significant[31]. Except for two samples (LL3.1 and B4.2), all our samples have ^{230}Th/^{232}Th activity $>$20, indicating sample purity.

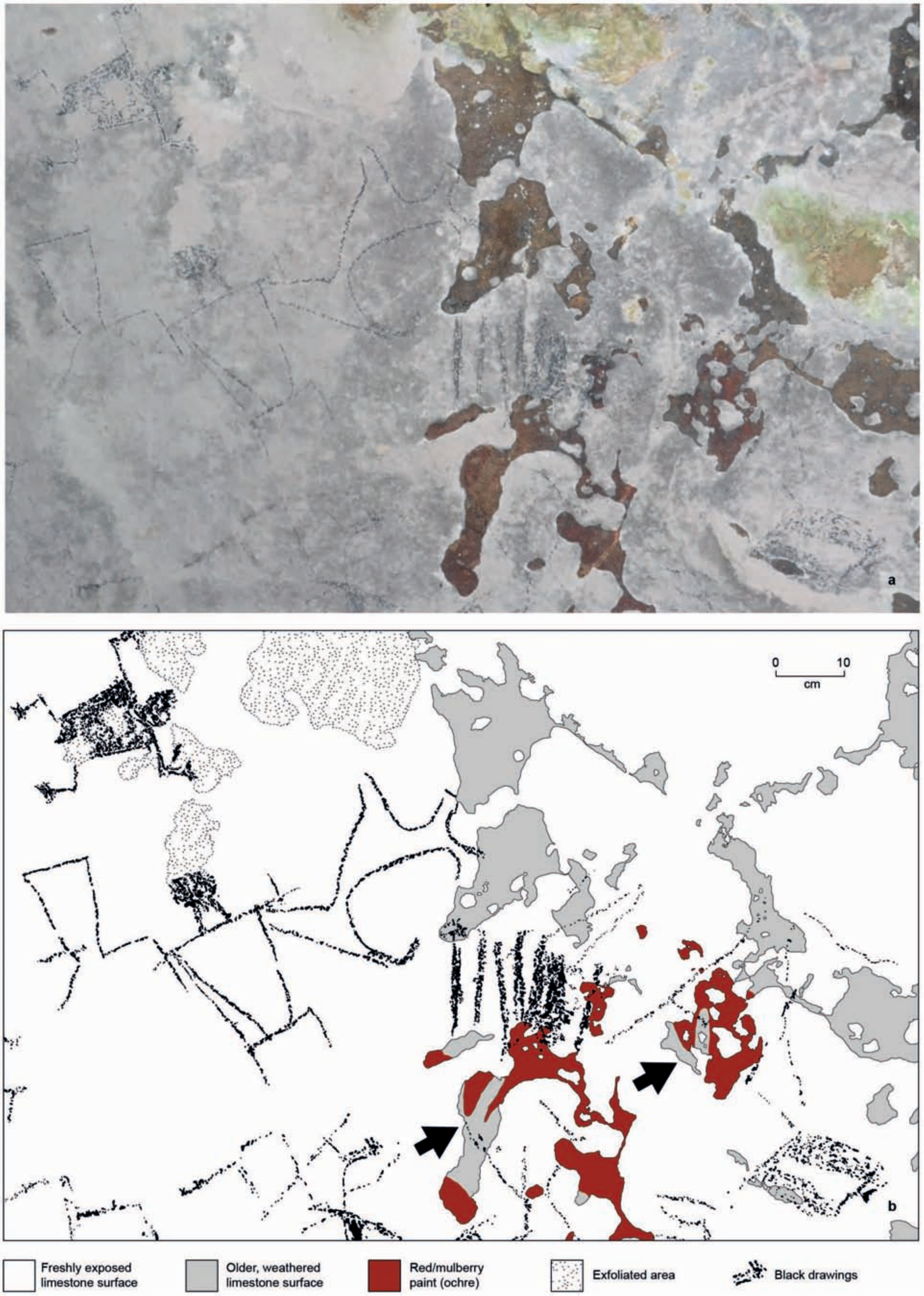
Sample preparation was conducted at the Wollongong Isotope Geochronology Laboratory, University of Wollongong. The small calcium carbonate samples were weighed separately in Savillex perfluoroalkoxy polymer resin (PFA) vials. The samples were covered with MilliQ water, and drops of Merck Ultrapur 60% HNO_3 were added until complete dissolution was achieved. A spike solution enriched in ^{236}U–^{229}Th was subsequently added and the mixture was left to equilibrate overnight. The solutions were evaporated to dryness and then redissolved in 1.5 M HNO_3 ready for ion-exchange chromatography, consisting of 0.25 ml of Eichrom TRU resin over 0.1 ml of Eichrom pre-filter resin. The resins were cleaned by passing 3 M HCl, 0.2 M HCl and a 0.1 M HCl + 0.3 M HF mixture through the columns before use and then preconditioned with 1.5 M HNO_3. After the sample solutions had been loaded on the TRU resin bed as solutions in 1.5 M HNO_3, the columns were washed with 1.5 M HNO_3 and 3 M HCl. Uranium and thorium were imperfectly separated from the ion-exchange medium with 0.2 M HCl (for thorium), and 0.1 M HCl + 0.3 M HF (for uranium). Finally, the samples were evaporated to dryness and redissolved in 4 ml of 2% HNO_3.

The U and Th solutions were introduced separately into a ThermoFinnigan Neptune Plus Multi-Collector inductively coupled plasma mass spectrometer at the Research School of Earth Sciences, Australian National University. The Neptune Plus is equipped with a large interface pump, Jet Sample and Skimmer cones, electrostatic analyser, secondary electron multiplier (SEM) and retarding potential quadrupole (RPQ) for high abundance sensitivity. Samples were aspirated using an electrospray ionization PFA-ST Aridus II nebulizer at an uptake rate of ~0.1 ml min^{-1}. The sweep gas (Ar) flow rate was set to ~3–4 l min^{-1} and nitrogen was set to ~2–4 ml min^{-1}. Sensitivity was $>$1 V per p.p.b. U.

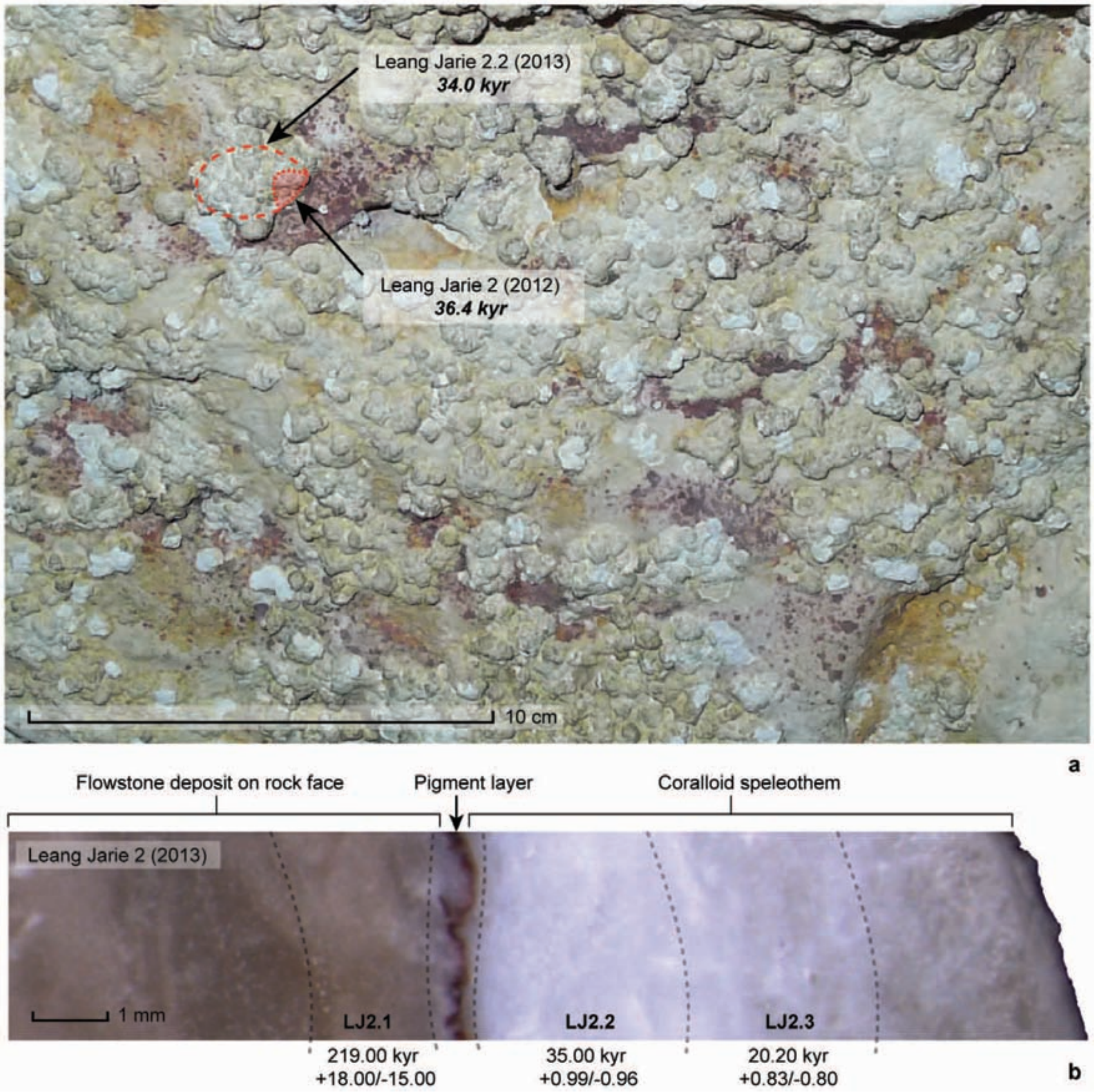
Uranium isotopes were measured with the RPQ off; thorium isotopes were measured with the RPQ on. Isotopic ratios were corrected for background, tailing of ^{238}U on ^{236}U and ^{234}U, SEM/Faraday yield and instrumental mass bias (using ^{238}U/^{235}U = 137.88) after subtraction of the minor spike component. The SEM/Faraday yield was calculated externally with the NBS 960 standard by alternating ^{235}U between the SEM and Faraday array while measuring ^{238}U on the Faraday array. This value was corrected for instrumental mass bias and compared with the true value in SRM 960 = 0.007265. The SRM 960 standard was measured every two samples. Relative gains derived from standard measurements were then interpolated to the unknowns. Other standards used in this study were AC-1, an Australian National University (ANU) coral powder with a measured TIMS U-series age of 125,550 years[32], and HU-1, a solution of secular equilibrium Harwell Uraninite, also supplied by the ANU. AC-1 and HU-1 results are shown in Supplementary Information, and in both cases are within the error of the expected values. Total procedure blanks were in the order of 0.9 pg for Th and 0.1 pg for U. Further details on our multi-collector inductively coupled plasma mass spectrometry procedure can be found in ref. 33.

Calculation of ages and initial ^{234}U/^{238}U ratios was performed with Isoplot 3.75 using the following decay constants (dc) and half-lives (hl): $^{238}U_{dc} = 1.55125 \times 10^{-10}$; $^{238}U_{hl} = 4.46831 \times 10^{9}$, $^{234}U_{dc} = 2.82207 \times 10^{-6}$; $^{234}U_{hl} = 2.45617 \times 10^{5}$, $^{232}Th_{dc} = 4.94752 \times 10^{-11}$; $^{232}Th_{hf} = 1.401 \times 10^{10}$, $^{230}Th_{dc} = 9.17052 \times 10^{-6}$; $^{230}Th_{hl} = 7.55843 \times 10^{4}$. Errors were calculated by Monte Carlo simulation (5,000 trials), ignoring the uncertainties in the ^{235}U and ^{238}U decay constants. Corrections for detrital components were calculated assuming a bulk Earth ^{232}Th/^{238}U concentration ratio of the upper crust of 3.8 ± 50%[34] and secular equilibrium for ^{230}Th, ^{234}U and ^{238}U.

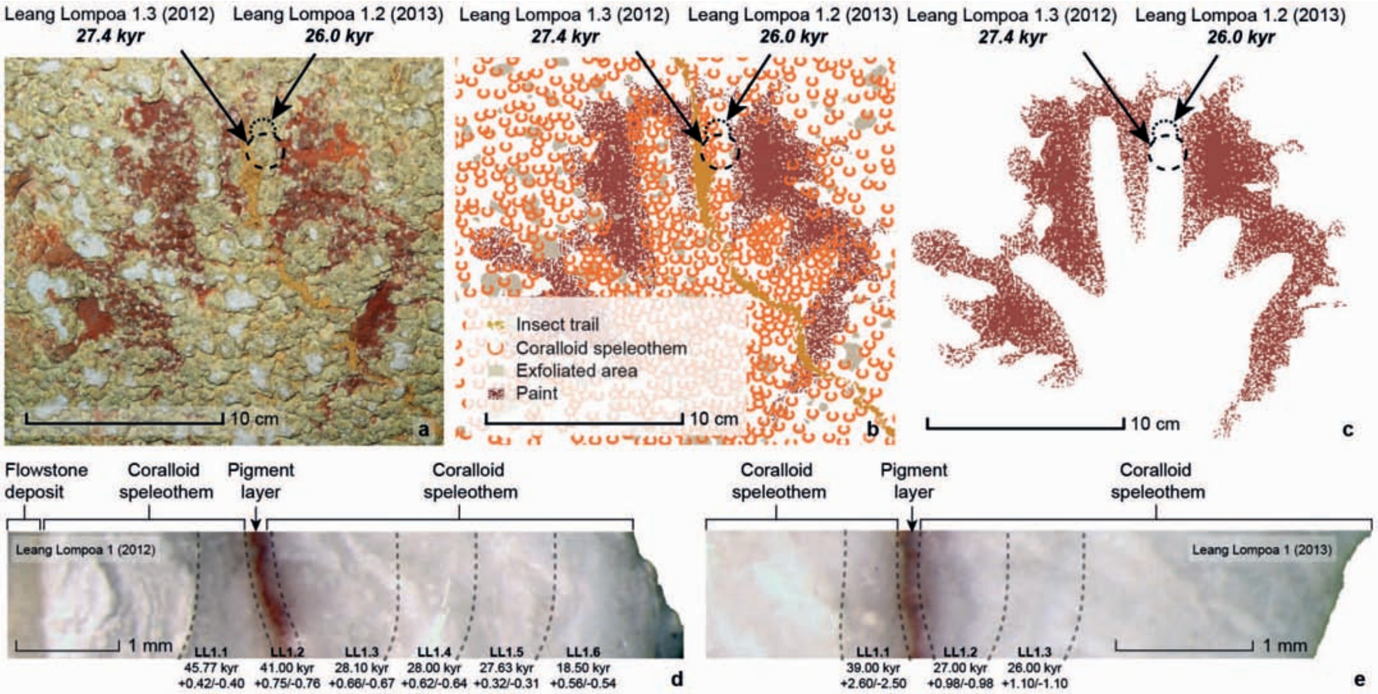
31. Bourdon, B., Henderson, G. M., Lundstrom, C. C. & Turner, S. P. *Uranium-series Geochemistry* (Mineralogical Society of America, 2003).
32. McCulloch, M. T. & Esat, T. The coral record of last interglacial sea levels and sea surface temperatures. *Chem. Geol.* **169,** 107–129 (2000).
33. McCulloch, M. T. & Mortimer, G. E. Applications of the ^{238}U–^{230}Th decay series to dating of fossil and modern corals using MC-ICPMS. *Aust. J. Earth Sci.* **55,** 955–965 (2008).
34. Cheng, H., Adkins, J., Edwards, R. & Boyle, E. U–Th dating of deep-sea corals. *Geochim. Cosmochim. Acta* **64,** 2401–2416 (2000).
35. Leclerc, P. in *Expédition Thaï-Maros 86* 147–153 (Association Pyrénéenne de Spéléologie, 1987).



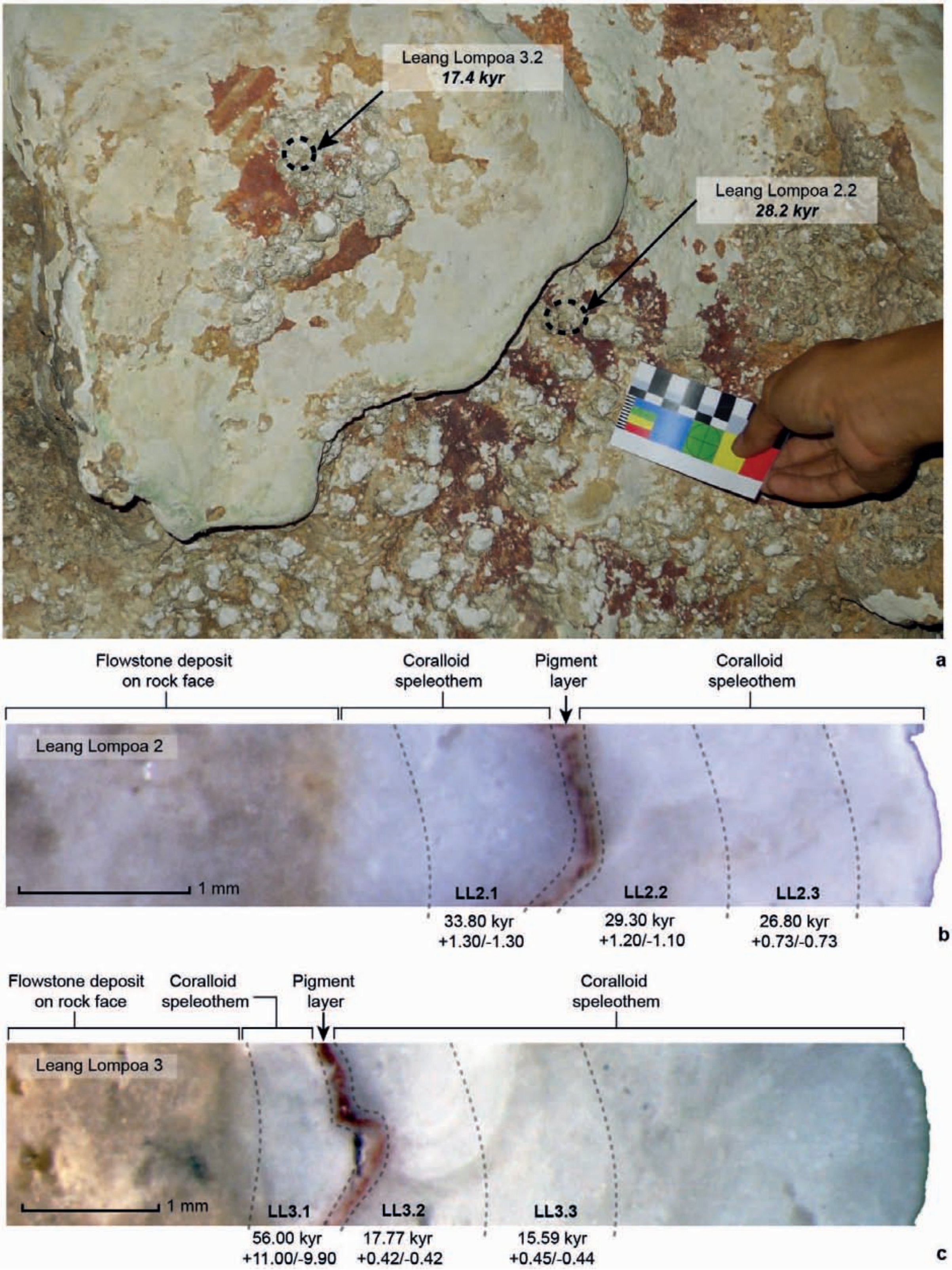
Extended Data Figure 1 | Rock art panel on the ceiling at Leang Bulu Bettue. **a**, Black drawings of early Austronesian style were made on a relatively freshly exposed limestone surface and are superimposed over remnant patches of a much older surface, now extremely heavily weathered and almost completely exfoliated, containing faded hand stencils (shown more clearly and highlighted by arrows in **b**). The same rock art panel was documented and illustrated in a publication by a team of French cavers in 1986, but the hand stencils were not identified[35].



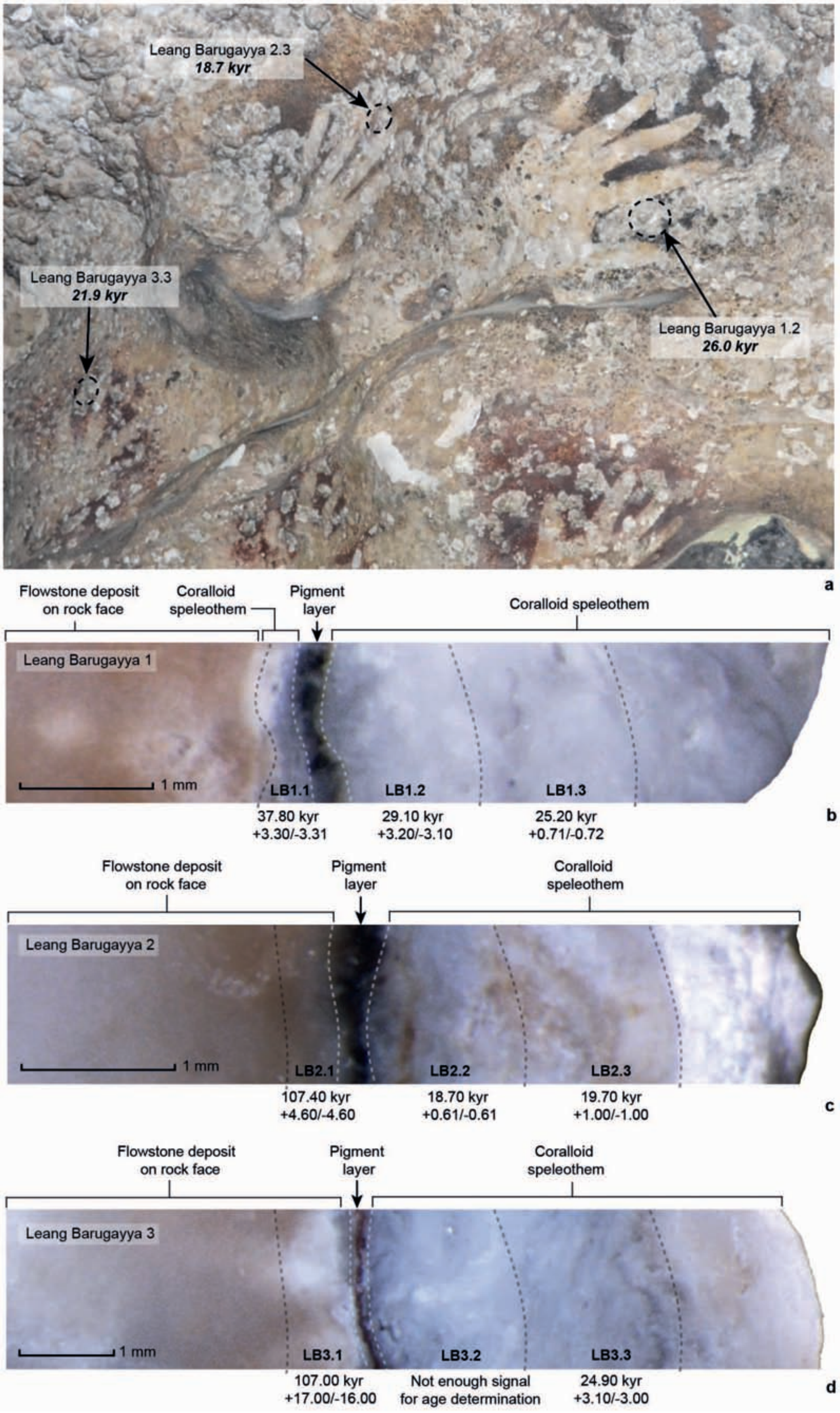
Extended Data Figure 2 | Dated rock art from Leang Jarie. a, Locations of the sampled coralloid speleothems and associated hand stencils. **b**, Profile of the coralloid speleothem showing the microexcavated subsamples bracketing the age of the paintings. The Leang Jarie 2 (2012) sample is from above the pigment layer and so only provides a minimum age for the underlying hand stencils.



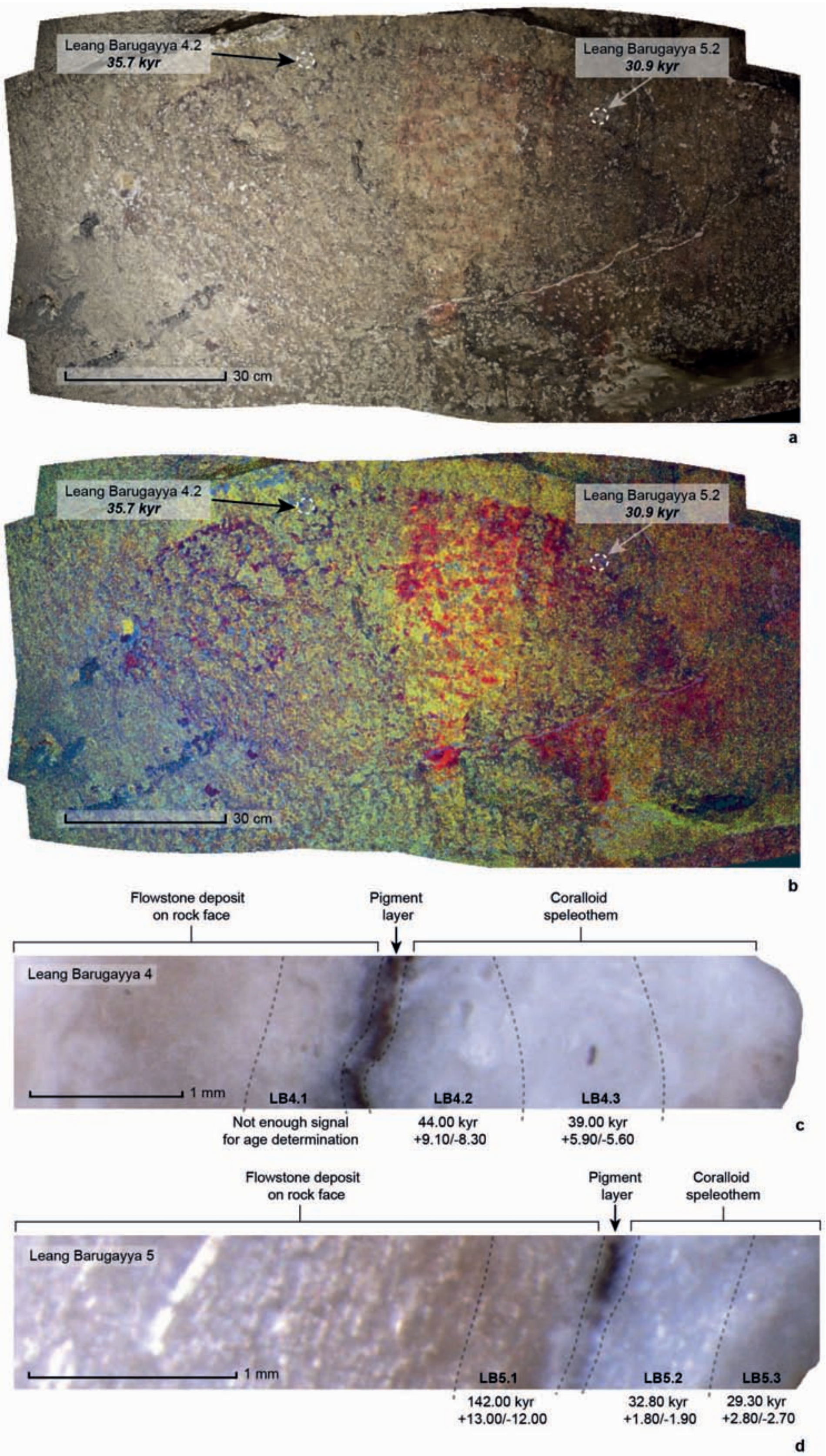
Extended Data Figure 3 | Dated rock art from Leang Lompoa. **a**, Photograph showing the locations of the sampled coralloid speleothems and associated hand stencil. **b**, **c**, Tracings showing the locations of the sampled coralloid speleothems and associated hand stencil. Although heavily obscured by coralloid speleothems, we interpret this image as a 'mutilated hand' stencil, which shows in outline a human hand with two amputated digits or with the third and fourth fingers folded into the palm. The hand stencil is located on the ceiling of a narrow, dimly lit passage leading off from the main entrance to the cave. Samples Leang Lompoa 1 (2012) and Leang Lompoa 1 (2013) are part of the same cluster of coralloid speleothems that formed over the hand stencil. **d**, **e**, Profiles of the coralloid speleothems showing the microexcavated subsamples bracketing the age of the motif. Note that sample LL1.2 (2012) does not represent the age of the hand stencil. The resultant age reflects a mixture of calcium carbonate from below and above the pigment layer. Tracing credit: Leslie Refine 'Graph & Co' (France).



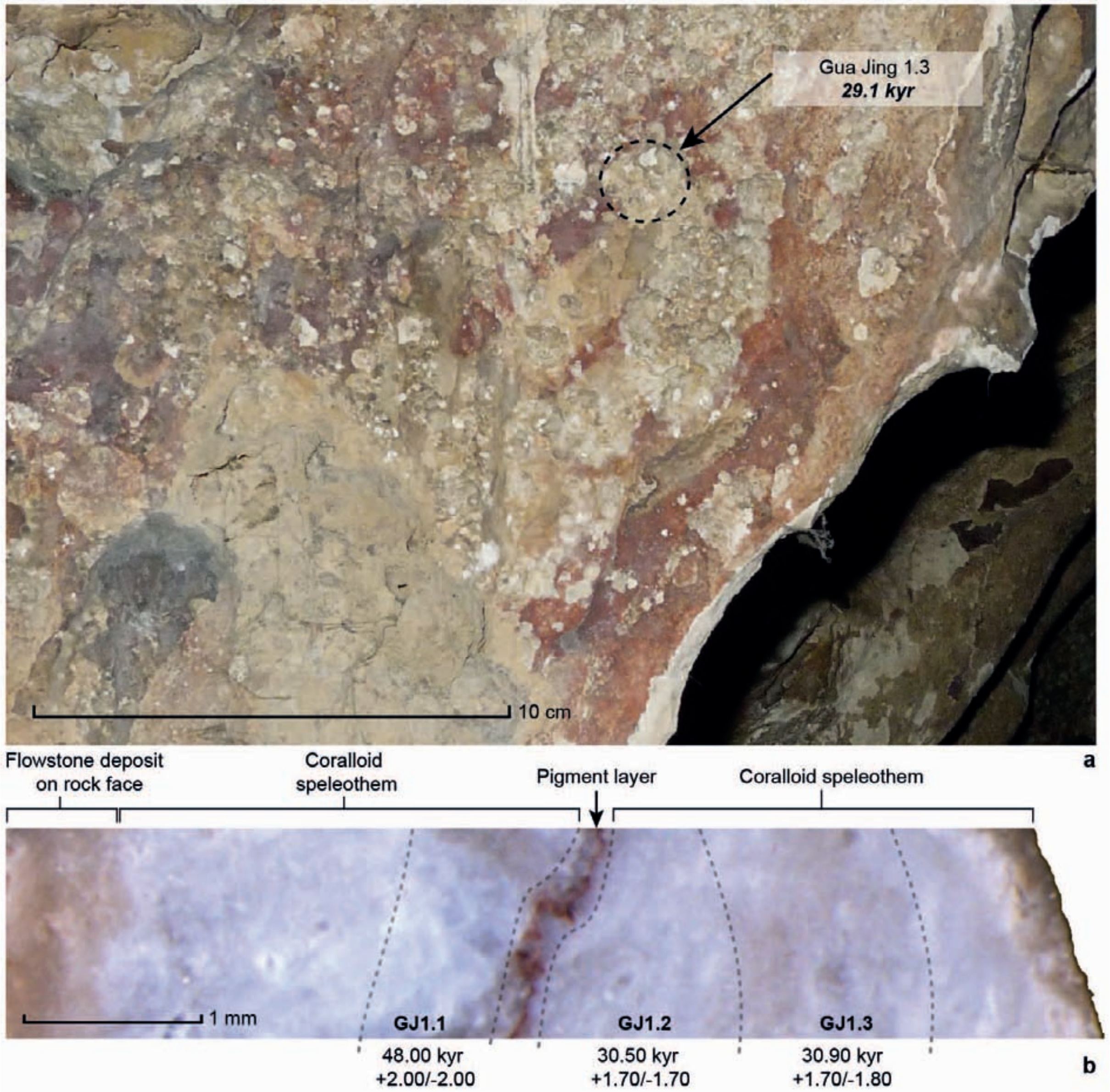
Extended Data Figure 4 | Dated rock art from Leang Lompoa. **a**, Locations of the sampled coralloid speleothems and associated hand stencils. The hand stencils occur on a 2.5-m-high ceiling in a small, dimly lit side chamber leading off from the cave mouth. The stencil at the left (Leang Lompoa 3) is stylistically distinct from the adjacent stencil (Leang Lompoa 2), with the fingers modified by brushwork subsequent to stencilling to produce slender and pointy forms. **b**, **c**, Profiles of the coralloid speleothems showing the microexcavated subsamples bracketing the age of the hand stencils.



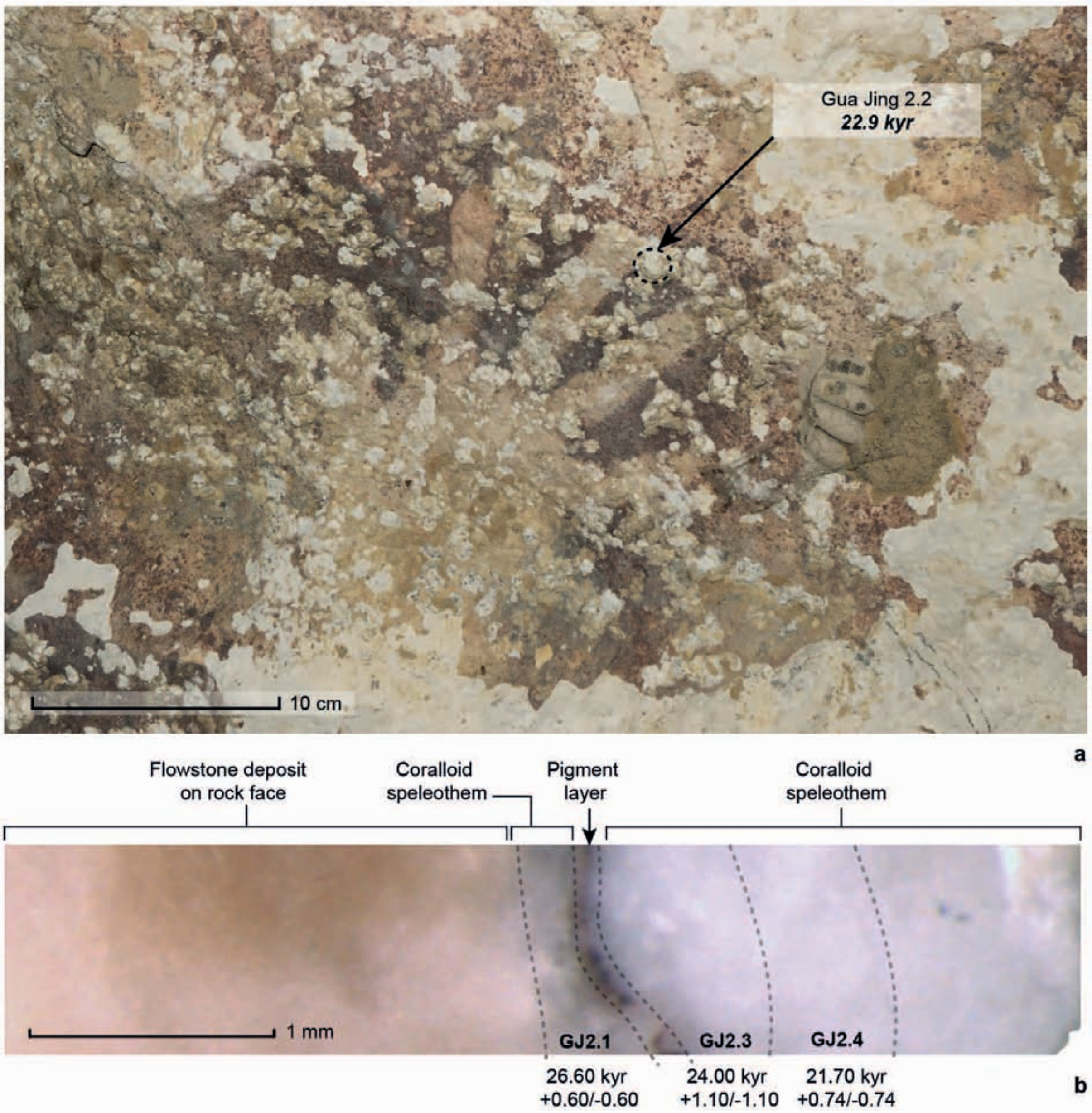
Extended Data Figure 5 | Dated rock art from Leang Barugayya 1. **a**, Locations of the sampled coralloid speleothems and associated cluster of hand stencils. The hand stencils are situated on a small rock art panel near the ceiling and close to the cave entrance. Samples LB1 and LB2 come from two distinct hand stencils that are dark mulberry (almost black) in colour. Sample LB3 is from over an adjacent red hand stencil. **b**–**d**, Profiles of the coralloid speleothems showing the microexcavated subsamples bracketing the age of the hand stencils.



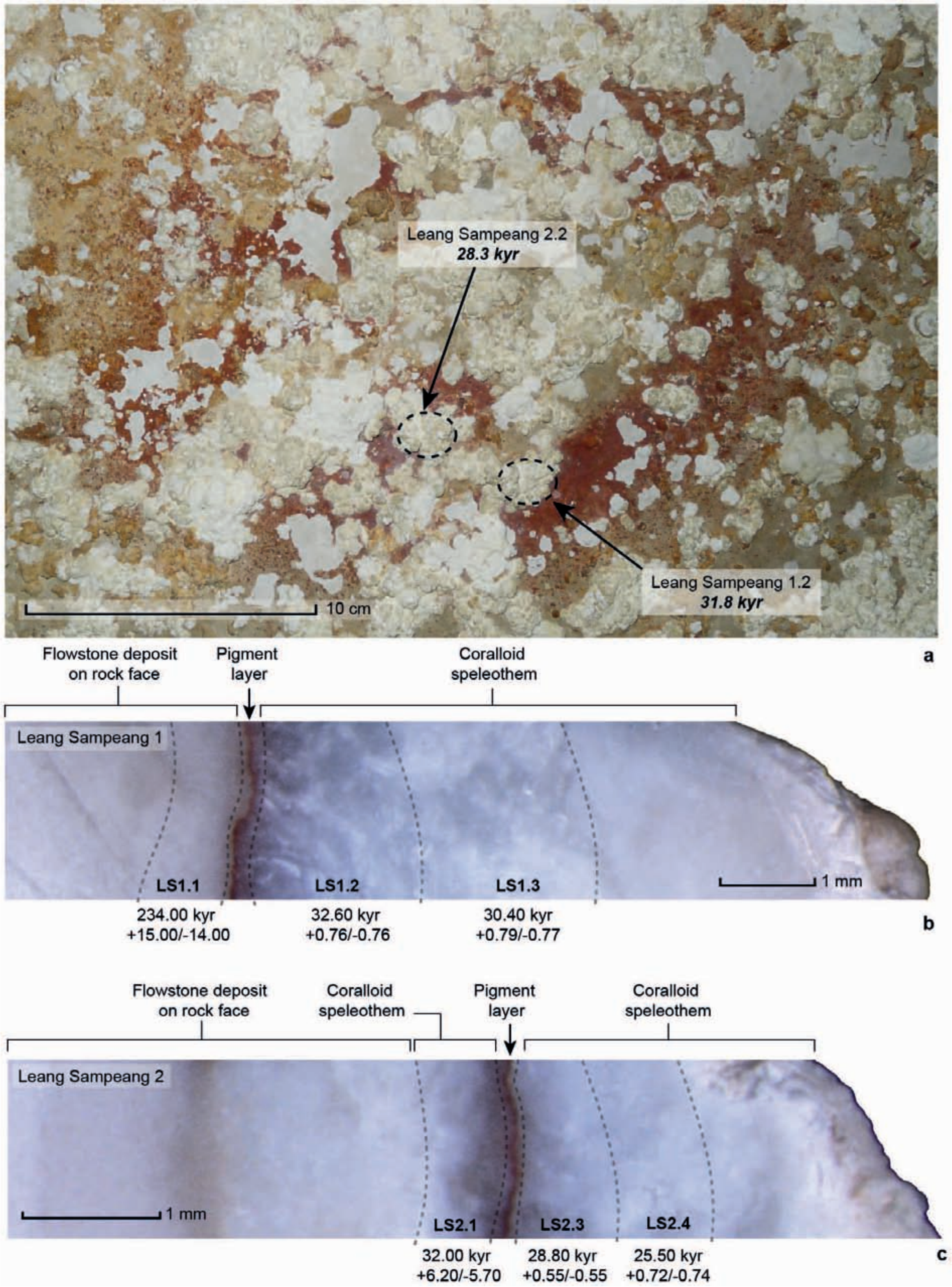
Extended Data Figure 6 | Dated animal painting from Leang Barugayya 2. **a**, **b**, Composite of photographs showing the locations of the sampled coralloid speleothems and associated large infilled red painting of an animal. Field photographs were altered in the software program DStretch to enhance the image (**b**). The animal species depicted is unidentified as a result of the extent of weathering and deterioration of the painting and the thick accumulation of coralloids over the art; however, the painting seems to show in profile a large land mammal, probably a pig (a babirusa or *Sus celebensis*), with the head facing right and the hindquarters at the left. **c**, **d**, Profile of the coralloid speleothems showing the microexcavated subsamples bracketing the age of the painting. Images **a** and **b** courtesy of A. A. Oktaviana.



Extended Data Figure 7 | Dated rock art from Gua Jing. **a**, Location of the sampled coralloid speleothem and associated hand stencil. The hand stencil is located on a stalactite curtain 15 m from the cave entrance and 2 m above the current cave floor. The cave itself comprises a dark, winding phreatic tube containing an extensive gallery of hand stencils and figurative animal motifs. **b**, Profile of the coralloid speleothem showing the microexcavated subsamples bracketing the age of the hand stencil.



Extended Data Figure 8 | Dated rock art from Gua Jing. **a**, Location of the sampled coralloid speleothem and associated hand stencil. **b**, Profile of the coralloid speleothem showing the microexcavated subsamples bracketing the age of the hand stencil.



Extended Data Figure 9 | Dated rock art from Leang Sampeang. **a**, Locations of the sampled coralloid speleothems and associated hand stencil. Leang Sampeang is a 20-m-deep, narrow chamber with paintings located on the ceiling at the back of the cave in complete darkness. In this area the cave is only 2.5 m wide and requires crawling to reach. Samples Leang Sampeang 1 and Leang Sampeang 2 came from the same red hand stencil located 17 m from the cave entrance and 18 cm above the current cave floor. **b**, **c**, Profiles of the coralloid speleothems showing the microexcavated subsamples bracketing the age of the hand stencil.

ARCHAEOLOGY

Art on the move

Studies of stencils and paintings from prehistoric caves in Indonesia date the art to at least 39,900 years ago — around the same age as the earliest cave art previously known, 13,000 kilometres away in western Europe. SEE LETTER P.223

WIL ROEBROEKS

Figure 1 | Prehistoric paintings. Aubert *et al.*[1] find that the oldest-known cave art in the Maros cave in Sulawesi, Indonesia, is of comparable age — around 40,000 years old — to the previously oldest-known paintings by humans, from El Castillo cave in Spain. It is not clear whether rock art was already part of the cultural repertoire of modern humans colonizing Eurasia from Africa, or whether artistic ability arose independently in various regions. There is extensive evidence of occupation by modern humans in Oceania from around this time and somewhat longer ago (archaeological sites with dates to 40,000 years and earlier denoted by white dots; sites mentioned in the text denoted by red dots). Lower sea levels in this period (approximately −60 metres; shaded area) meant that several present-day islands were connected, but vast stretches of open sea still had to be crossed by humans colonizing the region. (Map based on data in ref. 20.)

The Maros karst in Sulawesi, Indonesia, is a limestone area with many caves and a large body of rock art. This art was first reported in the 1950s, and it was long assumed to be less than 10,000 years old, because it was thought that rapid erosion rates in a tropical karst environment would prevent the survival of older cave paintings. In this issue, Aubert *et al.*[1] (page 223) actually date some of that art, and report that it is one of the oldest examples of cave art in the world. This spectacular finding suggests that the making of images on cave walls was already a widely shared practice 40,000 years ago.

Mineral-rich water trickling over cave walls can form thin layers of calcite containing trace amounts of uranium. The radioactive decay of uranium atoms acts like a clock, enabling dating of the calcite formations (also called speleothems) using the uranium–thorium dating method. In cases where calcite overlies cave paintings, dating its formation can yield a minimum age for the art.

In their study, Aubert and colleagues removed tiny samples from Maros rock-art panels using a rotary tool equipped with a diamond saw blade. The coralloid speleothems (known as cave popcorn) covering the art were less than 10 millimetres thick, and the samples were subsequently micro-excavated in the lab in 'spits' of less than 1 mm. This method, which proceeded from the exterior surface of the speleothem towards the pigment layer and sampled above, and sometimes also below, the pigment, yielded a robust minimum and in some cases a maximum age for the paintings.

The results were unexpected. One stencilled hand was painted at least 39,900 years ago, and images of a pig deer (babirusa) and a large, indeterminate animal, probably a pig, were created at least 35,400 and 35,700 years ago, respectively. These dates are in the age range of the earliest cave art found in the westernmost tip of Europe. There, comparable dating techniques applied to calcite overlying rock art in 11 caves in northern Spain established a minimum date of 40,800 years for a red disk from El Castillo, the oldest cave painting known so far[2]. A hand stencil from the *Panel de los Manos* at the same site yielded a minimum date of 37,300 years. A study[3] earlier this year claims to have identified an abstract pattern engraved by Neanderthals more than 39,000 years ago, in Gorham's Cave in Gibraltar. However, both the Neanderthal authorship (on the basis of its age) and the symbolic character of this 'rock art' have been questioned[4].

The earliest figurative rock art from western Europe is a painted rhinoceros from the Chauvet Cave in France, radiocarbon dated to 32,410 ± 720 ^{14}C years before present[5], which is 35,300 to 38,827 calendar years ago[2] (although doubts have been raised[6] about whether the art is in fact this old). Rock fragments with traces of red paint from the Italian site of Fumane indicate that paintings were produced there between 36,000 and 41,000 years ago[7].

A rich corpus of rock art also exists at the other side of the spatial distribution of modern humans, in Australia. But although the first human occupation there goes back about 50,000 years, no rock art older than 30,000 years is known. Nevertheless, worn ochre crayons recovered from 50,000-year-old deposits in Arnhem Land, in northern Australia, show that some form of pigment use did occur there too, from the very first occupation onward[8].

For the moment, the bottom line is that

cave art was practised in Europe and in southeast Asia at about the same time, before 40,000 years ago. That by itself is an important observation. But how to interpret this long-distance ‘contemporaneity’ is unclear. Southeast Asia was already occupied by the extinct hominin species *Homo erectus* at least 1 million years ago, and modern humans (members of our own species originating in Africa) reached this area probably sometime before 50,000 years ago. The modern-human occupation history of southeast Asia and the continent Sahul, which existed during periods of lower sea levels in the Pleistocene epoch (around 2.5 million to 12,000 years ago) and is now New Guinea, Australia and other islands, testifies to the role of marine navigation over vast stretches of open sea in this colonization process[9] (Fig. 1).

Whether rock art was an integral part of the cultural repertoire of colonizing modern humans, from western Europe to southeast Asia and beyond, or whether such practices developed independently in various regions, is unknown. What is clear is that no figurative art is known from before the time of the initial expansion of *Homo sapiens* into Asia and across Europe — neither from earlier *H. sapiens* in Africa nor from their contemporaries in western Eurasia, the Neanderthals, who became extinct during the period of modern-human expansion out of Africa. The dating technique applied by Aubert *et al.* requires only minute amounts of calcite, and hence holds great potential for dating rock art worldwide, to shed light on when this art first appeared as well as on how it developed through time and space.

Aubert and colleagues’ study underlines the great cultural–historical importance of the Maros area, which is under threat from large-scale limestone mining. Their findings also stress the great relevance of Asia, and especially southeast Asia, for the study of human evolution[10]. The huge Asian continent is the home of recent key finds, including a series of early *Homo* individuals at Dmanisi, Georgia, dating to between 1.7 million and 1.8 million years ago[11], and the mysterious Denisovans — members of a *Homo* species that are known only through their genetic signature[12]. The oldest-known *H. sapiens* genome was obtained from a 45,000-year-old femur, discovered at Ust-Ishi in Siberia[13]. Compared with Europe, Asia has seen little fieldwork, and new finds will keep on challenging what we think we know about human evolution. Even the evolution of the Neanderthals looks more and more like an Asian phenomenon[14,15], with Europe’s large number of Neanderthal remains — known from a long history of intensive research — possibly reflecting repeated colonizations from central and western Asia[16].

Southeast Asia also harbours the type site of *H. erectus*, at Trinil, Java, and Sulawesi’s neighbouring island, Borneo, contains the spectacular Greater Niah Cave, which has a record of human presence from about 50,000 years ago onward, including the first unambiguous fossil of a modern human in the area, a skull at least 40,000 years old[17]. Borneo also has a rich, but as-yet-undated, rock-art record, with some very striking similarities to the Maros paintings[18]. Finally, one of the most remarkable and least expected palaeoanthropological discoveries was made 400 kilometres south of the Maros area, on the island of Flores: here, the late Mike Morwood, one of the authors of the Maros cave-art study, discovered the skeleton of a puzzling diminutive hominin, presented 10 years ago as *Homo floresiensis*[19] and nicknamed ‘the hobbit’ — another illustration of the surprises that this region can offer. ■

Wil Roebroeks *is in the Human Origins group, Faculty of Archaeology, Leiden University, 2300 RA Leiden, the Netherlands.*
e-mail: w.roebroeks@arch.leidenuniv.nl

1. Aubert, M. *et al. Nature* **514,** 223–227 (2014).
2. Pike, A. W. G. *et al. Science* **336,** 1409–1413 (2012).
3. Rodríguez-Vidal, J. *et al. Proc. Natl Acad. Sci. USA* http://dx.doi.org/10.1073/pnas.1411529111 (2014).
4. Callaway, E. *Nature* http://dx.doi.org/10.1038/nature.2014.15805 (2014).
5. Valladas, H. *et al. Nature* **413,** 479 (2001).
6. Pettitt, P. B. *J. Hum. Evol.* **55,** 908–917 (2008).
7. Broglio, A. *et al. L’Anthropologie,* **113,** 753–761 (2009).
8. David, B. *et al. J. Archaeol. Sci.* **40,** 3–10 (2012).
9. O’Connell, J. F., Allen, J. & Hawkes, K. in *The Global Origins and Development of Seafaring* (eds Anderson, A., Barrett, J. & Boyle, K.) 57–68 (Cambridge Univ. Press, 2010).
10. Dennell, R. W. & Porr, M. (eds) *Southern Asia, Australia and the Search for Human Origins* (Cambridge Univ. Press, 2014).
11. Lordkipanidze, D. *et al. Science* **342,** 326–331 (2013).
12. Reich, D. *et al. Nature* **468,** 1053–1060 (2010).
13. Gibbons, A. *Science* **343,** 1417 (2014).
14. Dalén, L. *et al. Mol. Biol. Evol.* **29,** 1893–1897 (2012).
15. Prüfer, K. *et al. Nature* **505,** 43–49 (2014).
16. Hawks, J. *Annu. Rev. Anthropol.* **42,** 433–449 (2013).
17. Barker, G. (ed.) *Rainforest Foraging and Farming in Island Southeast Asia: The Archaeology of the Niah Caves, Sarawak* (McDonald Inst. Archaeol. Res., 2013).
18. Fage, L.-H. & Chazine, J.-M. *Borneo: Memory of the Caves* (Le Kalimanthrope, 2010).
19. Brown, P. *et al. Nature* **431,** 1055–1061 (2004).
20. O’Connell, J. F. & Allen, J. *Aust. Archaeol.* **74,** 5–31 (2012).

ULTRALUMINOUS X-RAY SOURCES

Small field with a large impact

The nature of ultraluminous X-ray astronomical sources has long been unclear. The latest observations of these rare systems provide some crucial clues, but still leave theorists scratching their heads. SEE LETTERS P.198 & P.202

JEANETTE C. GLADSTONE

In the late 1970s, astronomers discovered objects that emit unusually bright X-rays[1]. Given their extreme X-ray luminosity, these ultraluminous X-ray sources were thought to contain black holes. However, the mass of the black holes powering such objects has been a topic of much debate. Two studies in this issue, by Motch *et al.*[2] (page 198) and Bachetti *et al.*[3] (page 202), together with two recent reports by Pasham *et al.*[4] and Liu *et al.*[5], are changing our views about these systems.

Most black holes are created during the violent deaths of massive stars. Although such stellar-mass black holes weigh about 3 to 100 times the mass of our Sun, they can be difficult to see. Their extreme gravitational pull attracts anything that strays too close, even light. So, to learn more about them, we must observe them indirectly, by studying the effect they have on their environment.

If the stellar-mass black hole is orbited by a companion star, we can study its effects on the star. The black hole can pull material from the star’s wind and/or surface. As material falls in (accretes), forming an accretion disk, some of the material’s gravitational potential energy is lost as light — mainly X-rays. Such X-ray binary systems (Fig. 1) contain not just a disk but also an optically thin (transparent) medium, which is thought to sit either above and below the disk (a corona) or between the disk and the black hole (a hot inner flow). As the rate at which material travels through the accretion disk changes, the geometry of the system, and so its accretion state, will change accordingly.

X-ray binaries can also contain neutron stars — the smaller cousins of stellar-mass black holes. Like stellar-mass black holes, neutron stars are born in violent star deaths, but they are lighter, weighing only around 1.4 solar masses. The gravitational pull of these systems is again very strong, drawing in material. But unlike black holes, light can escape from them, and we can see their surface.

Black holes also have much heavier cousins, which reside in the centres of galaxies. They are known as supermassive black holes, and weigh