Constraining the chronology and ecology of Late Acheulean and Middle Palaeolithic occupations at the margins of the monsoon

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South Asia hosts the world’s youngest Acheulean sites, with dated records typically restricted to subhumid landscapes. The Thar Desert marks a major adaptive boundary between monsoonal Asia to the east and the Saharo-Arabian desert belt to the west, making it a key threshold to examine patterns of hominin ecological adaptation and its impacts on patterns of behaviour, demography and dispersal. Here, we investigate Palaeolithic occupations at the western margin of the South Asian monsoon at Singi Talav, undertaking new chronometric, sedimentological and palaeoecological studies of Acheulean and Middle Palaeolithic occupation horizons. We constrain occupations of the site between 248 and 65 thousand years ago. This presents the first direct palaeoecological evidence for landscapes occupied by South Asian Acheulean-producing populations, most notably in the main occupation horizon dating to 177 thousand years ago. Our results illustrate the potential role of the Thar Desert as an ecological, and demographic, frontier to Palaeolithic populations.

Acheulean technologies, characterised by the production of large bifacial tools, particularly handaxes and cleavers, are found across Africa and western Eurasia, first appearing ca. 1.75 million years ago (ma) in eastern Africa1 and persisting until ca. 130 thousand years ago (ka)2. During this timeframe significant changes are observed amongst hominin populations, such as geographic expansions3–5, demographic differentiation6, and encephalisation7–9. By the time Acheulean technologies were finally abandoned, substantial demographic complexity is observed amongst Eurasian hominin populations10,11. This includes expanding populations of Homo sapiens12–14, Neanderthals in Europe and western/central Asia14–16, Denisovans in north/eastern Asia16,17, and late Homo erectus populations18, the small-bodied Homo floresiensis19 and Homo luzonensis20 in South East Asia. The hominin demography of South Asia is poorly resolved until the appearance of Homo sapiens in the fossil record ca. 39–48 ka21, despite its central geographic placement in contrast to the range of other recent Eurasian hominin populations. Only a single fossil provides evidence for the earlier occupants of the region—best described as a Middle Pleistocene Homo population that shares mosaic features with populations to the east and west, which is associated with Acheulean technology22,23. In the absence of fossils, the transition in use of Acheulean to Middle Palaeolithic technologies provides crucial insights in to current debate surrounding the appearance of Homo sapiens in South Asia and their replacement of earlier hominin populations.

The antiquity of Acheulean habitation in South Asia is clearly demonstrated by archaeological evidence from Attirampakam, dating to 1.2–1.8 ma24, and Isampur, dating to >1.2 ma25. The late persistence of the Acheulean in India and its replacement by Middle Palaeolithic technologies has only recently become a key focus of debate, however26. Acheulean technologies remain in use until ca. 212 ka in eastern Africa27,28 and ca. 190 ka in Arabia29,30, but the youngest Acheulean assemblages in the world are found at Patpara and Bamburi in the Middle Son Valley, India, dating between 140 and 120 ka. Significant behavioural changes are observed across much of Africa and western Eurasia between 300 and 200 ka with the appearance of Middle Stone Age and Middle...
Palaeolithic assemblages\textsuperscript{31–33}. Evidence across a range of sites and regions supports the appearance of Middle Palaeolithic technologies in South Asia considerably later, emerging from 114 ka onwards\textsuperscript{34–38}, although recent studies from south-east India has been proposed as the earliest global evidence for Middle Palaeolithic technology ca. 385 ka\textsuperscript{39}. South Asia, therefore, presents a key global region in which substantial overlap between the use of Acheulean and Middle Palaeolithic technologies occurred demanding examination of patterns of technological innovation, ecological adaptation, and their relationships to demographic structure over this timeframe.

Well-dated Acheulean sites remain sparse in South Asia, and are predominately located within the river basins of central and southern India (Fig. 1) where undated Acheulean sites are also abundant\textsuperscript{40,41}. Palaeoenvironmental evidence from these sites is typically absent, yet central and southern India both receive considerable monsoonal rainfall that are likely to have supported sub-humid environments in spite of climatic flux throughout the Pleistocene. Western India marks a boundary of the modern monsoon system, with a sharp cline in precipitation present from the Aravalli range into the semi-arid to arid landscapes of the Thar Desert (Fig. 1)\textsuperscript{42}. The presence of sand dunes well beyond the boundaries of the modern Thar Desert and into modern sub-humid zones signal the direct impact of palaeoclimatic flux on the region and its potential to disrupt habitability for Palaeolithic hominins\textsuperscript{43}. Acheulean occupation, typified by the presence of handaxes and cleavers alongside sparser retouched flake tools, is restricted to the margins of western India, and is predominantly associated with larger, persistent rivers\textsuperscript{44}. Meanwhile, Middle Palaeolithic occupation, characterised by the use of Levallois technology and retouched flake and point tool kits alongside sparse use of bifacial tools, is widespread across the region and includes dated sites present within the modern arid core of the Thar Desert (Fig. 1)\textsuperscript{44}. As a result, the transition from Acheulean to Middle Palaeolithic appears to mark not only a change in the practices of stone tool production but also to the range of environments in which they were deployed. Examination of sites at the margins of the monsoonal zone is therefore critical for evaluating environmental adaptability amongst South Asia’s Acheulean populations.

Here, we present the results of a new study of the Palaeolithic occupations at Singi Talav (27°23′24.2″N 74°33′10.9″E; Fig. 1), undertaken in mitigation of immediate threats from industrial activity at the site. The lake-margin site was extensively excavated in the 1980’s, with archaeological assemblages from the upper 1 m of deposits described as microlithic (Layer 1), Middle Palaeolithic (Layer 2), and Acheulean (Layers 3–5) occupations, overlying a deeper sequence of lacustrine sediments (Layers 6–11)\textsuperscript{45–48} (See SI1). The assemblages from
Layers 3–5 are best described\(^1\), although the limited description of core technologies limits the potential to explore trajectories of change and innovation within these assemblages and the overlying Middle Palaeolithic (Layer 2) horizon. The sediment sequence at Singi Talav has not previously been directly dated, although a connection has been made to Amarpura Quarry\(^6,3\) where experimental Electron Spin Resonance dating returned a notionally age estimate of 797 ka\(^5\) from a carbonate rich sequence (See SI2). However, given experimental issues with the sample concerned\(^5\), the absence of any demonstrable stratigraphic correlation over the ca. 2 km between sites\(^3\), and substantial topographic differences between them (Figure SI1), no direct correlation is tenable. We present the results of new sedimentological and palaeoecological studies at Singi Talav and directly date the artefact bearing horizons using Optically Stimulated Luminescence. We explore the implication of these results for examining patterns of behavioural change in Palaeolithic South Asia and their relationship to wider trends in Eurasian hominin demography and palaeoecology.

Results

**Sediment sequence.** We examined two newly exposed sediment sections at the Singi Talav locale (Fig. 2; see “Methods”), revealing a common stratigraphic sequence with previous investigations (see SI3). The first site, a 0.8 m deep section which we designated SGT6, is located in immediate proximity to previous excavations, where human and non-human activity have eroded the edges of previously excavated sections. Surface deposits at SGT6 comprise an upper aeolian sand containing sparse, soft, small carbonate nodules (Layer 1: 0–0.15 m) overlying a series of lacustrine deposits with distinct changes in frequency, size, induration and bridging of carbonate nodules present, alongside visible changes in sediment colour. The second deposit (Layer 2: 0.15–0.45 m) is a pale grey silty sand matrix preserving common, small, firm carbonate nodules, with a discrete artefact bearing horizon at 0.35 m, that is distinct from the underlying horizon (Layer 3: 0.45–0.55 m) based on the increased density, size and compaction of fine carbonate nodules, which also includes fresh lithic artefacts. Layer 4 (0.55–0.75 m) comprises a pale grey fine sand to silt horizon including more compact large carbonate nodules, with sparser artefacts throughout, overlying Layer 5 (0.75–0.8 m), a pinkish grey sandy silt rich in powdery calcite, fusing carbonate nodules and rarer fine ferric nodules, yielding a single lithic piece.

Stepwise changes in the frequency and form of carbonate nodules are apparent in the sediment section, and broadly match the average increase in carbonate presence in the fine sediment fraction, comprising 9.7% (Layer 1), 24.2% (Layer 2), 42.6% (Layer 3), 63.3% (Layer 4) and 71.5% (Layer 5). With the exception of Layer 1, a comparable stepwise increase in total organic components is observed ranging from 1.9% in Layer 2 to 3.5% in Layer 5. A linear relationship exists between magnetic susceptibility results and the combined presence of organic and carbonates within fine sediments, suggesting observed variability with depth relates to the size of mineral component of fine sediments, rather than a change in sediment source. Layers 1 and 2 show higher values for both Chemical Index of Alteration (CIA; mean = 14.66 and 11.6 respectively) and Weathering Index of Parker (WIP; mean = 17.21 and 13.17 respectively), with a sharp change to Layer 3 (CIA mean = 6.61; WIP mean = 7.13), with comparable values in Layers 4 and 5 (CIA mean = 9.57 and 7.49 respectively; WIP mean = 10.62 and 8.1 respectively). Layers 1–5 at SGT6 directly match descriptions of Layers 1–5 reported from previous research at the site, including characterisations of fine sediment grain size and proportional presence of CaCO\(_3\), enabling robust correlations between these sequences (see SI1 and SI3).

SGT7 is located 400 m west of the earlier excavation site, where a deeper sediment sequence was revealed to a maximum depth of 2.35 m, leading to the identification of eight discrete layers. While the uppermost five layers are more clearly comparable to the SGT6 sequence and previous excavations, the lower three layers show differing grain size characteristics, likely resulting from differential inputs from aeolian activity. At SGT7, we refer to Layers 1–5, providing a close match to SGT6 and previous excavations, and Layers 6*, 7*, and 8* in recognition that they are broadly comparable to these layers from previous excavations, but with some different features. Layer 1 (0–0.55 m) comprises an aeolian fine sand deposit, with very rare, fine carbonates, overlying Layer 2 (0.55–0.65 m) a reworked aeolian sand with more frequent carbonate nodules. A change in the size and frequency of carbonate nodules marks the transition to Layer 3 (0.65–1 m), and between Layers 4 (1–1.15 m) and 5 (1.15–1.6 m), along the concentrated presence of powdery calcrites in the latter. A sharp contact with Layer 6* (1.6–1.85 m) is identified, a mid-orangish brown silt with dense, firm and large, bridging carbonate nodules, overlying Layer 7* (1.85–2.05 m), and upward coarsening mid reddish-brown silt to sand. The lowest observed deposits (Layer 8*: 2.05–2.35 m) is an indurated dark reddish brown silty sand with indurated carbonates and fine ferric nodules. Stepped increases in the presence of calcium carbonate is observed between the top five layers, followed by high but fluctuating levels in the lower horizons. A more complex pattern is observed for total organic content, with distinct, high levels identified in Layer 3, alongside more muted peaks in Layer 5 and 6*. With the exception of Layer 1, CIA and WIP values show limited change throughout the sequence, and, as at SGT6, magnetic susceptibility results vary with respect to the mineral component of fine sediments, suggesting a single shared sediment source.

Both sites reflect key changes in the sediment sequence previously reported from the site. In particular, the transition to carbonate rich deposits starting with Layer 3 is clearly evident at both sites, reflected in both the macroscopic presence of carbonates, and changes in composition of fine sediments. The presence of dense, powdery calcrites in Layer 5 enables close comparisons between SGT6 and 7, as well as earlier excavations, constraining the key archaeological horizons at the site. Previous excavations highlighted discrete changes in sedimentation below Layer 5, and a comparable break is observed below Layer 5 at SGT7, though with some divergence with respect to the originally reported sequences, potentially representing lateral variability in broadly similar geomorphic contexts. Discrete, rather than continuous, changes in the sequences may suggest that sediment deposition at the site was pulsed, rather than continuous, and may reflect phases of enhanced monsoonal intensity, potentially complicated by the removal of unconsolidated fine sediment through aeolian erosion.
Luminescence dating. Luminescence samples were taken from Layers 2 (0.34 m), 4 (0.57 m) and 5 (0.78 m) at SGT6, and Layers 3 (0.77 m), 5 (1.26 m), 6* (1.63 m), 7* (1.91 m), and 8* (2.26 m) at SGT7. Ages were calculated from potassium feldspar signals and range between 65.14 ± 5.28 ka and 260.21 ± 20.14 ka, with key luminescence dating results presented in Table 1 and further detailed in Methods and SI.5. The three ages at SGT6 are stratigraphically consistent, and the measured luminescence signals have properties considered suitable for dating, which are within the saturation limit of the technique (see SI.3). We date Layer 2 to 65.14 ± 5.28 ka, Layer 4 to 176.67 ± 16.83 ka, and Layer 5 to 248.14 ± 26.75 ka.

At SGT7 ages vary between 85.27 ± 6.26 ka and 260.21 ± 20.14 ka and increase with depth for samples OSL-ST7-1 to -3. Like SGT6, the signals measured from samples from SGT7 meet luminescence screening criteria, although some individual signals appear to be in saturation (see SI.4). The very limited amount of material available for dating precluded the further testing of these samples or the use of alternative signals for verification (when tested, quartz signals were found to be in saturation). With regards to the apparent age inversion at the

Figure 2. Sediment sequences exposed at Singi Talav [SGT6 (top) and SGT7 (bottom)], synthesising (from left to right) results of geochronology, section photo, sediment log (illustrating the location of dating samples), identification of layers, grain size summary statistics, magnetic susceptibility, loss on ignition results differentiating between alternate organic components, and between total organics (TOC) and carbonates, geochemical weathering indices (CIA; WIP), results of stable isotope analyses on carbonate nodules, and phytolith analysis (for SGT7 only). Layers 6*, 7* and 8* at SGT7 are broadly comparable to previous reports, but we use this notation in identification of some minor differences, whereas all other layers provide a direct match to previous reports. See SI3 and SI6 for further description and datasets.
In contrast to C3 grass types, which were most prevalent in Layers 5 and 8*, C4 grass types dominate the vegetation record, making up at least 60% of the assemblage. The lowermost units, Layers 6–8*, contain 62–84% C4 types, with a peak at Layer 8* (84%). The highest proportion of C4 grasses is found in the lower deposits of Layer 5, suggesting an increase in woody vegetation, and lower levels observed associated with the upper deposits of Layer 3, which contains the lowest two units. Amongst C4 grasses, the *Panicoid* diagnostic types, with rarer occluded or patinated forms and poorer preservation of phytoliths, are particularly well represented in the lower levels, indicating a shift towards more woody vegetation.

### Table 1. Luminescence dating summary. All calculations made prior to rounding. For further data and details relating to the dating, see Methods and SI.

| Sample | Depth (m) | Equivalent dose (Gy) | Dose rate (Gy ka⁻¹) |
|--------|----------|----------------------|--------------------|
|        |          |                      | Alpha  | Beta  | Gamma | Cosmic | Total  | Age (ka) |
| ST6-1  | 0.34     | 188.96 ± 7.42        | 0.13 ± 0.05 | 1.72 ± 0.50 | 0.82 ± 0.05 | 0.23 ± 0.02 | 2.90 ± 0.24 | 65.14 ± 5.28 |
| ST6-2  | 0.57     | 406.16 ± 8.79        | 0.09 ± 0.03 | 1.41 ± 0.41 | 0.59 ± 0.04 | 0.21 ± 0.02 | 2.30 ± 0.22 | 176.67 ± 16.83 |
| ST6-3  | 0.78     | 485.6 ± 12.26        | 0.09 ± 0.03 | 1.19 ± 0.34 | 0.49 ± 0.03 | 0.19 ± 0.02 | 1.96 ± 0.21 | 248.14 ± 26.75 |
| ST7-1  | 0.77     | 285.65 ± 13.16       | 0.22 ± 0.08 | 1.90 ± 0.54 | 1.04 ± 0.07 | 0.19 ± 0.02 | 3.35 ± 0.25 | 85.27 ± 6.26 |
| ST7-2  | 1.26     | 754.34 ± 26.14       | 0.18 ± 0.06 | 1.89 ± 0.54 | 0.93 ± 0.06 | 0.18 ± 0.02 | 3.18 ± 0.24 | 237.44 ± 18.16 |
| ST7-3  | 1.63     | 823.83 ± 27.99       | 0.23 ± 0.08 | 1.77 ± 0.50 | 1.00 ± 0.07 | 0.17 ± 0.02 | 3.17 ± 0.25 | 260.21 ± 20.14 |
| ST7-5  | 2.26     | 683.39 ± 19.77       | 0.21 ± 0.08 | 1.70 ± 0.49 | 1.18 ± 0.08 | 0.16 ± 0.02 | 3.69 ± 0.26 | 185.20 ± 13.05 |

The phytolith record thus illuminates greater variability in floral communities than the stable carbon isotope record. This may partly be explained by the seasonality of warm and dry conditions required for carbonate formation within a monsoonal climate offering a partial, seasonally selective record of vegetation that provides a more detailed picture of the environment. The combination of phytoliths and stable isotope analysis provides a more comprehensive understanding of the palaeoenvironmental conditions at Singi Talav.
237.44 ± 18.16 ka from SGT7. The main archaeological sequence at Singi Talav overlies the date of Layer 6* from SGT7 of 260.21 ± 20.14 ka.

Discussion

Our results place Palaeolithic occupations at Singi Talav within a clear chronometric and ecological framework for the first time. Critically, our new luminescence ages directly date occupations at the site to ~ 248 ka, ~ 177 ka, ~ 85 ka and ~ 65 ka. The oldest major occupation identified at Singi Talav (Layer 5) significantly pre-dates comparable evidence from elsewhere in the Thar Desert region, and spans a timeframe in which no directly dated sites are known across South Asia, but is younger than dated Acheulean occupations at Sadab (ca.290 ka) and Teggihalli (ca. 287 ka) and Nevassa (> 350 ka) and Yedurwadi (> 350 ka), as well as the oldest Middle Palaeolithic occupation reported at Attirampakam. More intensive occupation of Singi Talav is attested to by the larger lithic assemblages from Layer 4, dating to early MIS 6 (~ 177 ka). This is contemporaneous to the presence of hominin activity at 16R Dune, and matched by evidence for Acheulean activity elsewhere in the Thar Desert (e.g. Junagadh [Adi Chadi Wao] & Umrethi; the Mahi, Orsang and Sabarmati Valleys) and across South Asia (e.g. Patpada and Bamburi; Bhimbetka; Kaldevanhalli-I) at the end of the Middle Pleistocene, alongside the reported presence of Middle Palaeolithic technology at Attirampakam. Layers 3 and 2 mark early Late Pleistocene occupation of the site, dating to ~ 85 ka and ~ 65 ka respectively, which are broadly coincident with Middle Palaeolithic occupations of the nearby sites of 16R Dune (80–40 ka) and Katoati (96–45 ka), as well as a range of Middle Palaeolithic sites across the Thar Desert and South Asia. Dating of the Palaeolithic occupations at Singi Talav, therefore, demonstrates the antiquity of inhabitation of western India and spans a critical timeframe for examining the Acheulean to Middle Palaeolithic transition across the subcontinent.

Layers 5–3 at Singi Talav have been attributed to the Acheulean (SI4), in part reflecting the acceptance of an Early Pleistocene chronology. The limited available description of the Layer 5 assemblage, its relatively small size, the prevalence of flaking debris, and scarcity of larger tools, are not directly diagnostic of Acheulean technology, but are consistent with such an attribution given their chrono-stratigraphic context. The Layer 4 assemblage contains a high proportion of handaxes (n = 18) and includes cleavers (n = 3) and other large cutting tools, with further evidence for a focus on bifacial reduction evident in the debitage assemblage, which are features consistent with contemporaneous Acheulean assemblages from across South Asia. Singi Talav Layer 4 clearly documents the late persistence of Acheulean technology in South Asia, here dating to 177 ka, post-dating the most recent Acheulean occupations of either Arabia and eastern Africa, making it one of the youngest Acheulean sites worldwide. The assemblage is also notable for the presence of a collection of six quartz crystals intentionally transported to the site with no clear utilitarian purpose and therefore mark the oldest dated non-utilitarian objects in the South Asian record at present. The Layer 3 assemblage includes a small number of handaxes (n = 3), but lacks other clear features that are directly diagnostic of Acheulean technology (e.g. the presence of cleavers), alongside a greater focus on core technology. An Acheulean occupation at Singi Talav at...
85 ka is consistent with recent models suggesting late continuity of Acheulean and substantial overlaps with the Middle Palaeolithic across Asia70. However, the sparse use of bifacial tools alongside greater focus on diverse core reduction technologies is now shown to be a consistent feature of the Thar Desert Middle Palaeolithic81, with the earliest Middle Palaeolithic occupations in the region appearing from 114 ka16. Further direct study of this assemblage is required to adequately resolve whether it presents a consistent character with other young Late Acheulean or older Middle Palaeolithic assemblages, or a mosaic of features indicating more complexity than presently documented for this cultural transition. This ambiguity prohibits assigning the Layer 3 assemblage as the youngest Acheulean in South Asia or the world.

Our research presents the first detailed study of lacustrine sedimentation in South Asia that extends into the Middle Pleistocene, including the first comparison of alternate palaeoecological proxies to contextualise Middle Pleistocene archaeological sites. Palaeoecological evidence for humid phases in the Thar Desert region has been largely restricted to Holocene and terminal Pleistocene lake records71–77, with broader palaeoenvironmental evidence available from Late Pleistocene fluvial sequences34,53,78–80. More limited evidence for Middle Pleistocene environments derive from studies of aeolian79,81,82 and fluvial83 activity, the chronology of which is exceeded by this study of Singi Talav. MIS 6 occupations at Singi Talav are, however, contemporaneous with evidence for fluvial activity in the central Thar Desert85. The presence of active lakes and rivers may have presented a substantially different structure of regional ecology and habitability for hominins in contrast to the modern constellation of plays and ephemeral or seasonal streams. The accretion of the upper 18 m of SW-NE linear dune over the past 187 ± 43 ka, exposed at 16R Dune81,84, demonstrates the potential for aeolian activity to disrupt such humid landscape features during the course of occupation of the site, and potentially separated Singi Talav from the larger, adjacent, Didwana lake during the Middle Pleistocene (Fig. 1c). Yet the phytolith and stable isotope records demonstrate that phases of lacustrine deposition at Singi Talav supported C₃ floras communities, which thrive under the seasonally hot, humid conditions promoted by a strong, summer monsoon regime. Wider evidence from across the Thar Desert supports a pattern of Palaeolithic occupation associated with comparable flora and associated with peaks in monsoonal intensity34,85. The accumulation of lake deposits and flourishing C₃ ecologies at Singi Talav spans both peaks and troughs in monsoonal intensity, including episodes of dissonance between Arabian Sea and Bay of Bengal records (Fig. 4). This highlights the importance of terrestrial records to resolve the environmental context of hominin occupations, and particularly in landscape characterised by significant flux, such as the monsoonal threshold in western India. Our study provides the first direct evidence from South Asia to demonstrate Acheulean populations directly engaged with landscapes at the margins of the monsoon.

Comparative studies of bifaces at multiple South Asian Acheulean sites have suggested a trend of increasing refinement (defined as the ratio of thickness to width) through time86. However, poorly refined bifaces from the final Middle Pleistocene occupations at Singi Talav confound this pattern. Preferential and invasive flaking of bifaces and bifacial cores, including piecemeal evidence for Levallois technology, is highlighted amongst the youngest Acheulean sites in South Asia86,87. Comparative artefacts appear to occur at Singi Talav (Figs. 3d, 5), further supporting recognition of one of the youngest Acheulean assemblages in the world. This may be indicative of broad changes in technological practice shared amongst late Acheulean populations, adaptations to the unique ecological challenges at the margins of the monsoon at Singi Talav, or a combination of both. The occurrence of young Acheulean occupations in west and central India contrasts with the recent report of an early Middle Palaeolithic88, with the earliest Middle Palaeolithic occupations in the region appearing from 114 ka16. Further direct study of this assemblage is required to adequately resolve whether it presents a consistent character with other young Late Acheulean or older Middle Palaeolithic assemblages, or a mosaic of features indicating more complexity than presently documented for this cultural transition. This ambiguity prohibits assigning the Layer 3 assemblage as the youngest Acheulean in South Asia or the world.

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The persistence of the Acheulean until the very end of the Middle Pleistocene in South Asia is remarkable and coincides with significant demographic and behavioural upheaval across Eurasia. The longevity of the Acheulean in South Asia is paralleled by the persistence of Homo erectus in Southeast Asia, the hominin typically associated with the initial spread of Acheulean technologies into Asia40. Genetic records for Denisovan populations also point to enduring patterns of demographic structure, with introgression from discrete Denisovan populations evident in modern populations suggesting distinct geographic distributions92,93. Modern South Asians preserve significant evidence for Denisovan introgression, in contrast to South West Asians94, raising the prospect that a Denisovan population inhabited South Asia during the timeframe of modern human expansions across Asia. Recent discoveries that suggest further demographic variability amongst late Middle Pleistocene Asian hominins complicate these issues further95. Regardless of which hominin populations produced Acheulean toolkits at Singi Talav at the end of the Middle Pleistocene, they had begun to engage with more marginal environments at the western edge of monsoonal Asia and the eastern edge of the Saharo-Arabian desert belt, a major biogeographic threshold96. Such ecological tenacity parallels records from South West Asia and eastern Africa, where the youngest Acheulean sites are found in the arid interior of Arabia or higher-altitude locations in the Ethiopian rift, at times when Middle Palaeolithic/Stone Age sites are found in less challenging settings, reflecting the enduring utility of Acheulean toolkits and adaptability of the hominin populations that used them. At Singi Talav this tenacity led to late survival of Acheulean technology, contemporaneous to the expansions of Homo sapiens into
South West Asia and immediately prior to their eastward dispersals across Asia. The biogeographic threshold between the Saharo-Arabian desert belt and monsoonal Asia encountered by eastward expanding populations would have been further accentuated by a stark behavioural, and potentially demographic, frontier at the onset of the Late Pleistocene, that may have hosted a range of interactions between distinct hominin groups.

**Methods**

**Fieldwork.** Fieldwork was conducted in June 2016, with the intervention at SGT6 undertaken within a 1×1 m square using hand tools, distinguishing between discrete sediment units and subdividing units into 10 cm levels where necessary to ensure controlled recovery of any artefacts, supported by sieving of excavated sediments through 5 mm mesh. Digging below 0.8 m was prohibited by the appearance of groundwater, relating to use of the old quarry as part of industrial activity at the site. The sediment sequence was sampled at 5 cm levels.
resolution for diverse sedimentological and palaeoenvironmental studies. Opaque metal tubes were hammered into the section wall to recover samples for luminescence dating. Following sampling, the intervention was backfilled. At SGT7, a mechanical digger was removing modern silt, relating to industrial activity, and was able to reveal a fresh section of the sediment deposits to the base of the modern sump/silt trap. This was monitored for the appearance of archaeological material, which was absent. The sediment sequence was sampled at 5 cm resolution for diverse sedimentological and palaeoenvironmental studies. Opaque metal tubes were again hammered into the section wall to recover samples for luminescence dating.

**LPSA:** Individual sediment samples (~10 g) were sieved to remove particles larger than 2 mm and bathed in 1% HCl for a minimum of 24 h in a water bath at 90 °C to fully evolve carbonates and disaggregate fine material. Purified water was added to the samples, which were then centrifuged at 3500 rpm for 13 min, with the excess liquid decanted off. Samples were agitated on a whirlmixer and subsampled for measurement using a Malvern Mastersizer 2000, selected from the centre of the resultant vortex. Summary statistics and sediment descriptions were produced using Gradistat96.

**Loss on ignition.** Fine sediment samples (~10 g; <2 mm) were weighed and heated in a muffle furnace to 105 °C, 400 °C, 480 °C, 550 °C and 950 °C for 6 h, allowing sediments to cool to 105 °C for weighing at each
interval and calculate the proportion of material lost from the dried (105 °C) sample at each interval relating to simple carbohydrates (400 °C), complex carbohydrates (480 °C), carbon (550 °C) and carbonate (950 °C) (following 27–29). The remaining sample constitutes the total mineral residue, with total organic carbon comprising all material lost between 105 and 550 °C 100.

Constrained hierarchical clustering. The mean, sorting, skew and kurtosis of fine sediment fractions and the proportions of organic and carbonate fractions resulting from Loss on Ignition (see SI6 for data) were analysed using chisel function of rija package 101 in R 102, as an aid to resolve patterns of stratigraphic continuity. These results, combined with field observations on sediment colour, texture and composition (including macroscopic features such as size and density of carbonate nodules), were used to resolve between sediment units, correlate stratigraphic sections between SGT6 and SGT7, and identify corresponding layers from earlier excavations.

Magnetic susceptibility. Magnetic susceptibility was measured in the laboratory using a Bartlington MS3 magnetic susceptibility meter coupled with the MS3B sensor to analyse 10 cm³ samples in plastic pots, weighed on precision scales to enable calculation of mass specific values following drying at 105 °C. Both high (4.6 kHz; HF) and low (0.46 kHz; LF) frequency magnetic susceptibility was recorded, enabling calculation of the percentage frequency dependant susceptibility (FD%). We identified a linear relationship between LF magnetic susceptibility values and the proportion of mineral residue from each sample, indicating that changing values in magnetic susceptibility values correspond to the non-mineral component of sediment samples, rather than a change in sediment source.

ICP-OES. One cubic centimetre sediment samples were fully evolved in aqua regia in water baths at 90 °C. Sub-samples of the resulting supernatant were then analysed using a Perkin-Elmer ICP-OES, undertaking three replicate measurements and producing a mean concentration in ppm (mg/l) and relative standard deviation (%RSD). The Weathering Index of Parker  (WIP103) was calculated using molar weights of each element as oxides according to the formula: 100 × (2Na₂O/0.35 + MgO/0.9 + 2K₂O/0.25 + CaO/0.7). The Chemical Index of Alteration (CIA104) was calculated using molar weights of each element as oxides according to the formula: Al₂O₃/(Al₂O₃ + CaO + Na₂O + K₂O) × 100.

Stable isotope analysis. Pedogenic carbonates were analysed for their stable carbon (δ¹³C) and oxygen (δ¹⁸O) isotope values from throughout the SGT6 and SGT7 sequences. The rhizomorphs and nodules selected from excavated strata were analogous to both those observed in deflated contexts on the playa surface and in the surrounding dune fields at Singi Talav stand in stark contrast to either powdery calcrites or hardpan calcrites observed elsewhere across the landscape. Up to ten individual carbonates were sampled for each level where available, amalgamated together to form a single sample in each case following Blinkhorn and colleagues104.

Every sample of pedogenic carbonate was subjected to an ethanol rinse in order to remove any sediments stuck to the nodule prior to crushing using an agate pestle and mortar. The samples were then dried for 24 h at 40 °C before being placed into borosilicate vials. The vials were flush/filled with helium at 100 ml/min for 10 min. After reaction with 100% phosphoric acid, δ¹³C and δ¹⁸O measurements were performed on the evolved gases using a Thermo Gas Bench 2 connected to a Thermo Delta V Advantage Mass Spectrometer in the Stable Isotope Laboratory of the Department of Archaeology, Max Planck Institute for the Science of Human History. δ¹³C and δ¹⁸O values were compared against those measured for international reference standards (IAEA NBS 18: δ¹³C = 0.032 ‰, IAEA 603: δ¹³C = 0.01 ‰, IAEA CO8: δ¹³C = 0.032 ‰, USGS44: δ¹³C = 0.032 ‰, δ¹⁸O = 0.0 ‰) and the proportions of organic and carbonate fractions resulting from Loss on Ignition (see SI6 for data) were analysed using chisel function of rija package 101 in R 102, as an aid to resolve patterns of stratigraphic continuity. These results, combined with field observations on sediment colour, texture and composition (including macroscopic features such as size and density of carbonate nodules), were used to resolve between sediment units, correlate stratigraphic sections between SGT6 and SGT7, and identify corresponding layers from earlier excavations.

Phytolith analysis. Phytolith analysis was conducted by Dr. Sanjay Eksambekar, Phytolith Research Institute (PRI), Pune, India. Phytolith extraction was undertaken in the laboratory with removal of carbonates and nitrates followed by heavy density separation 105. Up to 300 phytoliths were observed and counted using an Olympus research microscope with photomicrographs taken using 45X magnification, alongside observations of morphology and preservation. Classifications follow Twiss106 and Eksambekar107 and were made with reference to the extensive South Asian phytolith database at the PRI.

Luminescence dating. Samples for luminescence dating were collected by hammering opaque tubes into cleaned sediment faces and were opened and prepared under subdued orange light conditions at the Oxford Luminescence Dating laboratory. Laboratory treatment followed standard procedures (e.g. 34) to isolate potassium rich feldspar grains for measurement. Elevated temperature post infrared infrared signals measured from very small aliquots (1 mm diameter) of sand-sized grains were used for equivalent dose measurement, and dose rates were derived from radionuclide concentrations determined via inductively coupled plasma mass spectrometry. Final age calculation was undertaken using DRAC108. The luminescence dating is discussed in fuller detail in the supplementary information.
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J.B. and H.A. conducted the fieldwork, laboratory analyses were conducted by J.B., J.D., P.R., J.I., and all authors wrote and reviewed the manuscript.

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Competing interests

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Additional information

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