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A geoarchaeological timeline of India

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ABSTRACT

In the last decade, the growing interest in understanding the long-term human-environment interaction and its enduring impact on Earth systems has drawn scientists from around the world into multidisciplinary studies, including geology, archaeology, palaeoclimatology and palaeoecology. With the current trend towards understanding the roots of human impact on the landscape, the 'Anthropocene', and the complexities within the geosphere, biosphere and hydrosphere, it is high time to link geological, climatological and archaeological events at regional and global scales to human history, and therefore to introduce a first of its kind geoarchaeological timeline. Here we present a comprehensive geoarchaeological timeline that aligns major archaeological technological innovations and historical events in India with the geological timescale provided by the International Commission on Stratigraphy. This timeline will be crucial for understanding critical periods in India's history and for guiding current and future research on human-environment interactions, particularly in navigating the Anthropocene crisis. This timeline should be regularly updated as new knowledge is gained from future studies.

1. Introduction

Understanding the complex interplay between geological epochs and archaeological cultures is crucial to advancing our knowledge of human-environment interactions (Steffen et al., 2016; Jha et al., 2020, 2024a; Roberts et al., 2024). Interdisciplinary work between archaeology and geology began as early as the 1830s, a time when such collaboration was rare (Beuzen-Waller et al., 2018). For example, Boucher de Crèvecoeur de Perthes's 1837 research in the French Somme Valley emphasised the importance of correlating artefacts within geological strata (Beuzen-Waller et al., 2018). This approach was later extended by the geologist Charles Lyell, who published *Geological Evidences of the Antiquity of Man*, emphasising the fundamental role of geology in the study of early human history (Rapp and Hill, 2006). Therefore, the development of a combined timescale that integrates the geological and archaeological record is a fundamental tool for researchers to understand human-environment interactions during the Quaternary period (~2.58 Ma to present). This approach also allows for a more comprehensive understanding of how human evolution has shaped, and been shaped by, the Quaternary climate and landscape (e.g., Williams and Royce, 1982; Acharyya and Basu, 1993; Rajaguru et al., 1997; Ambrose, 1998; Petraglia et al., 2007, 2012; Chakrabarti, 2009; Williams et al., 2009; Patnaik et al., 2009; Clarkson et al., 2020; Dennell, 2023; Tiwari et al., 2023; Jha et al., 2020, 2021 2024a, 2024b; Bates et al., 2025; Jha et al., 2025).

The necessity of combining geological and archaeological timelines lies in the need to construct a unified framework that can accurately reflect the dynamic interactions between natural events and human activities (Chakrabarti, 2009). The Quaternary geological records, marked by significant epochs and events (Cohen and Gibbard, 2019; Cohen et al., 2024), provide a chronological backbone against which archaeological evidence of human activities, technological advancements, and societal changes can be marked and mapped (Rajaguru and Mishra, 1997; Chakrabarti, 2009; Singh, 2009; Jha et al., 2020, 2021, 2024a; Bates et al., 2025; Vaishnav et al., 2025a, b; Tiwari et al., 2023). By reviewing archaeological literature published since 1800s with the geological timescale provided by the International Commission on Stratigraphy (ICS; Cohen and Gibbard, 2019; Cohen et al., 2024), researchers can construct a detailed timeline that highlights the major geological events, technological adaptations and advancement of human societies over time.

This integrated framework is vital for several reasons. Firstly, it

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elucidates the timing and nature of human responses to environmental changes, enhancing our spatio-temporal understanding of past human-environment interactions. For example, aligning periods of climatic shifts with archaeological evidence of technological innovation or societal restructuring can reveal how ancient populations adapted to and survived environmental stresses (Jha et al., 2020, 2021, 2024a; Bates et al., 2025). Secondly, it helps identifying patterns of human adaptation and resilience in the face of climatic and environmental shifts, providing valuable insights for contemporary environmental and social challenges (Behrensmeyer, 2006; Petraglia et al., 2007; Jha et al., 2020; Timmermann et al., 2022). Understanding these patterns can inform current strategies to address similar challenges posed by climate change and environmental degradation (Braje, 2015; Roberts et al., 2024). Therefore, here we undertake a narrative review with chronological synthesis, collating archaeologically dated discoveries and integrating them with geological and climatological condition of the last 2.6 Ma in India (Fig. 1). Rather than a systematic or scoping review, our approach emphasises the creation of first of its kind "Geoarchaeological Timeline of India" (Fig. 2), providing a comprehensive chronological framework that aligns archaeological events with Earth system processes.

2. Data and methods

We compiled geoarchaeological information through a structured literature review of excavation, survey, geochemical, and geochronological studies published since 1800s. Primary sources included the *Archaeological Survey of India (ASI) reports*, JSTOR, and Google Scholar. Searches were carried out using targeted keyword combinations such as: *Indian Palaeolithic, Indian Archaeology, Indian Acheulean, Late Acheulean, Dated Palaeolithic sites, OSL dating in Indian Archaeology, AMS* ^{14}C *dating of Indian archaeological sites, South Asian archaeology, Palaeoclimate of the Indian Quaternary, Past environments of archaeological sites in India, Geochronology of archaeological sites, Microlithic sites of South Asia, Indus Valley sites, Geochemical data from archaeological sites, Diet of past populations in India, Evidence of fire in South Asia, Urbanisation of South Asia, History of India, Historical timeline of colonialism in India, and Environmental history of India.*

For each publication retrieved, we also applied a snowballing strategy, consulting its reference list to identify earlier relevant studies (backward snowballing) and using citation tracking to locate more recent works that cited it (forward snowballing). The collected records were organised into a database of well-dated archaeological and geological events, which was then arranged in a chronological framework to construct the "First Geoarchaeological Timeline of India".

3. Oldowan and Palaeolithic phases

The stratigraphy of the Masol Formation (Siwalik Frontal Range, India) is contemporaneous with the Late Pliocene Tatrot Member of the Upper Siwalik, as confirmed by magnetostratigraphic studies (Rao, 1993; Rao et al., 1995). This formation was deposited during the Gauss chron, before 2.58 million years ago (Ma) (Gradstein et al., 2004). Consequently, the Quranwala Fossil Zone (QZ) (Sahni and Khan, 1964), located in the lower part of the Masol Formation, is older than 2.58 Ma, with fossils indicating the Late Pliocene Tatrot (See location in Fig. 1).

The lithostratigraphy of the assemblage and the techno-typology of the first flakes recovered from the deepest fossil layer (older than 2.6 Ma, as shown by magnetostratigraphy) were described and

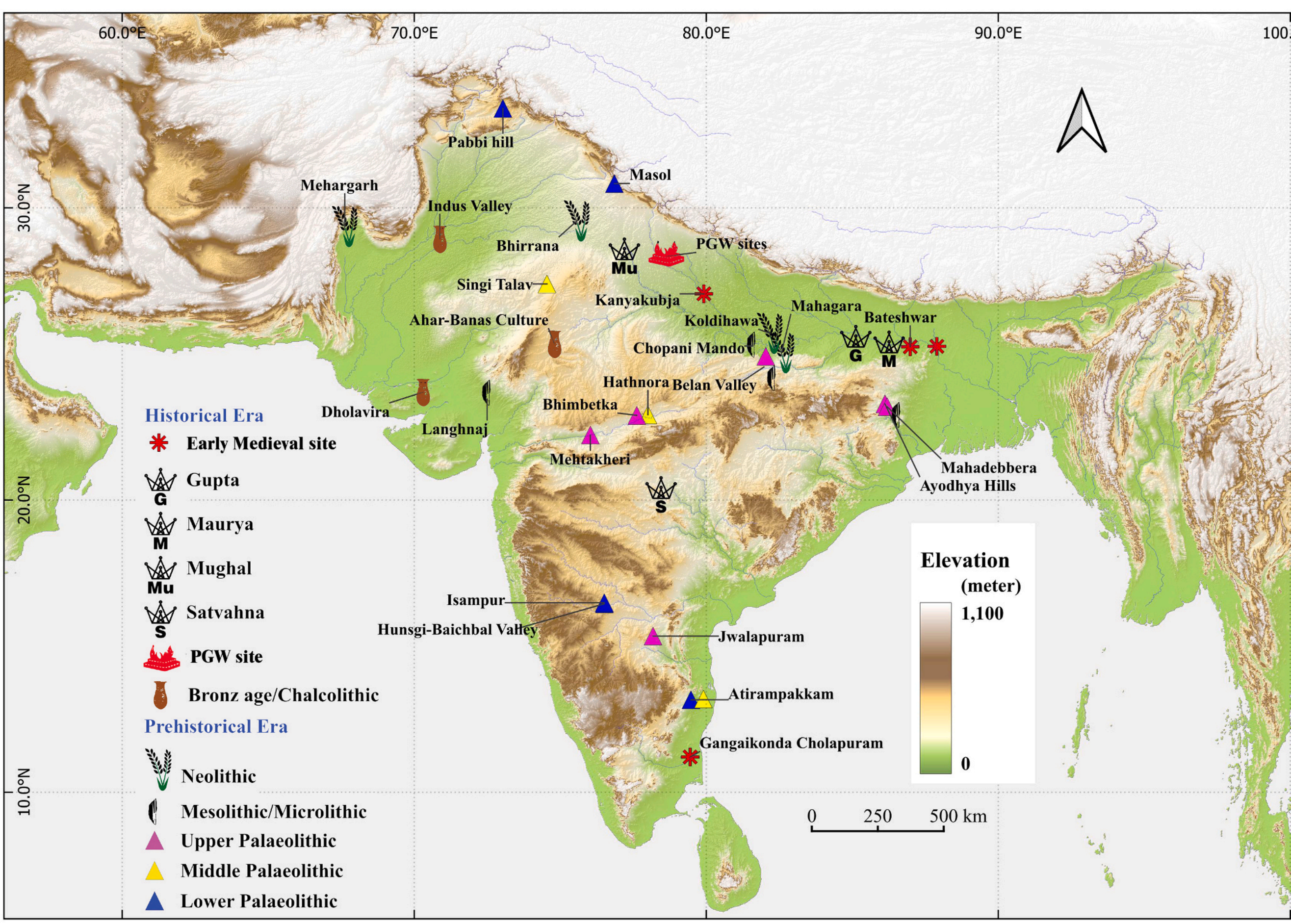

Fig. 1. Spatial distribution of major dated archaeological/historical sites in India and region mentioned in Geoarchaeological Timeline.

compared with assemblages from the Masol and other major palaeontological and archaeological sites (Cauche et al., 2021; Dennell, 2023). The characteristics of the Masol lithic assemblage differ from the Early Lower Pleistocene African Oldowan (2.55 Ma), but are similar to the Chinese lithic industry of Longgupo (2.5 Ma). These results provide new insights into the phylogenetic and geographic origins of these Asian hominins and their descendants, and support the need for further surveys and test excavations in the QZ (Cauche et al., 2021).

A new magnetostratigraphic study was conducted to refine the dating of cut marks on fossil bones found in the QZ (Chapon Sao et al., 2024). The study confirmed detrital haematite as the main magnetic host and placed the entire Masol Formation within the Gauss chron, with the Gauss-Matuyama reversal occurring outside the study area. A magnetic excursion at the base of the QZ was compared with others dated between 2.62 and 2.95 Ma. This, together with sedimentation rates, suggests that the cut marks on the bones date between 2.68 and 2.95 Ma, representing the oldest known evidence of intentional hominin activity in Asia (Figs. 1 and 2).

A significant example of geoarchaeological study in India comes from Attirampakkam (ATM) archaeological sites, Tamil Nadu, where palaeomagnetic measurements and direct $^{26}Al/^{10}Be$ burial dating of stone artifacts now place the earliest Acheulian levels at no younger than 1.07 Ma, with a pooled average age of 1.51 ± 0.07 Ma (Pappu et al., 2011). These results reveal that during the Early Pleistocene, India was already occupied by hominins proficient in Acheulian technology, including the preparation and use of heavy duty tools. Additionally, post-infrared (pIR) stimulated luminescence (pIR-IRSL) dating at the stratified prehistoric site of Attirampakkam has shown that processes signifying the end of the Acheulian culture and the emergence of a Middle Palaeolithic culture occurred at 385 ± 64 ka (Akhilesh et al., 2018), a timeline much earlier than what used to be conventionally presumed for South Asia. The Middle Palaeolithic continued at Attirampakkam until 172 ± 41 ka. Chronologies of Middle Palaeolithic technologies in regions distant from Africa and Europe are crucial for testing theories about the origins and early evolution of these cultures, understanding their association with modern humans or archaic hominins, their links with preceding Acheulian cultures, and the spread of Levallois lithic technologies (Akhilesh et al., 2018).

The 1982 discovery of the Narmada Man, a fossilised skullcap from the Narmada Valley in central India by geologist Arun Sonakia, is among the few hominin fossils found in the Indian subcontinent, shedding light on prehistoric human populations in the region (Sonakia, 1984). Estimated to be between 250 and 125 ka (Patnaik et al., 2009), its classification is debated: some researchers identify it as *Homo erectus*, while others suggest it could be an early form of *Homo sapiens* or a transitional species. The skullcap exhibits a blend of archaic features, such as thick cranial bones and a prominent brow ridge, along with modern traits like a higher cranial vault, underlining the complexity of the process of human evolution. The Narmada calvaria is probably best classified as *Homo sp. indet.* (Athreya, 2007; Fig. 2) until more diagnostic specimens are recovered. The Narmada Man provides crucial evidence for understanding early human migration and evolution in South Asia, suggesting that the Indian subcontinent was inhabited by hominins who may have interacted with populations from both Africa and Southeast Asia. Overall, the Narmada Man enhances our knowledge of the diverse and intricate evolutionary history of early humans in South Asia and specifically in India (Fig. 1).

Blinkhorn et al. (2021) conducted an investigation unveiling Palaeolithic occupations along the western margin of the South Asian monsoon at Singi Talav, Thar Desert. Their study introduces fresh chronometric, sedimentological, and palaeoecological analyses of Acheulean and Middle Palaeolithic occupation layers. The research delineates the occupation timeframe of the site to be between 248 and 65 ka, presenting the direct palaeoecological evidence of landscapes inhabited by South Asia's youngest Acheulean-producing populations. Notably, the primary occupation horizon, dating to approximately 177 ka, stands out in this regard.

Around 74 ka, the Toba super-eruption blanketed parts of the Indian subcontinent with a layer of volcanic ash known as the Youngest Toba Tuff (YTT) (Williams and Royce, 1982; Acharyya and Basu, 1993; Ambrose, 1998; Petraglia et al., 2007, 2012; Williams et al., 2009; Jones, 2010; Haslam et al., 2010; Biswas et al., 2013; Korisettar, 2014). The event has been considered cataclysmic, which left an indelible mark on the region's landscape and its ancient inhabitants. In the Jurreru Valley of southern India and the Belan and Middle Son valleys in north-central India, researchers have uncovered clues about the climate and vegetation during this period. Evidence points to a rise in C_4 plants, which thrive in arid conditions, suggesting a shift towards a drier climate (Petraglia et al., 2007, 2012; Jones, 2010; Korisettar, 2014: ; Jha et al., 2020; Jha et al., 2025).

The Middle Son Valley holds particular significance due to the discovery of Middle Palaeolithic artifacts within the YTT deposits. These artifacts, found in association with the ash layer, indicate that hominins occupied the area both before and after the eruption, demonstrating remarkable resilience and continuity (Acharyya and Basu, 1993). Similarly, the Jwalapuram site in the Jurreru Valley revealed an extensive collection of Middle Palaeolithic tools above and below the YTT layer, further supporting the notion of demographic stability in the wake of the eruption (Petraglia et al., 2007).

Further north, at the Dhaba site in the Middle Son River Valley, researchers have uncovered evidence of a long-term human presence spanning approximately 80 ka. The Dhaba lithic industry, characterised by its unchanging stone tool technology, persisted through the Toba eruption. These tools bear a striking resemblance to those from the African Middle Stone Age, Arabia, and early Australian sites, hinting at a shared technological heritage among early *Homo sapiens* as they migrated eastward out of Africa (Clarkson et al., 2020).

The recent study by Jha et al. (2020) on the Late Quaternary climate and vegetational history of north-central India provides significant insights into the interaction between climate and human activities in the Belan Valley from the Palaeolithic to the Neolithic periods. The research highlights those climatic fluctuations were major drivers of human settlement patterns, with phases of intensified monsoon and arid conditions aligning with shifts in population density and migrations. Two prominent humid phases, around 100–75 ka and 18–3 ka, facilitated human settlement, while the Last Glacial Maximum (25–18 ka) marked a period of aridity and reduced archaeological activity. The study also reveals a dominance of C_4 plants in a mixed C_3-C_4 environment between 75 and 25 ka, transitioning to C_3 vegetation, such as rice, with increased monsoonal rainfall during the early Holocene. This shift in vegetation reflects changes in resource availability that likely influenced human subsistence strategies. Furthermore, Jha et al. (2021) provided the first plausible evidence of the controlled use of fire by the Middle Palaeolithic population of the Belan Valley, India. Later, the use of GIS-based maps (geology, geomorphology, rainfall, and biomes) and the distribution of archaeological sites with different typo-technologies in the Ganga Basin reflected early inhabitants' preference for resource-rich environments (Jha et al., 2024a). During the Palaeolithic phase, older alluvial plains and higher hills with abundant rocks were preferred for tool-making, while later, prehistoric humans shifted to the fertile Ganga Plain due to its plentiful water, vegetation, and food resources, making it both environmentally and geologically advantageous for settlements (Jha et al., 2024a). The discoveries at these sites (e.g., Dhaba and Belan Valley) suggest that early human groups in the region responded to environmental fluctuations primarily through flexible mobility strategies, rather than through significant innovations in settlement or subsistence systems.

4. Transition from Palaeolithic to Microlithic / Mesolithic phases

The uninterrupted presence of microblade technology alongside

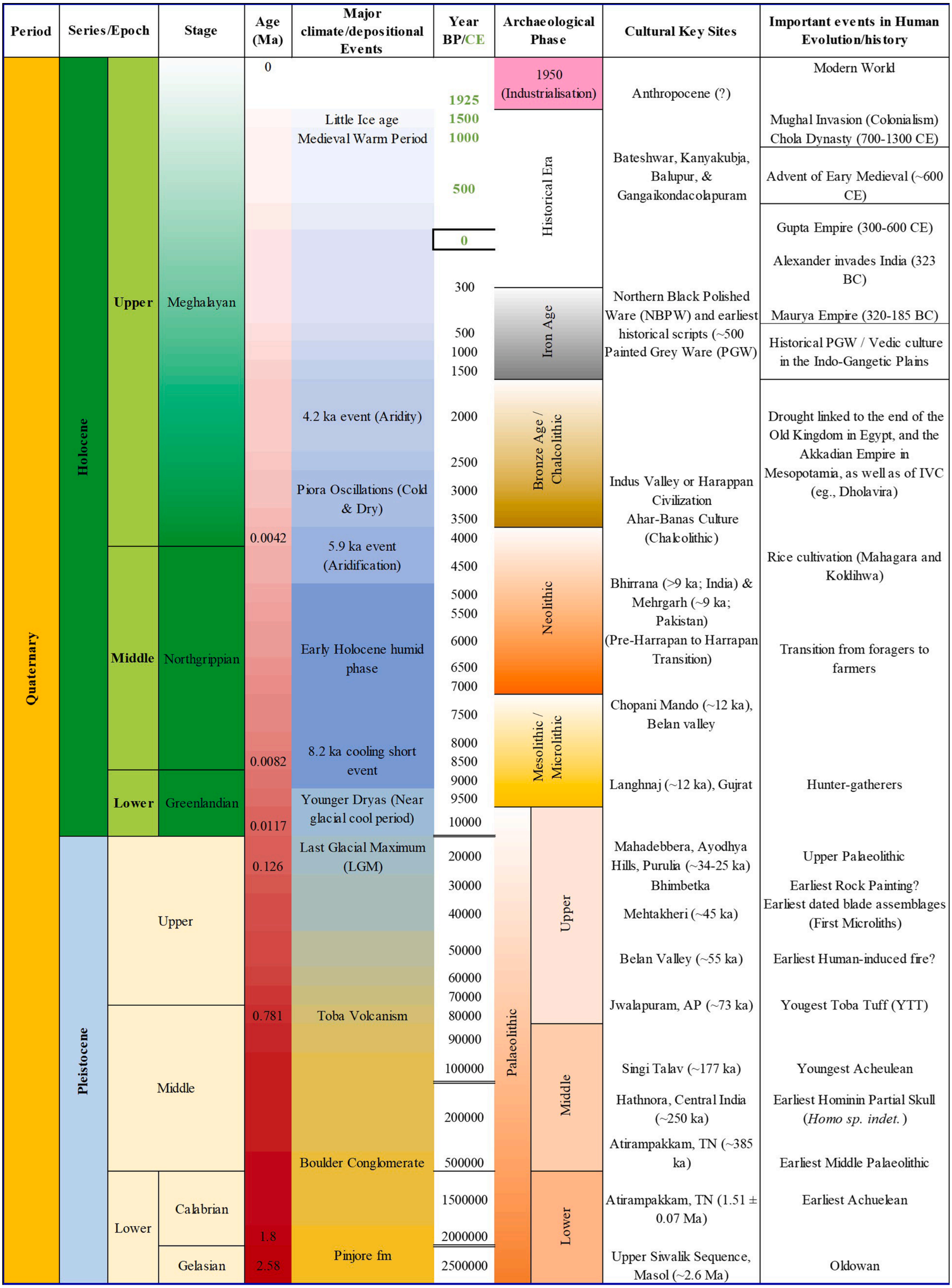

Fig. 2. Geoarchaeological Timeline of India, showing the temporal correlation of major dated archaeological and historical sites in India with the geological time scale provided by the International Commission on Stratigraphy.

modern humans in the Indian subcontinent remains unchallenged, evidenced by its continuation until approximately 3 ka. This claim finds support in the analysis of twelve radiocarbon dates obtained from eight sites in the Nimar region, with Mehtakheri serving as a notable illustration (Mishra et al., 2013). Within the trajectory of the Indian Palaeolithic, a smooth transition unfolds from the Acheulian to the Middle Palaeolithic and onward to the Iron Age, encompassing the emergence of microblade assemblages. Noteworthy is the fact that microblade technology did not originate within the Indian subcontinent, as its presence is documented elsewhere. Nevertheless, Mehtakheri stands out as the earliest dated microblade site within the Indian subcontinent, pushing the technology's origins back to ~44 ± 2 ka based on the weighted average of four dates. Alternatively, if we prioritise the oldest date as the most accurate, this origin extends to around ~48 ka. While microblade technology is closely linked with modern humans in the Indian subcontinent, this association is not widespread elsewhere, at least not until much later periods. Hence, Mishra et al. (2013) proposed that modern humans likely migrated into the Indian subcontinent during the arid climate of MIS 4, coinciding with their disappearance from the Middle East and North Africa. However, recent research suggests that this hypothesis may need reconsideration, as stone tools Dhaba predating the Toba super-eruption (~74 ka) strongly resembles assemblages from the African Middle Stone Age (MSA) and Arabia, as well as the earliest artefacts from Australia, suggesting that humans may have entered South Asia earlier than MIS 4 (Petraglia et al., 2007; Clarkson et al., 2020; Jha et al., 2025). Additionally, genetic studies reveal early population expansions across Southern Asia before the major migration around 60,000 years ago (Narasimhan et al., 2019). Furthermore, recent findings highlight the ecological adaptability of early humans, who were able to exploit diverse environments, including arid regions, facilitating dispersal into South Asia (Hallett et al., 2025). These insights suggest a more complex and flexible model of human migration into the subcontinent than previously proposed, warranting a nuanced reinterpretation of the timing and environmental context of these movements.

The Bhimbetka rock paintings, located in Madhya Pradesh, span across multiple prehistoric periods, offering a wide chronology of human development. The dating of the earliest paintings has been debated for decades. Mathpal (1984) initially proposed that some of the dynamic human and animal figures in green pigment, excavated from a Palaeolithic level in Shelter IIIA-28 (Misra, 1978), might belong to the Upper Palaeolithic. Subsequent research has questioned this attribution. Tyagi (1992) noted that green figures often appear alongside intricate motifs and tend to follow geometric traditions, while Bednarik (1993) and Blinkhorn et al. (2012) caution against assigning paintings to the Palaeolithic on stylistic or pigment grounds alone.

What remains clearer is the broader cultural sequence represented at the site. The rock art transition through the Mesolithic (~10,000 BCE), Chalcolithic, and Historic periods (Mathpal, 1984). Early depictions include large, linear representation of wild animals such as bison and boars, alongside stick-like human figures, reflecting a hunter-gatherer lifestyle. Later, Mesolithic art is more compact and detailed, often showing group hunting scenes with spears and bows, suggesting increasing social organisation (Mathpal, 1984). These paintings hold significance as South Asia's earliest known rock art tradition, offering insights into prehistoric cognition, social structures, and interactions with the environment (Mathpal, 1984).

The Mahadebbera site in Purulia, West Bengal, was excavated in 2011–2012 within the Ayodhya Hills' foothill region (Basak et al., 2014). Mahadebbera is part of a rich concentration of Microlithic sites discovered during first multidisciplinary explorations in 1998–2007. Microliths are small, finely crafted stone tools indicative of a shift toward blade-based technologies. These tools, often made from nonlocal raw materials, highlight mobility patterns and resource exploitation strategies. The site's microlithic assemblages are dated to between 34 and 25 ka using Optically Stimulated Luminescence (OSL), making them the earliest known Microlithic industries in eastern India (Basak et al., 2014). The prolonged presence of microliths over this 9000-year span suggests a stable human occupation, with slow colluvial deposition preserving the artifacts in situ within a hill-slope context—a rare geomorphic setting in the Indian subcontinent. This thick colluvium (3.29 m) with embedded artefacts, primarily composed of gravelly silty sand derived from the surrounding Precambrian rocks, points to slow rates of weathering and erosion at the sites and suggests a Late Pleistocene landscape conducive to sustained habitation (Basak et al., 2021).

5. Transition from foragers to farmers

Langhnaj, in the Mehsana district of Gujarat, is a key site in Indian archaeology for its evidence of Mesolithic hunter-gatherers coexisting with early food producers around 10,000–8000 BCE. Excavations, notably by H.D. Sankalia from 1941 to 1949 (Sankalia, 1946) and B. Subbarao from 1952 to 1954 (Subbarao, 1958), have unearthed microliths, animal bones (e.g., rhinoceros, wild boar), pottery sherds and several human burials on a fossilised sand dune near the Sabarmati River. This challenges the traditional linear progression of cultural phases - from Palaeolithic to Neolithic–and reveals a complex, overlapping timeline of subsistence strategies, where hunting and foraging for wild fauna coexisted with early experimentation in cultivation and food production (Sankalia, 1946; Subbarao, 1958). The presence of coarse pottery alongside microliths suggests interactions with neighbouring agricultural communities, providing insights into social and environmental transitions during the Mesolithic (Sankalia, 1946; Subbarao, 1958).

The Bhimbetka site also preserves the Chalcolithic paintings that introduce agricultural themes, marking the shift to permanent sedentary life, while Historic period art depicts warriors and religious motifs, suggesting complex societies (Mathpal, 1984). This sequence mirrors human evolution from nomadic foraging to settled farming and cultural expression. Similarly, a significant site has been discovered in the Belan Valley, Uttar Pradesh (Fig. 1), called Chopani Mando, located in the Vindhya range, which represents the transition from a hunter-gatherer lifestyle to sedentary farming communities during the Mesolithic and early Neolithic periods (~10,000–5000 BCE; Sharma, 1980). Excavations led by G.R. Sharma in the 1960s revealed a sequence of cultural layers from the Upper Palaeolithic to the Neolithic, making it a rare transitional site in Indian prehistory (Sharma, 1980; Fig. 2).

The earliest layers contain Microliths, alongside evidence of wild grains like rice and legumes. Subsequent layers show a shift to ground stone tools, such as querns and mullers, indicating the processing of cultivated cereals, alongside crude handmade pottery and signs of animal domestication (e.g., cattle and goats; Sharma,1980; Misra, 2001). This progression reflects the gradual domestication of plants and animals and early modification of the local environment, rather than immediate adaptation, likely influenced by interactions with neighbouring agricultural groups or local experimentation with plant cultivation in the fertile Vindhyan foothills. Chopani Mando this provides key insights into the long-term processes of human management and transformation of the biosphere in post-Pleistocene South Asia (Sharma,1980; Misra, 2001; Jha et al., 2020).

Mehrgarh, located in Balochistan, Pakistan, dated from ~7000–2500 BCE, it represents one of Indian subcontinents's earliest known farming settlements, predating the Indus Valley Civilisation (IVC; Jarrige, 1995). Excavations, led by Jean-François Jarrige from 1974 to 1986 and 1997–2000, unearthed evidence of a gradual shift from a hunter-gatherer lifestyle to settled agriculture, with domesticated wheat, barley, and animals like cattle and goats (Jarrige, 1995). This transition marks the advent of Neolithic in the region, foundational to later urban cultures like Harappa. Mehrgarh's significance lies in its continuous occupation across seven periods, revealing technological advancements such as pottery (from Period II, 5500 BCE), metallurgy, and proto-dentistry (evidenced by drilled teeth, 7.5–9.0 ka; Moulherat et al., 2002). It also provides the earliest evidence of cotton use in the

Old World (6th millennium BCE; Moulherat et al., 2002).

Bhirrana, situated on the now-dry Ghaggar River in Haryana (Fig. 1), is among the oldest known Harappan settlements in the Indian subcontinent, with continuous occupation from the Hakra culture (~9.5 ka BP) to the Mature Harappan phase (~2.8 ka BP) (Sarkar et al., 2016). Stratigraphic and radiometric data, including radiocarbon and OSL dating, affirms the site's antiquity and cultural continuity. In comparison to Mehrgarh, which exhibits early Neolithic traits around 7000 BCE in Baluchistan, and Kalibangan, known for its Early Harappan ploughed fields, Bhirrana offers a uniquely complete cultural sequence that traces the transformation from a ceramic Neolithic to urban Harappan lifeways within a single locality (Sarkar et al., 2016; Krishnan et al., 2012).

The ceramic assemblage from Bhirrana spans all major Harappan cultural stages and includes characteristic Hakra wares such as mud appliqué, bichrome, and incised pottery, as well as evolved red and grey wares with painted motifs in later levels (Krishnan et al., 2012). Petrographic analyses of over 120 ceramic samples revealed a diversity of raw material sources and paste recipes, with at least ten major fabric groups identified, indicating localised ceramic production and a variety of technological choices. This ceramic variability parallels the diversity seen in Early Harappan contexts at Kalibangan, which also featured pre-Harappan Hakra elements (Krishnan et al., 2012).

Faunal remains from Bhirrana indicate a subsistence economy centred on mixed agropastoral practices. Zooarchaeological evidence includes domestic species such as cattle (*Bos indicus*), buffalo (*Bubalus bubalis*), sheep (*Ovis aries*), and goat (*Capra hircus*), alongside wild taxa like nilgai and blackbuck, suggesting a broad-spectrum subsistence strategy from the earliest levels (Atkulwar et al., 2024). Notably, ancient DNA analysis of two bovid bones identified unique haplotypes of *Bos indicus* based on mitochondrial cytochrome b sequences, highlighting the early presence and possible independent domestication of zebu (*Bos taurus indicus*) cattle in the Ghaggar-Hakra region (Atkulwar et al., 2024). This complements earlier findings from Mehrgarh, where domestic cattle are also attested in Neolithic contexts, but without such direct genetic evidence.

Palaeoclimatic reconstruction from $\delta^{18}O$ analysis of faunal bioapatites from Bhirrana provides a high-resolution record of Holocene monsoon variability directly tied to cultural levels. These data show strong monsoonal conditions between ~9–7 ka BP, followed by a gradual decline through the Early and Mature Harappan phases (Sarkar et al., 2016). Despite decreasing rainfall, human occupation persisted, indicating resilience through shifts in subsistence strategies, including changes in crops and possibly animal management. This adaptability is echoed at Kalibangan, where irrigation and ploughing techniques suggest early responses to hydrological stress. Together, the chronological depth, ceramic complexity, faunal economy, ancient DNA evidence, and embedded palaeoclimate archive make Bhirrana a key site for understanding the development of agro-pastoral lifeways and their transition into urbanism within the IVC (Figs. 1 and 2).

A significant example of the transition from foragers to farmers, identified through archaeobotanical research including charred plant remains, diatoms, and phytoliths, whichprovides evidence for rice cultivation in the Middle Gangetic Plains as early as 8350 cal yr BP, notably from the Lahuradewa site in Uttar Pradesh (Saxena et al., 2006; Tewari et al., 2008; Thakur et al., 2018). This evidence includes morphologically wild rice (*Oryza rufipogon*) dating back to 10,300 cal yr BP, transitioning to domesticated forms (*Oryza sativa*) by 8350 cal yr BP, as identified through grain size analysis and spikelet bases suggesting early human management of wild stands by the 7th millennium BCE.

However, a recent study by Patel et al. (2022) revised the chronology of agricultural adaptation. Based on six ^{14}C AMS dates and analyses of organic matter and stable isotopes ($\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$), they proposed a pre-agricultural or peat formation phase between 10,899 and 7451 cal yr BP. The early agricultural zone is now identified between 7450 and 2623 cal yr BP. This work is significant for Indian prehistory, as it pushes back the timeline of rice cultivation and challenges earlier assumptions that rice was introduced from China around 2000 BCE. It underscores an independent origin of agriculture in the Gangetic region, complements evidence from sites like Mehrgarh from Indus Valley, and highlights the regional diversity of domestication processes.

6. Development of urban centres

The IVC represents a critical milestone in human evolution, showcasing one of humanity's first urban societies with sophisticated urban planning, advanced metallurgy, standardised weights, script, and extensive trade networks (Kenoyer, 1998; Wright, 2010). Chronologically divided into Early (3300–2600 BCE), Mature (2600–1900 BCE), and Late phases (1900–1300 BCE), the IVC's decline and de-urbanisation phase is characterised by settlement abandonment, population dispersal, de-urbanisation, and cultural transformation (Possehl, 2002). Multiple factors contributed to this transformation, prominently including climate change. palaeoclimatic data indicates a weakening of the Indian Summer Monsoon and increased aridity around 4.2–4.0 ka, coinciding with a broader climatic event that affected several ancient civilisations (Staubwasser et al., 2003; Dixit et al., 2014; Berkelhammer et al., 2012; Kathayat et al., 2018; Jahan and Quamar, 2024).

This climatic anomaly is documented in multiple proxies from the region, including fossil pollen reflecting vegetation shifts (Singh et al., 1972, 1990; Possehl, 1997), $\delta^{18}O$ values of gastropod aragonite indicating hydrological stress (Dixit et al., 2014), animal phosphate isotopes showing dietary and water stress in fauna (Sarkar et al., 2016), archaeobotanical and geochemical analyses revealing changes in crop cultivation and land use (Pokharia et al., 2017), stable carbon isotopes ($\delta^{13}C$) reflecting ecosystem responses to aridity (Pokharia et al., 2017), U–Pb zircon dating for sediment provenance (Clift et al., 2012), and fluvial morpho-dynamics documenting changes in river flow and sedimentation patterns in the Ghaggar-Hakra/Sarasvati system (Giosan et al., 2012). These records together indicate significant environmental stress, which likely influenced settlement patterns and subsistence strategies. Additional factors in the civilisation's transformation include overexploitation of resources, changing trade patterns, and possible socio-political instability (Madella and Fuller, 2006). Rather than catastrophic collapse, the late Harappan phase represents a complex cultural adaptation to changing environmental conditions, with communities dispersing into smaller settlements throughout northwestern India, maintaining certain cultural traditions while developing new adaptive strategies (Petrie et al., 2017; Green and Petrie, 2018).

The advanced scientific analysis such as DNA studies from Rakhigarhi, a major IVC site (Fig. 1), provides significant insights into the population dynamics of the Indian subcontinent. The genome of an individual from Rakhigarhi showed continuity with the Ancestral South Indian (ASI) lineage, indicating that the IVC populations contributed significantly to modern Indian or South Asian populations (Shinde et al., 2019). The DNA lacked Steppe ancestry, suggesting that the arrival of Steppe pastoralists occurred after the decline of the IVC, around 2000 BCE (Shinde et al., 2019). The Rakhigarhi genome also exhibited genetic links with ancient Iranian farmers, but this similarity likely resulted from a shared ancestry rather than direct migration (Narasimhan et al., 2019). These findings challenge simplistic models of Aryan migration, highlighting the complexity of population dynamics in ancient India. Although genetic results are important, the primary drivers of transformation during the Late Harappan phase were environmental, which shaped settlement trajectories, including the dispersal of communities into smaller settlements, adaptation of subsistence strategies, and reorganization of land use. Pottery styles and other material culture provide complementary evidence of cultural continuity and adaptation but are secondary to the environmental pressures that structured human responses (Madella and Fuller, 2006; Petrie et al., 2017; Green and Petrie, 2018). Rather than a catastrophic collapse, the Late Harappan phase represents a complex cultural adaptation to changing environmental conditions, with communities maintaining certain traditions while developing new strategies to cope with hydrological stress and declining monsoon intensity.

The composite time span contemporary to the composition of the Vedas, spanning roughly from 1500 to 800 BCE (Fig. 2), is a crucial phase in cultural evolution, marking the transition from prehistoric to historic societies through the development of complex religious, social, and linguistic orders. Chronologically positioned after the decline of the IVC, this era witnessed the gradual eastward movement of Indo-Aryan linguistic groups through the Gangetic plain, documented through ceramic markers like Painted Grey Ware (PGW; 1200–800 BCE) and Northern Black Polished Ware (NBPW; 700–200 BCE) (Chakrabarti, 2006; Singh, 2009). Advent of the NBPW and a specific type of punch-marked coin called the Bent Bar mark the shift from semi-nomadic pastoral subsistence strategy to sedentary settlement and urban growth in the Gangetic plains (Fig. 1).

The importance of this phase lies in the evolution of human thought and oral traditions crystallised into the writing of Vedas, laying foundations for intellectual development through its philosophical concepts that fundamentally shaped subsequent religious and philosophical traditions across Asia (Flood, 1996; Olivelle, 1998). Socially, the Vedic texts are witness to the crystallisation of the varna system (*priests, warriors, traders, laborers*), early forms of statecraft evolving from tribal (*jana*) to territorial (*janapada*) structures, and the emergence of large urban centres in Asia (Thapar, 2003; Sharma, 1999). Historically and chronologically, the era of the composition of the Vedic literature bridges the Bronze and Iron Ages, (~1200 BCE), that saw the advancement in iron metallurgy, development of advanced agricultural tools, enabling agricultural expansion and forest clearance that transformed the subcontinent's landscape and settlement patterns (Erdosy, 1995; Possehl, 2002; Singh, 2009). We must put on record that the earliest date of iron in the mid-Ganga plains has secure radiometric dates between early and late 2nd millennium BCE (Tewari, 2003). Recent claims of early dates from Tamil Nadu have added new ingredients for the date-of-iron debate in India (Rajan and Sivanantham, 2025).

The Ahar-Banas (3000–1700 BCE) and Jodhpura-Ganeshwar (2500–1700 BCE) cultures represent important Chalcolithic traditions of Rajasthan that were contemporaneous with the IVC (~3300–1300 BCE) or Harappan Civilisation (Agrawal and Kumar, 1982; Misra, 2005). The Ahar-Banas culture (Fig. 1), centred in southeastern Rajasthan along the Banas River, is characterised by distinctive black-and-red ware pottery and permanent settlements at sites such as Ahar, Gilund, and Balathal (Shinde, 2006; Misra, 1997). In contrast, the Jodhpura-Ganeshwar culture of northwestern Rajasthan specialised in copper metallurgy at sites like Ganeshwar and Jodhpura, and likely supplied copper to Harappan urban centres (Agrawal and Kumar, 1982; Misra, 2005).

Both cultures maintained their distinct identities while engaging in economic interactions with the IVC, as evidenced by the presence of Harappan artifacts at several sites (Possehl, 2002). The archaeological record indicates that these regional cultures participated in resource exchange networks while preserving their cultural autonomy, reflecting the complex socio-economic landscape of Bronze Age northwestern India (Hooja, 1988). These cultures, along with others such as Kayatha and Malwa, represent significant regional developments that challenge simplistic views of the IVC as culturally monolithic (Shinde, 2006).

Protohistoric cultures of eastern India demonstrate a distinct line of development, having its genesis around early second millennium BCE, with some sites in Bihar and Odisha dated to this phase (Possehl, 1988). The chronological horizon of development in western Bengal along the eastern fringe of the Chhotanagpur plateau and also some recent discoveries along the coast in southwestern West Bengal appears to be considerably late, in the late second or early first millennium BCE (Naskar et al., 2021). The standard archaeological marker of growth and expansion of settlements of this level is eastern India is the well-known Black and Red Ware ceramics, associated with the use of microliths and copper (Naskar et al., 2021).

7. Early historic to medieval and beyond

The first known foreign invasion of India is widely considered to be the Aryans who faced the IVC populations between 1800 and 1500 BCE. However, it is believed to be confined in north and north-western region of Indian subcontinent (Shinde et al., 2019). The second invasion occurred ~500 BCE, when the Persians occupied the northwestern sectors of the subcontinent. It is believed that the Persian impact was marginal compared to the Aryans. The Persian empire was in turn conquered by the Greek Empire under Alexander the Great, who swept as far as the River Beas in the Indian subcontinent in 326 BCE. This marked the Alexander's invasion of northwestern India (326–325 BCE), a crucial contact between Hellenistic and Indian dominions, though his actual territorial control was for a limited period (Bosworth, 1996; Holt, 2005).

This is a time that witnessed the rise of the Mauryan Empire under Chandragupta (322–298 BCE), culminating under the Asoka (268–31 BCE), who helped propagating Buddhism across Asia (Chakrabarti, 2009; Allen, 2012; Singh, 2009; Thapar, 2012). A large number of Asokan sites and artefact (Falk, 2006), along with epigraphic texts inscribed on varying categories of stone surfaces across wide geographies in South Asia, underline the maturity of a complex process of state formation. Following the gradual decline of the Mauryan empire around the 2nd century BCE, a further complex political landscape emerged with Indo-Greek, Saka, Parthian, and Kushana rule in northwestern regions, while indigenous powers like the Satavahanas dominated central and southern territories (Cribb and Herrmann, 2007; Sinopoli, 2001).

The Satavahana dynasty, often identified with the Andhras mentioned in the Puranas, probably flourished around the 2nd century BCE and ruled for some 300–460 years according to various Puranic accounts (Chakrabarti, 2009; Cribb and Herrmann, 2007; Singh, 2009; Sinopoli, 2001). There is scholarly debate about the initial power base of the Satavahanas. Some evidence, such as early coin finds at Kotalingala and Sangareddy in Andhra Pradesh, suggests an eastern Deccan origin. However, inscriptions at Naneghat and Nashik in the western Deccan support the theory that the dynasty began around Pratishthana (modern Paithan) and then expanded eastwards into Andhra and along the western coast (Cribb and Herrmann, 2007; Sinopoli, 2001; Singh, 2009). Recent excavations at smaller Satavahana sites have yielded interesting evidence on crafts specialization in Deccan in the early historic period (Paddayya, 2008). The Satavahana empire eventually encompassed a large area including present-day Andhra Pradesh and Maharashtra, and at times extended into northern Karnataka, eastern and southern Madhya Pradesh, and parts of Saurashtra (Singh, 2009).

The Gupta polity (320–550 CE; Fig. 2) indicated a "Golden Age" characterised by remarkable achievements in science, mathematics, literature, art, and architecture, with figures like Kalidasa, Aryabhata, and Varahamihira making enduring contributions to human knowledge, though the notion of the "Golden Age" has been subsequently subjected to serious critique (Williams, 1982; Kulke, 1995; Kulke and Rothermund, 2016). After Gupta disintegration, regional powers including the Pushyabhutis, the Gaudas, the Later Guptas, Chalukyas, Pallavas, and indigenous polities in eastern and northern India emerged, with the rise of the Pala dynasty (750–1120 CE) ruling eastern India for nearly four centuries, establishing or expanding major educational institutions like Nalanda and Vikramashila, while developing distinctive art forms and maintaining diplomatic relations with Tibet and Southeast Asia (Majumdar, 1971; Huntington, 1984). This millennium-long period witnessed transformative developments including the mature codification of Brahmanical philosophical systems, gradual decline of Buddhism in its homeland alongside its flourishing in East Asia, the emergence of tantric traditions, profound artistic and architectural innovation, and the integration of Central Asian influences into South Asian cultural frameworks (Davidson, 2002; Asher and Talbot, 2006). Beyond the domain of sources reflecting the dynamism of political and religious processes, recent excavations at the site of Balupur in the northern alluvial tracts of West Bengal has delineated excellent evidence of the continuously changing contours of a human settlement in a fluvially hyperactive terrain, with secure AMS 14 C dates ranging from the 9th to the 18th centuries (Panja et al., 2015).

On the whole, the period between the 7th and the 13th centuries witnessed rapid expansion of agrarian landscapes, as vindicated by the discovery of thousands of copperplate charters across the length and breadth of the country. While these have been extensively used in understanding state and society in the early medieval period (for a collection on varying views, Kulke, 1995), the crucially significant point of our interest here is that these records bear testimony to large-scale change in the land use pattern which, in corollary, brought in considerable shift in human-environment networks in an essentially rural world (for e.g., see, Sanyal and Ghosh, 2019).

Majority of early medieval ruing lineages declined around the 13th century, while the Delhi Sultanate has its inception in the early second millennium CE, as the first major Islamic polity in the Indian subcontinent, established in 1206 by Qutb al-Din Aibak. The Delhi Sultanate ruled over large parts of the Indian subcontinent for over three centuries, from ~1206–1526, and encompassed five dynasties: Mamluk, Khalji, Tughlaq, Sayyid, and Lodi (Richards, 1993; Habib, 1963).

The Mughal Empire's establishment following Babur's victory over the Lodi rulers at Panipat (1526 CE; Figs. 1 and 2) initiated profound environmental transformations through extensive agricultural expansion, irrigation systems, and urbanisation projects, though ecological impacts remained regionally confined (Richards, 1993; Habib, 1963). These included widespread deforestation for cultivation, soil erosion and sedimentation from irrigation works, and altered river regimes around growing urban centres. While moderate in scale compared to later colonial interventions, many of these changes, such as forest clearance and channel shifts, proved difficult to reverse. Agricultural growth relied on expanding irrigation networks of canals and wells; projects like the Narmada Canal extended cultivation but disrupted natural river flows (Grove et al., 1998). The introduction of cash crops such as cotton and sugarcane further strained water supplies by diverting rivers and reducing downstream availability. At the same time, cities like Agra and Delhi reshaped local ecologies as impervious surfaces increased runoff and reconfigured drainage. To meet urban demand, the construction of Baolis (stepwells) and reservoirs secured water supplies but modified groundwater recharge and surrounding hydrological systems (Ludden, 1999). Under Emperor Akbar (1556–1605) and his successors, systematic land measurement, revenue systems, and crop diversification intensified human-environment interactions while facilitating proto-industrial developments that reorganised resource extraction patterns (Ludden, 1999; Grove et al., 1998).

The British colonial period, beginning with East India Company territorial control after the Battle of Plassey (1757) and transitioning to Crown rule following the 1857 Rebellion, represents a critical accelerator of Anthropocene processes through fundamental transformations of forest management, agricultural systems, and resource extraction (Grove, 1996; Gadgil and Guha, 1993). Colonial forestry policies, particularly after the Forest Acts of 1865 and 1878, dramatically altered traditional ecological relationships through scientific forestry, introducing plantation monocultures while enabling unprecedented timber extraction that reconfigured landscapes across the subcontinent (Rangarajan, 1996; D'Souza, 2006). Railway expansion (post-1853) triggered substantial coal mining, deforestation, and land use transitions while facilitating commodity exploitation for global markets, making India an early participant in fossil-fuel-driven industrialisation and carbon emission patterns characteristic of the Anthropocene (Ahuja, 2021; Mann, 2017). These colonial interventions created lasting socio-ecological vulnerabilities through disrupted traditional systems, engineered hydrological regimes prone to failure during extreme events, and extractive economic frameworks that continue to influence South Asia's climate vulnerability and adaptive capacity even in post-independence developments (Damodaran, 2006; DeLoughrey et al., 2015).

The environmental and ecological impacts from historical periods to the present have profoundly influenced Earth system feedbacks over relatively short timescales and are closely linked to the Anthropocene crisis (Roberts et al., 2024). Agricultural expansion across historical regimes not only reshaped land use but also generated feedback loops that reverberated through ecological systems. In the biosphere, vegetation clearance and the spread of monocultures led to deforestation, habitat fragmentation, and biodiversity loss, often reducing ecosystems' capacity to recover from disturbance (Grove, 1996; Gadgil and Guha, 1993). In the hydrosphere, the construction of irrigation networks and rising urban water demands caused river channel modification, wetland drainage, altered surface runoff, and groundwater depletion, sometimes intensifying flood risks and lowering water quality (Mosse, 2003). In the lithosphere, intensified cultivation may have accelerated soil erosion, nutrient depletion, salinization, and, in some regions, slope instability, undermining long-term soil fertility and productivity (Richards, 1993).

The scale, intensity, and reversibility of these impacts varied according to local ecological conditions, cultural practices, and political economies. Nonetheless, recurring patterns emerge across regions and periods, including the gradual reduction of ecological resilience under sustained human pressure (Habib, 1963; Ludden, 1999). In more recent times, land use changes have intensified further. Activities such as gravel extraction, landscape levelling, and large-scale irrigation have permanently altered geomorphology, disrupted sediment transport, and impaired hydrological systems. These largely irreversible modifications underscore how long-term trajectories of anthropogenic change have shifted from regionally confined adjustments to systemic, large-scale reconfigurations of landscapes.

8. Summary and future directions

The Quaternary archaeological heritage of India presents one of the most continuous but fragmentary and diverse records of human history in the world. From the earliest tools of the Lower Palaeolithic to modern environmental challenges, the subcontinent's past reveals a long trajectory of human adaptation, technological innovation, and deep entanglement with the natural world. The development of a combined geoarchaeological timeline, synthesising both cultural and environmental data, holds enormous potential not only for academic research but also for informing contemporary policy, sustainability strategies, and environmental education.

The earliest traces of human activity in South Asia appear in the form of Oldowan-type stone tools found at sites like Masol, Riwat, Pothohar Plateau and the Pabbi Hills dating back to 2.5 Ma from the Himalayan region (North), and from Attirampakkam in Tamil Nadu (South), dated to 1.5 Ma. The discoveries of Oldowan tools in South Asia, particularly at Attirampakkam challenge the "*Out of Africa*" theory by suggesting that the migration of humans to South Asia may have occurred earlier than previously believed. The appearance of Acheulean handaxes, as seen at sites like Attirampakkam, and Isampur and Hunsgi-Baichbal in Karnataka, illustrates a more advanced toolkit developed around 1.5 Ma. These tools, associated with *Homo erectus* and early *Homo sapiens*, reflect how early humans navigated the shifting river systems and fluctuating climate of the Indian subcontinent.

As time progressed into the Middle and Upper Palaeolithic, tool types diversified, showing greater regional variation and more refined flake-based technologies. The significant Middle Palaeolithic dated sites are Attirampakkam (385 ka), Hathnora (250 ka), Singi Talav (177 ka), which also show continuity with Acheulean technology and provide a context for the debate on typo-technological advancement and continuity in the South Asia. Further, advanced scientific analyses from Middle Palaeolithic sites like Jwalapuram (73 ka) and multi-cultural site like Belan Valley (55 ka) suggest resiliency and adaptability during critical climate events such as Toba super-eruption and development of controlled use of fire to adapt and exploit the surrounding environments. The transitional phase to Microlihtic/Mesolithic is recorded at sites like Mehtakheri (45 ka) and Mahadebbera (32–25 ka), provide evidence on further development and advancement of culture in India. The Mesolithic sites like Langhnaj (12 ka) and Chopani Mando (12 ka) to Bhirrana (>9 ka) and Mehegarh (>9 ka) provide a unique glimpse into this continuity, as they span from Mesolithic into early Harappan settlement phases. This period marked a subtle but critical shift toward more localised and seasonal interactions with the environment.

Around 7000 BCE, the Neolithic revolution emerged in South Asia, best exemplified by the site of Mehrgarh, Bhirrana, and Chopani Mando. These early farming communities transitioned from foraging to food production, domesticating plants and animals and constructing permanent dwellings. They also began to experiment with water management and irrigation techniques that foreshadowed more advanced forms of environmental control in later urban societies. These early adaptations demonstrate how prehistoric communities responded to arid climates and resource pressures, offering potential insights into contemporary agricultural resilience. By the third millennium BCE, the IVC had developed one of the most advanced urban cultures of the ancient world. Cities such as Harappa, Mohenjo-daro, Dholavira, and Rakhigarhi featured standardised brick architecture, sophisticated drainage systems, and evidence of complex social organisation. These urban centres were deeply reliant on river systems like the Indus and the now-dry Ghaggar-Hakra. Geoarchaeological research at sites like Bhirrana suggests that shifting monsoon patterns and the gradual desiccation of river systems contributed to the decline of this civilisation. This historical example is a powerful reminder of the vulnerability of human societies to environmental shifts, especially in the context of climate change.

Following the IVC period, the post-IVC and Iron Age cultures gave rise to state formations such as Magadha and, eventually, large empires like the Maurya and the Gupta. The Mauryan emperor Ashoka advocated for animal protection and environmental stewardship, early examples of state-led ecological consciousness. Further south, the Chola dynasty constructed sophisticated irrigation systems, including the Grand Anicut on the Kaveri River, which remains functional to this day. These ancient innovations exemplify how political systems often responded to environmental demands with infrastructure and policies that prioritised sustainability. In the medieval period, the arrival of Islamic rule and later of the Mughals, also defined as the beginning of the colonial period, introduced new extractive technologies and administrative practices. While their contributions to architecture and water management were significant, they also initiated long-term changes in land use and the socio-economic conditions of India's indigenous population. The British colonial period, however, marked a more extractive approach to the environment through deforestation, canal building and plantation economies. These actions often disrupted traditional ecological knowledge and left lasting scars on India's environment and landscape.

Since independence in 1947, India has experienced rapid industrialisation and urban growth. While this development has improved living standards for many, it has also intensified environmental degradation. Air and water pollution, groundwater depletion, biodiversity loss, and increasingly erratic weather patterns characterise India's entry into the Anthropocene—a new period/phase defined by human influence on Earth's systems.

The importance of this combined timescale extends beyond academic inquiry. It offers a practical tool for policymakers, conservationists, and educators. For instance, understanding how prehistoric communities in South Asia adapted to changes in their environment can offer lessons for modern societies facing the Anthropocene crisis. By studying past human-environment interactions, we can better anticipate and manage future environmental challenges. The integration of geological and archaeological timelines is also essential for reconstructing the evolutionary history of humans in South Asia and beyond. It provides context for the development and spread of ancient technologies, migration patterns, and cultural transformations. This contextual understanding is crucial for piecing together the broader narrative of human history in the region, offering insights into the factors that have shaped human development and cultural diversity over millennia.

Future research could build on this study in several complementary ways. One promising avenue is the selective application of chrono-systemic frameworks to specific time periods (e.g., the Late Pleistocene–Holocene transition) or subregions with rich archaeological and palaeoenvironmental records (e.g., the Indus Valley Civilization). Incorporating such chrono-systemic overlays in these targeted contexts may provide valuable insights into temporal patterns and human–environment interactions. Additionally, more thematically focused timelines, such as those addressing Palaeolithic site formation or ecological dynamics over shorter timeframes could offer deeper perspectives on particular aspects of India's geoarchaeological record. While this study emphasises synthesis and temporal alignment rather than critical paradigm evaluation, the comprehensive chronological framework presented here serves as a reference point for future archaeological, geological, and palaeoenvironmental studies. Finally, systematic comparisons of ecological zones and more detailed meta-analyses, though beyond the current scope, represent important directions for subsequent work.

CRediT authorship contribution statement

Rajat Sanyal: Writing – review & editing, Visualization, Validation, Conceptualization. **Sujit Dasgupta:** Writing – review & editing, Visualization, Validation, Conceptualization. **Deepak Kumar Jha:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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