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Article

Earliest parietal art: hominin hand and foot traces from the middle Pleistocene of Tibet

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ABSTRACT

At Quesang on the Tibetan Plateau we report a series of hand and foot impressions that appear to have been intentionally placed on the surface of a unit of soft travertine. The travertine was deposited by water from a hot spring which is now inactive and as the travertine lithified it preserved the traces. On the basis of the sizes of the hand and foot traces, we suggest that two track-makers were involved and were likely children. We interpret this event as a deliberate artistic act that created a work of parietal art. The travertine unit on which the traces were imprinted dates to between ~169 and 226 ka BP. This would make the site the earliest currently known example of parietal art in the world and would also provide the earliest evidence discovered to date for hominins on the High Tibetan Plateau (above 4000 m a.s.l.). This remarkable discovery adds to the body of research that identifies children as some of the earliest artists within the genus *Homo*.

1. Introduction

Behavioural expression in the form of art is a feature of our genus *Homo*, and hands are one of the earliest motifs identified within parietal art (paintings, drawings and engravings on immobile rock surfaces) [1]. The use of hands as stencils in cave paintings dates from around 40,000 years ago in Sulawesi (Indonesia) [2] and at El Castillo (Spain) [3]. Here we present a series of previously unreported hand and foot impressions from a fossil hot spring at Quesang on the Tibetan Plateau (4269 m a.s.l.; 30°00′25″N, 90°46′07″E; Figs. 1 and 2). We argue that these traces were imprinted into soft travertine (pre-lithification) and were not carved after the travertine had lithified. On the basis of Uranium series dating the travertine unit in which the tracks are impressed dates from between ~169 and 226 ka BP. Based on the size of the tracks the track-makers were likely two children and the traces were not imprinted during normal locomotion or by the use of hands to stabilize motion as reported at the Rocomonfina track site in Italy [4]. Consequently, we argue that the deliberate track-making was likely an early act of parietal art. What constitutes art, however, is a subject of considerable debate [5,6] and even if one does not accept this as art, the site provides the earliest evidence yet for hominin presence on the High Tibetan Plateau.

The active Quesang Hot Spring is located close to the Quesang Village, approximately 80 km northwest of Lhasa in Tibet on a tributary of the Xiong Qu River (Fig. 1a). In 1988, the first author

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Fig. 1. Ichnological traces at Quesang in Tibet. (a) Regional context for the site showing other key hominin localities. (b) Locational context for the parietal art. The site consists of a rocky promontory and the art-panel was exposed on the surface of one of these blocks by the natural removal of an overlying block. (c) Parietal art-panel. The base image in (a) is from the GEOTOPO30 30-Arc DEM supplied by USGS Earth Explore (www.earthexplorer.usgs.gov) and processed in ArcMap 10.1.3 (www.desktop.arcgis.com).

found handprints and footprints in the vicinity of the hot spring bathhouse [7,8]. Recent investigations between 2018 and 2020 led to the discovery of the potential parietal art. On the Tibetan Plateau, hydrothermal springs and travertine deposits are common and preferentially occur along north–south trending active graben systems [9]. At Quesang the travertine associated with both fossil

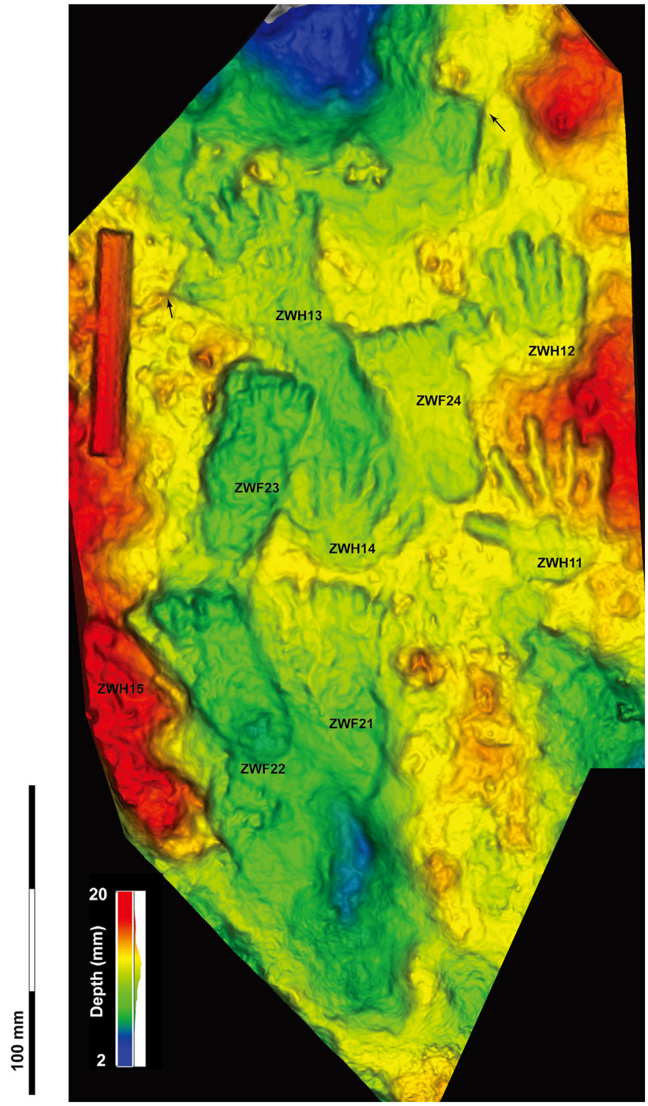

Fig. 2. Colour rendered 3D model of the parietal art-panel. The individual track codes are indicated along with the approximate location and date of two samples extracted from the slab. The 3D was created in Agisoft Metashape v.1.5.2 (https://www.agisoft.com), processed in DigTrace (www.digatrace.co.uk; auto-rotated and cropped) and colour rendered in CloudCompare (https://www.danielgm.net/cc).

and active hot springs forms a fan-like veneer across the slope with the fossil springs forming localized, ring-shaped mounds that rise from the general fan surface [10]. The tracks reported here were found towards the base of the regional slope on a small rocky promontory (Figs. 1b and S1 online).

2. Methods

2.1. Dating

Field sampling was undertaken by permission of the local government and involved taking bulk samples using a hammer and chisel from which precise samples were subsequently drilled using a diamond tipped drill in the laboratory. Uranium series dating has been widely used in dating carbonate deposits [11] with a range of archaeological, paleoclimatic and paleoenvironmental applications [12,13]. Moreover, it has been successfully used elsewhere in Tibet for dating thermogene travertine similar to those at Quesang [14]. The dense travertine layers at Quesang form with the thicknesses of between 200 and 2000 mm [10]. The calcite crystals are inlaid closely with only a few pores and the dense laminated travertine has no, or little, recrystallization and few impurities. There is no evidence of bioturbation. The measured δ^{234}U and ^{230}Th/^{238}U activity ratios show that all dated travertine samples demonstrate closed-system behaviour (Fig. S2; Tables S1 and S2 online), confirmed further by our binocular observations on the U-Th dating samples (Figs. S3–S5 online). Impurity content is reflected in the ^{230}Th/^{232}Th ratio and a lower ^{230}Th/^{232}Th ratio indicates high levels of detrital ^{232}Th impurity in the sample [15,16]. Consequently, samples/dates with a ^{230}Th/^{232}Th ratio $<20 \times 10^{-6}$ were rejected from the age modelling (Tables S1 and S2 online). Details of the laboratory protocols and standards used are outlined in the Supplementary materials.

The dates were modelled using a kernel density estimate (KDE) distribution for all sampled units, including those that contained the tracks and from those located above and below the tracked horizon. KDE modelling is a hybrid Bayesian/frequentist approach that is used to estimate and graphically represent the underlying distributions of discrete data points [17]. In this study, KDE modelling was done using the KDE_Model function in OxCal 4.4.2, which employs a Markov Chain Monte Carlo (MCMC) implementation to generate an equal number of random samples from each of the events specified within the kernel probability distribution. The calibration component of OxCal was disabled allowing older dates to be modelled. We used the default values in OxCal for both the kernel and bandwidth estimates to evaluate the age distribution. In addition, the start and end boundary ages were determined using the Boundary function in OxCal.

2.2. Ichnological methods

Best practice as set out in Falkingham et al. [18] and Bennett and Budka [19] was followed. Three-dimensional models were captured using both OpenMVG (https://github.com/openMVG/openMVG) running as part of the freeware DigTrace (www.digtrace.co.uk) and Agisoft Metashape v.1.5.2 (https://www.agisoft.com). These models were also scaled and auto-rotated in DigTrace. Contour maps were exported from DigTrace into Adobe Illustrator (CS6) and colour rendered models were produced in CloudCompare (https://www.danielgm.net/cc). Landmarks were placed in DigTrace on 3D models and in the case of the modern hand data obtained from Hassanat et al. [20] ($N = 193$) on 2D images. Landmarks were subject to Generalized Procrustes Analysis (GPA) for removing aspects of size and the subsequent coordinates used in Principal Component Analysis (PCA) were optimized for geometric analysis within the software PAST v4.03 [21]. The methods by which track-maker ages were determined are outlined in the Supplementary materials.

3. Results

3.1. Ichnology

Five handprints and five footprints were recovered from a new locality at the site of Quesang on the Tibet Plateau (Figs. 1c and 2). Without prejudice to any final interpretation these traces are hereafter collectively referred to as the “art-panel” for ease of reference. The art-panel consists of four right footprints (+one superimposed left), and five handprints (Figs. 2 and 3a–d). The footprints have a mean size of 192.26 ± 5.35 mm (from heel to digit II; Table S3 online) and a minimum track-maker estimate gives a value of one [22]. The footprints resemble the ichnotaxa *Hominipes modernus* [23] (i.e., type example of modern human footprint morphology) and have dimensional ratios and morphology consistent

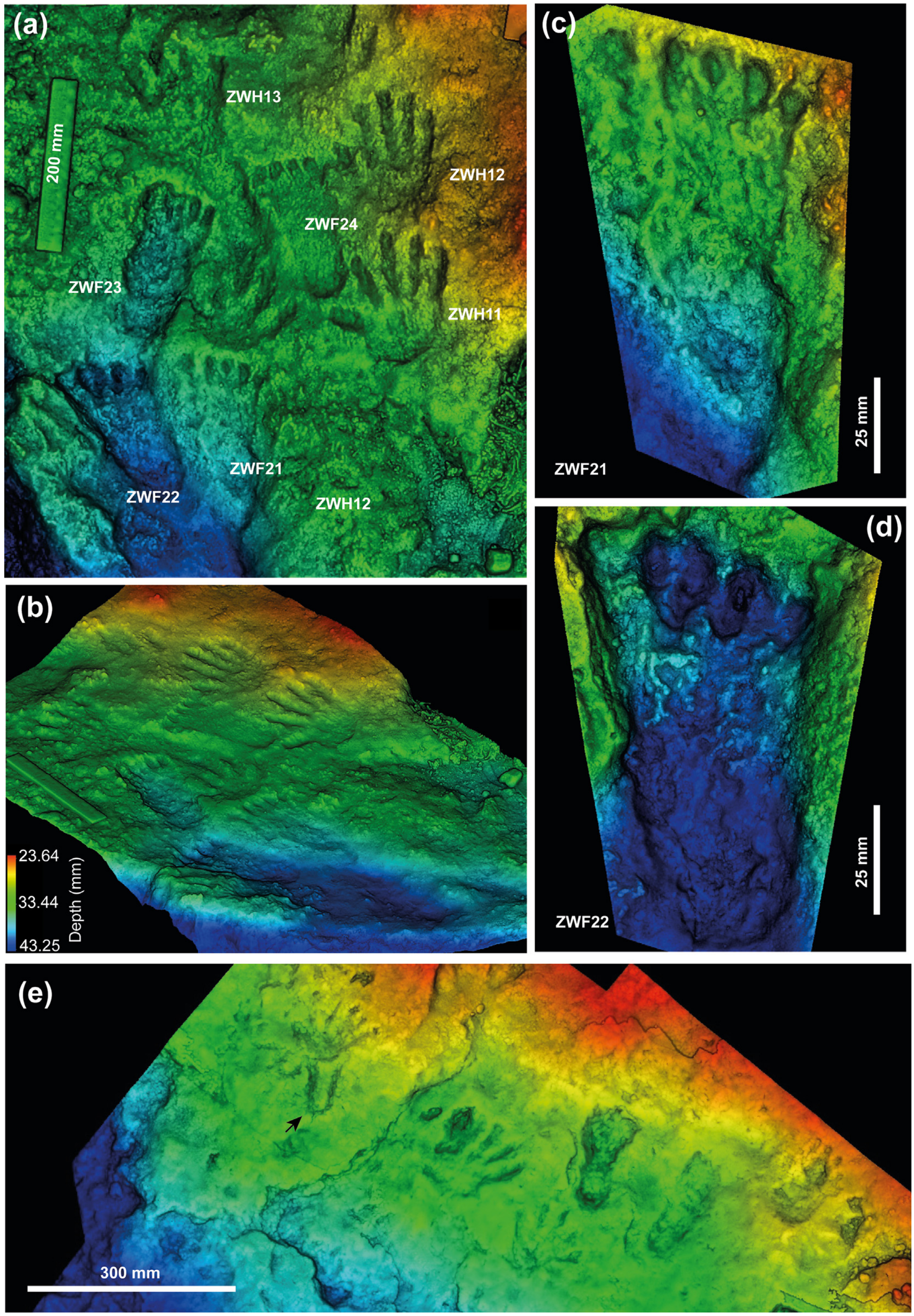

Fig. 3. Colour rendered 3D models of the parietal art-panels. (a) High resolution scan of the surface, note the plane has not been corrected to the orthogonal to minimise processing due to the size of this model. The 3D was created in Agisoft Metashape v.1.5.2 (https://www.agisoft.com). (b) Oblique image of the art-panel. (c, d) Close-up images of selected tracks. (e) Holocene tracks close to the current bathhouse at Quesang and interpreted here as an example of parietal art. Note the finger flute to the posterior of the handprint – arrowed.

with modern and fossil footprints from other sites (Fig. S6 online). A geometric morphometric comparison of tracks with a set of modern ($N = 356$) and fossil footprints from Namibia ($N = 78$) and White Sands National Park (USA; $N = 33$) show broad similarity (Fig. S6 online). The art-panel footprints plot in a similar space to those from White Sands. A growth curve [24] suggests that the track-maker was of equivalent size to a *Homo sapiens* child with a mean age of 7.75 ± 0.12 a (Table S3 online). Two right footed tracks (ZWF21 and ZWF22 in Fig. S2 online) are morphologically similar with a slightly divergent hallux, prominent lesser toe pads, and well-defined heels. The longitudinal medial arch is poorly developed, and the plantar surface is flat. These two tracks were used to compute an average morphology by co-registering and computing measures of central tendency (Fig. S7e online). The two other footprints present have slightly different morphologies. ZWF23 consists of a superimposed left and right feet (Fig. S8 online), while ZWF24 is more challenging to decipher with pronounced similarity in the distal toe lengths, resulting in an unusually straight front-edge to the track (Fig. 2). The toe pads are much smaller and more circular than those on adjacent tracks and may suggest vertical imprinting consistent with bunched or curled toes and rotations around the first and second toes. It is also possible that the track may have been augmented by the action of a finger in the soft mud.

The hand impressions are morphologically more varied although consistent with modern hand reference data [20] (Fig. S9 online). The length to width ratio of the hands falls within the modern range, although the fingers are more elongated. The average hand length is 161.07 ± 2.72 mm, which equates to a child with a mean age of 12.17 ± 0.18 a, using a modern *Homo sapiens* growth curve [24]. Other hand dimensions give a similar age estimate, except for the middle finger length which equates effectively to those of an adult (mean age = 17.15 ± 0.43 a). ZWH12 and ZWH14 do not have complete palm prints and consequently slippage leading to elongation of the fingers may have occurred. This is a less credible explanation in the case of ZWH11 and the finger dimension in ZWH13 and ZWH15 are less well defined. The trackmaker may have had long fingers and was also potentially older than the individual that made the feet impressions (Table S3 online). In the case of ZWH13 a forearm impression extends from the palm print and shows the evidence of movement (abduction–adduction) of the thumb during emplacement, creating a wider impression (Fig. 4). ZWH11 and ZWH14 may be a paired set of handprints (one right, one left) although ZWH14 has been deformed by the emplacement of ZWF21 and ZWF24 (Figs. 2–4).

Care appears to have been taken with the composition, and while some of the tracks crosscut each other they have clearly been positioned into the available space. The following sequential order is apparent (Fig. 4). The handprint and forearm (ZWH13) were imprinted first. The lesser toes of ZWF23 deformed the outline of the forearm, as do the medial toes of ZWF24. ZWH14 was imprinted after ZWF23, but before ZWF24. Note how the tip of the index finger of this trace was moved laterally by ZWF24. The thumb of ZWH12 infringed the medial toes of ZWF24 and therefore came next and with the digits of ZWH11 being spread thereby avoiding damage to ZWF24. ZWH14 was further deformed, by compression of the palm, by the placement of ZWF21. The medial toes of ZWF21 were compressed and show low relief curvilinear deformation ridges associated with the imprinting of ZWF22 (Fig. 4). ZWH15 appears to have been the final print, although the original slab may have extended further to the left.

3.2. Stratigraphy and geochronology

The art-panel occurs in one of four travertine units (I to IV) that make up the rocky promontory (Figs. 1b and S10 online). Unit IV forms the volume of the spur and was both weathered and eroded prior to the deposition of subsequent units. Locally travertine from unit III is seen to cement travertine breccia derived from unit IV, as well as colluvium and river gravels. Faulting, and associated minor mass movement of rock, occurred after the deposition of all four units, potentially resulting in the removal of the strata overlying the art-panel.

Dating of the art-panel relies on the fact that all the traces were imprinted in soft travertine and that modern field observations at the current hot spring indicate that diagenesis is one-directional and hardening of the rock is typically achieved in less than two years once the water supply is cut (Fig. 5). The age of the art-panel is therefore considered to be equivalent to the age of the travertine unit in which it was impressed. Although the art-panel was discovered without any overlying strata, unit II can be shown to be overlain laterally by unit I that provides a *terminus post quem* and underlain by unit III that provides the *terminus ante quem* (Figs. 6 and S11 online). Most of the travertine samples contain few impurities with little or no recrystallization and therefore can be used for the U/Th dating. Over 50 samples were taken, of which yielded 43 successful dates, although only 33 have ^{230}U/^{232}Th ratios in excess of 20×10^{-6} (Tables S1 and S2; Fig. S11 online). This threshold is used here as the minimum ratio for a reliable U/Th date and only dates with ratios above this threshold have been used in the age modelling (Fig. 6). Dates for unit II range from 185.7 ± 15.74 to 219.2 ± 10.5 ka BP. It should be noted that the rims from a handprint in art panel (ZWH15) are dated 187.7 ± 9.6 and 207.3 ± 9.4 ka BP respectively (ZWH15-1 and -2, Fig. S11 online). To determine the underlying distribution of discrete data points and provide a firm age range we applied the kernel density estimation (KDE) model (KDE_Model) function of OxCal 4.4.2 [17]. In addition, we used the Span and Boundary functions [17] to determine the start and end dates for this unit. The modelling results show that unit II has an age span of 153–215 ka BP at a 95.4% confidence level. Using the OxCal boundary function unit II has a youngest possible age for the *terminus post quem* boundary of ~169 ka BP and a maximum age for the *terminus ante quem* boundary of ~226 ka BP (Fig. 6).

Between the team's field visits in 2019 and 2020, part of the slab was damaged by persons or processes unknown. The damaged fragment was recovered however and found to tessellate with the damaged portion of the art-panel confirming its provenance (Fig. S12 online). The fragment contains two finger impressions of the ZWH15 print (Fig. 2). A face of this fragment was polished and dating samples were extracted using a drill (Fig. S12 online). Samples in the ridges pushed-up by the first and second digits yield dates of 187.7 ± 9.6 and 207.3 ± 9.4 ka BP. Taking together with this all suggests that unit II was deposited sometime between ~169 and ~226 ka BP and by association the art-panel dates from this interval.

4. Interpretation and discussion

Three basic questions arise from these observations. First, do the traces represent natural impressions as interpreted by the authors? Second, do these impressions constitute art? And finally, do the traces pre-date the Holocene and the currently accepted date [8] for permanent occupation of the Tibetan Plateau, although this date has been challenged [25]. We will take each of these questions in turn.

4.1. Natural impressions?

One essential question is whether the traces were imprinted into soft travertine or carved post-lithification. As experienced ichnologists [26] we openly favour the former interpretation, but given the potential implications of the discovery the alternative hypothesis needs to be considered carefully. Fig. 5a shows a series of three hand impressions made by the senior author in modern travertine close to the current hot spring in 2019. Note the: (1) consistent anatomical form and size of the impressions; (2) rim or push-up structures to posterior of the palm (Print-1, Fig. 5a) and sediment expulsion between the digits on all prints and along the lateral edge of the Print-1 (Fig. 5a); (3) a clear order/sequence

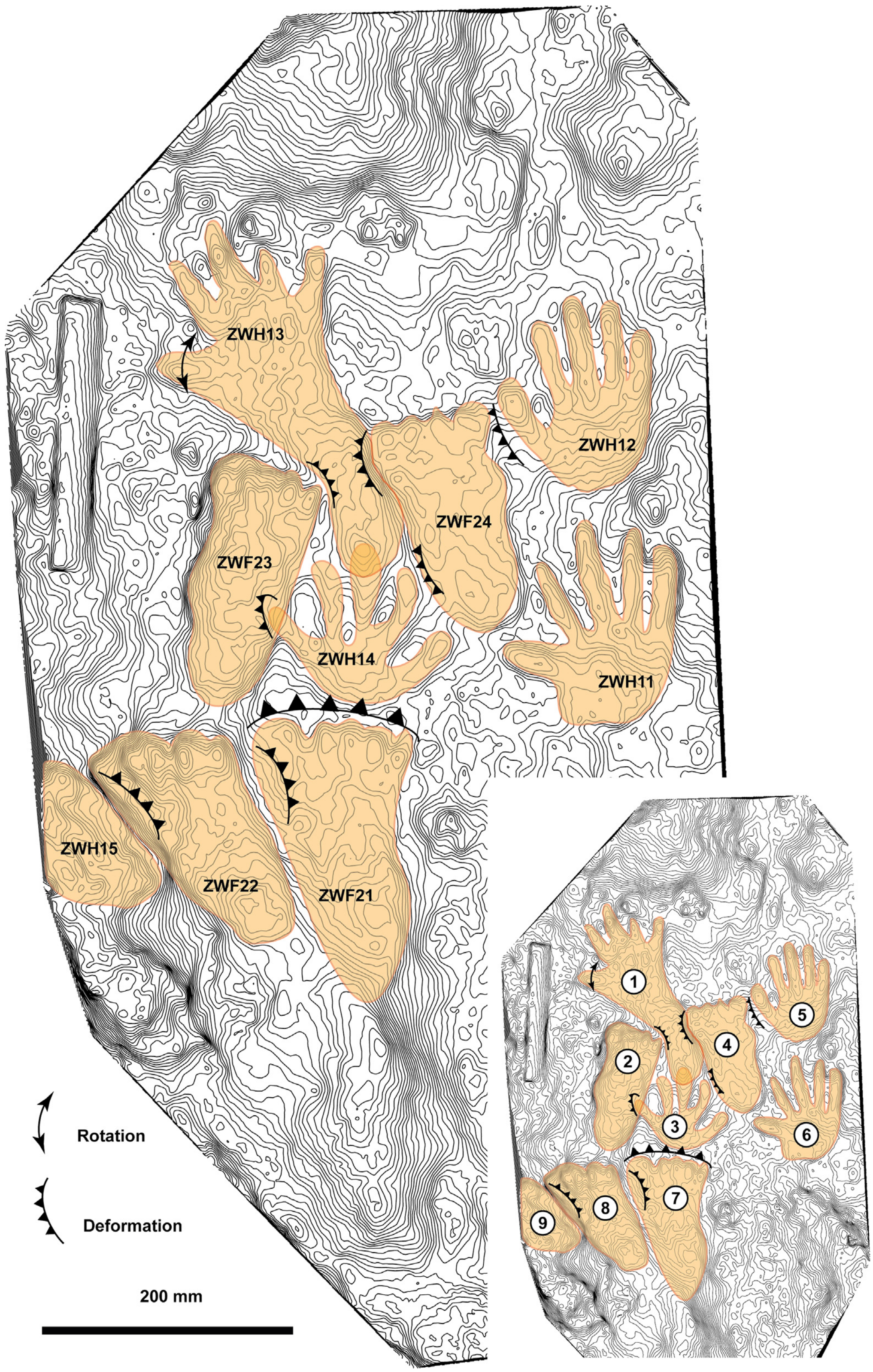

Fig. 4. Deformation and cross-cut track patterns with the art-plate. Contour map of the art-plate with 1 mm contour interval extracted from the 3D model using DigTrace and exported into Adobe Illustrator (CS6). Note the rotation of the thumb in the case of ZWH13 and the deformation between respective tracks. The forearm of ZWH13 is pinched by both ZWF23 and ZWF24. Also note how the medial heel of ZWF24 has caused the curved deformation of the index finger in ZWH14. Imprinting of ZWF21 has caused the deformation of ZWH14. The order of imprinting is shown in the inset.

to the impressions visible as the latest track impacts adjacent ones due to lateral sediment movement; (4) differential digit widths and depths associated with different digit pressures, plantar forces and lateral movement of digits; (5) contrast in surface texture between the smooth digits/palms and the surrounding area, exacerbated post-imprinting by the routing of water over the prints. Absent

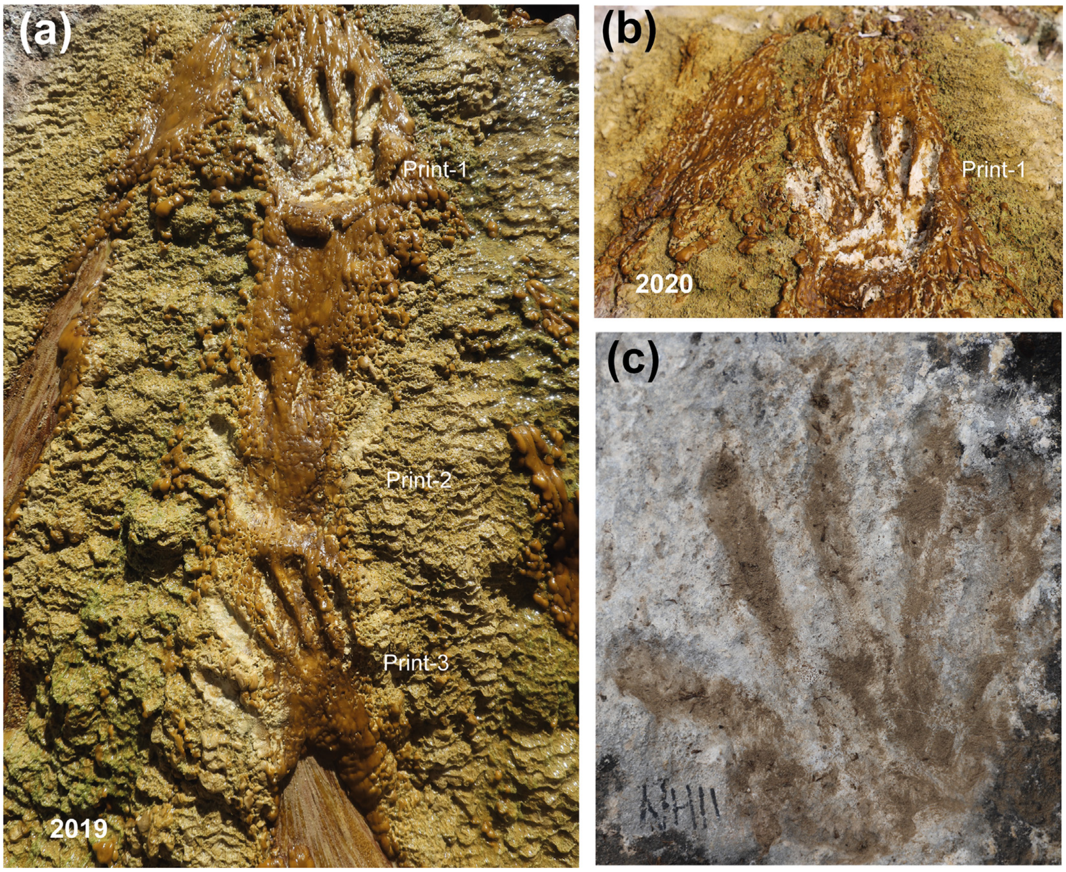

Fig. 5. Handprints modern and ancient at Quesang. (a) Active seep/stream below current hot spring with soft travertine in which the first author has placed three handprints in 2019. (b) Print-1 in 2020 showing a lithified handprint. Lithification occurred as soon as the water source was re-routed and is one directional. (c) Handprint ZWH11 from the art-panel. Note the lack of obvious percussion or other tool marks.

are: (6) percussion or other tool marks. These six criteria provide a critical test for the art-panel.

Anatomically, in terms of both shape and size the tracks of the art-panel are internally consistent and yield reasonable track-maker age estimates (i.e., they were not made by unusually sized humans). Track shape is consistent with other reference materials (Figs. S6 and S9 online), although the morphology of ZWF24 is atypical for a natural print and it would have required a complex set of foot movements to create the trace. Print ZWF23 also requires a double-step to explain the morphology. That is the track-maker made the initial impression with one foot and then placed the other foot in the same track aligning the heel and long axis of the track. The anatomy is more accurate, however, than the hand and foot motifs found at many petroglyph sites [27,28], although not at rock art sites where hand stencils have been used [29]. This is rather a weak point since one can always find a site or example to favour either version of this argument. Furthermore, caution is required since accurately carved foot motifs are common in the veneration of Muslim and Buddhist prophets [30]. Feet impressions at these shrines usually have good anatomical form, stereotypical depth variation, but crucially consist of adult feet and usually occur in pairs [31]. The evidence for imprinting based on anatomy alone is not conclusive and therefore subject to one's natural biases. The second and third criteria provide clearer evidence for imprinting, however. Push-up structures, cross-cutting patterns, and lateral deformation of one print by another are present as documented in Fig. 4. Why would these be included if the impressions were carved?

Additionally, the tracks of the art-panel vary in depth spatially with clear heel strike areas and greater depths associated with the medial digits, all of which is consistent with stereotypical patterns of plantar pressure [32]. Finger widths and depths vary as they do in the modern analogue handprints (Fig. 5a, b). The surface texture of the impressions is both smooth and compressed compared to the surrounding areas (Fig. 3a–d). This leaves the presence or absence of tool marks as a final criterion. Three rectilinear line-sets are visible on the art-panel (arrows, Fig. 2) and could represent chisel marks or other tool marks. They could also have occurred by normally joint controlled spalling. Isolated linear scratches of a few millimetres in width are present in a few locations but are not widespread and do not form patterns consistent with stone working. There is an absence of percussion marks, like those observed at travertine petroglyph sites [33] or similar to the experimental marks made by Bednarik [34]. Toe and finger pads are rounded and have smooth outlines (Fig. 3c).

Having applied the six criteria we believe that the most parsimonious explanation is that the art-panel was imprinted rather than carved. Furthermore, there is an existing consensus that the handprints and footprints previously found around the current bathhouse are natural imprints [7,8]. We would suggest that one of these sets of traces (Fig. 3e) is also an example of parietal art and includes an unreported example of finger fluting. There is no difference in morphology or surface texture to suggest one is natural and the other is not as a simple comparison of Fig. 3a, e shows. The area around the Holocene tracks is more polished however, which reflects the repeated touch of pilgrims.

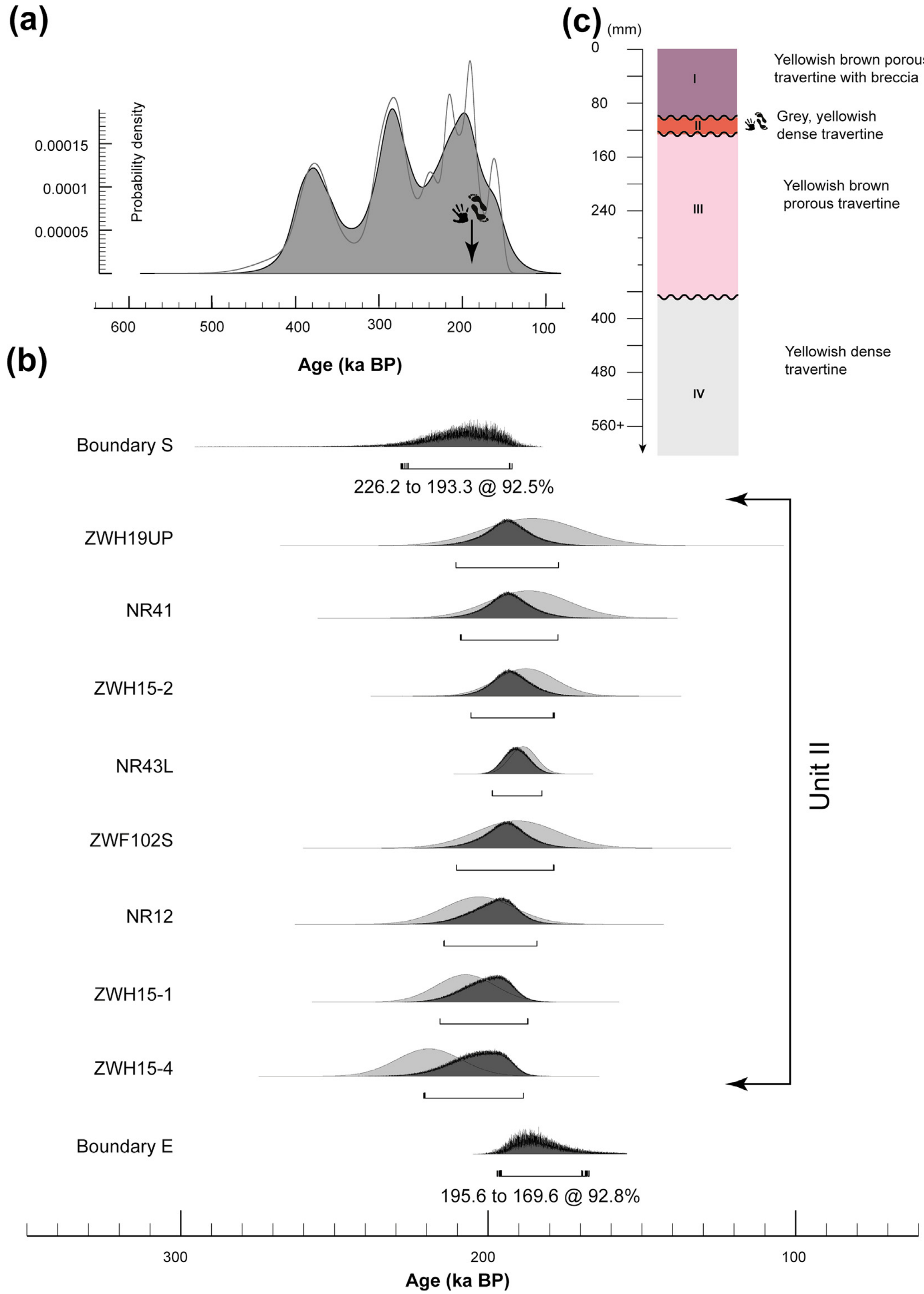

Fig. 6. Age modelling. (a) Kernel density estimate (KDE) modelling results for the U/Th dates with a $^{230}Th/^{232}Th$ ratio >20 × 10^{-6} in units I to IV (Tables S1 and S2 online). The dark grey distribution outlined in black is the KDE distribution. The light grey distribution is the sum distribution for reference. (b) The modelled start and end boundaries for unit II, the grey distributions are the date with errors and the dark grey distributions are the result of the MCMC modelling. Both plots were generated using the KDE_Model and Boundary functions in OxCal v.4.4.2 r:5 [1]. (c) Stratigraphic column of the travertine deposition of the site.

4.2. Is it art?

Defining what is art depends on the definition one applies [5]. Aristotle through the Greek concept *mimesis* (to mimic) provides us with a potential definition [35]. Here art is a copy of something else. Much of what is defined as art fits this definition up until the late nineteenth and early twentieth centuries when notable breaks occurred with the idea of imitative art. In the mimesis definition, the artist sees something and imitates it, notwithstanding any additional flourishes they might make. The Tibetan art-panel meets this basic criterion, but with its own flourishes. The placement of the prints is not as they would naturally occur, with tracks spaced by movement, or hands placed to stabilize [4]; rather, the artist has taken a form that was already known through lived experience (i.e., the artist presumably having seen their own footprints), and took that form (the footprint) and reproduced it in a context and pattern in which it would not normally appear. This is made even clearer by the addition of the handprints, which are not commonly seen in lived experience. In the context of parietal art, Crowther [6] states that art is not necessarily a revered object or image but items that form aesthetic configurations, whose style is original from the creator's viewpoint and thereby creates a distinctive kind of aesthetic unity. It is a definition that has echoes in that provided by Davies [36] where excellence of skill no doubt derived from Kant is highlighted, along with traditions of a genre and the intention of the maker that it should be received as art. Lewis-Williams, on the other hand, suggests that art was born of leisure with the simple aim of enjoyment, fun or decoration [1], the action of an idle or playful moment would fall under such a definition. Two children playing in the mud and intentionally creating a set of tessellated prints during an idle moment is what we probably have at Quesang and falls under most of the definitions of art outlined above. After all, most parents would describe their children's tentative artistic endeavours as art and proudly display them. Moreover, the art-panel falls into the artistic tradition of creating art via hand stencils, which is accepted as common examples of parietal art [37]. There is also an established tradition of children as Palaeolithic cave artists [38,39]. We therefore conclude that the composition of hand and foot traces described here constitutes "art" under a range of definitions, although given the range of possible definitions some might disagree.

4.3. Does it pre-date the Holocene?

Dating of the traces assumes that they are imprinted and relied on dating of the travertine unit in which they are imprinted (unit II) in the absence of an excavated overlying unit. While the lack of an excavated overlying unit is not ideal, this site would not be the first to be dated on the basis of the age of an imprinted layer [e.g., [4,40,41]]. Given that lithification is a one-directional process once the water source is removed (Fig. 5b), this is not an unreasonable assumption and suggests the art dates from between ~169 and 226 ka BP. It is also possible to demonstrate laterally what the overlying unit would have been, and this unit is younger in age (Figs. S10 and S11; Tables S1 and S2 online).

4.4. Implications

We conclude that on balance the art-panel consists of naturally imprinted hominin traces, meets a reasonable definition of parietal art, and is imprinted into travertine layers of the middle Pleistocene age. We therefore suggest that pending a fuller investigation of the whole site at Quesang the art-panel is likely an example of parietal art dating from the middle Pleistocene. If accepted, by the scientific community as a whole, this would significantly extend the age range of this type of artist endeavour. Currently the oldest art of this type, that includes hand motifs as hand stencils in cave paintings dated from around 40 ka BP in Sulawesi (Indonesia) [2] and at El Castillo (Spain) [3]. We are comparing different artistic endeavours here, but our point is that the use of body parts as artistic devices has a long tradition within our genus and the work reported here extends this.

Given the age of unit II the artists could have been *Homo sapiens* or perhaps more likely a Denisovan given that a Denisovan-like hominin has recently been found and dated (~160 ka BP) on the edge of the Tibetan Plateau (Baishiya Cave, 3200 m a.s.l.; Fig. 1a) [42]. Sun et al. [43] argued on the basis of DNA for the late arrival of *Homo sapiens* in China, which might also indicate a Denisovan track-maker according to the early age. It is worth to note that Denisovan-like DNA is carried by modern Tibetans [44]. If attributed to Denisovans then the appropriateness of the *Homo sapiens* growth model used to make the age estimates is open to question, although there is little to suggest in the (admittedly limited) body fossils currently available for Denisovans that they had a radically different body morph [45].

5. Conclusions

In conclusion, our study had resulted in two significant discoveries. Firstly, it provides evidence for the earliest known example of parietal art, dating to the middle Pleistocene. This adds to our understanding of the artistic repertoire of archaic hominins. Secondly, it provides evidence for the earliest known occupation (or visitation) of the Tibetan Plateau (>4000 m a.s.l.). Notwithstanding the possibility that the artists were children and therefore potentially at play, there is evidence of a deliberate attempt to create a careful composition, which we suggest is an act of artistic creation. The oldest parietal art is currently known from the Sulawesi region dating to 39.9 [40] and 43.9 ka [35] and is also the oldest known use of hand motifs. The evidence from Tibet clearly indicates an even older origin for the parietal art in the world and highlights the central role that hominin children may have played in artistic exploration and creation.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

David D. Zhang, Matthew R. Bennett, and Hai Cheng conceptualized and designed the study. David D. Zhang, Leibin Wang, Xiaoqing Wang, Yafeng Wang, Shengda Zhang and Dongju Zhang discovered the imprints and collected field data. Matthew R. Bennett, Sally C. Reynolds, Qing Pei, Cong Wang, and David D. Zhang performed the morphological analyses of the imprints. David D. Zhang, Leibin Wang, Xiaoqing Wang, Hai Cheng, Haiwei Zhang, Chunru Liu, Zhifeng Wu, and Teng Li carried out sampling and subsampling. Hai Cheng, Haiwei Zhang, R. Lawrence Edwards and Pu

Zhang, conducted U–Th dating and methods. Matthew R. Bennett completed the visualization. Matthew R. Bennett, Tommy Urban, and David D. Zhang wrote the original draft. Matthew R. Bennett, David D. Zhang, Sally C. Reynolds and Dongju Zhang reviewed and revised the manuscript.

Appendix A. Supplementary materials

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