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Agricultural adaptation and resilience through climatic shifts in semi-arid India: 2000 years of archaeobotanical evidence from Vadnagar, Gujarat

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ABSTRACT

The relationship between historical climate change and past agricultural production contributes to a better understanding of the impacts of projected climate change by providing empirical data for resilient human responses. This study explores the periods of dynastic transitions and crop production at the urban site of Vadnagar, in semi-arid northwest India through several climate events, generally characterised by weakening summer monsoon precipitation during the Late Holocene. Artefacts from the site present an unbroken sequence of seven successive cultures from the first century BCE to the nineteenth century CE. Archaeobotanical data indicate the sufficient water availability during the Historic and Medieval periods, allowing crop production dominated large-grained cereals (C_3 plants). However, during the Post-Medieval period (ca.1300−1850 CE) a resilient crop economy based on small-grained cereals (C_4 plants) dominated, representing a human adaptation to prolonged weakening of monsoonal precipitation. Isotopic and phytolith data at the site present a clear signal of changing local environmental conditions over two millennia, consistent with regional palaeoclimate records, providing and interpretive context for agricultural evidence at Vadnagar. Despite long-term reduction in summer humidity, we argue that an adaptable agricultural package coupled with suitable water management systems allowed for the resilience of the urban settlement at Vadnagar.

1. Introduction

Northern Gujarat is situated within one of the most extensive semi-arid areas of South Asia, bordering the Thar Desert, where local ecological conditions vary extensively relative to minor changes in annual rainfall (Bharucha and Meher-Homji, 1965). In this region, the minimum annual rainfall for cultivation of the most drought tolerant millet is around 300 mm, while zones with 500 mm annual precipitation (sufficient for more water demanding crops) are located only 80 km–100 km east and south highlighting the geographical proximity of zones with very different agricultural potential. Variations in agricultural systems and hydraulic adaptations to these semi-marginal environments are therefore a fundamental factor in how complex societies adapt to differing environmental conditions in areas such as arid Gujarat. Archaeology offers the potential to provide a long-term record of both agricultural systems and hydraulic adaptations, their forms, stability, and adaptive shifts, providing information relevant to current and future concerns, especially where climatic events intersect with highly vulnerable semi-arid environments (Pokharia et al., 2017).

Previous regional studies have documented climatic variability over

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[1] In memory of our friend and colleague, lost to us in 2023

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the course of the Holocene in the Thar Desert and its adjacent savannah (Agrawal, 1992; Enzel et al., 1999; Singh et al., 1990). These studies have been correlated with cultural changes in prehistory, such as the emergence of Bronze Age urbanisation with the Indus Valley Civilisation as well as its subsequent "collapse" (Dixit et al., 2018; Giesche et al., 2023; Giosan et al., 2018; Madella and Fuller, 2006; Prasad et al., 2014). In the period, ca. 2000−1500 Before Common Era (BCE), a weakening monsoon resulting in multidecadal droughts appears to have driven increased agricultural diversity, increased reliance upon drought tolerant summer crops such as millets, and a region wide deurbanisation (or "collapse") that was characterised by a marked reduction in population density and regional migration (Giesche et al., 2023; Giosan et al., 2018; Madella and Fuller, 2006; Petrie and Bates, 2017; Pokharia et al., 2017). Indeed, archaeologists have drawn similar correlations between extended periods of severe drought and deurbanisation or "collapse" globally, from Mesoamerica (Douglas et al., 2015; Kennett et al., 2022; Medina-Elizalde and Rohling, 2012) to Mesopotamia (Cookson et al., 2019; Manning et al., 2023), the Greenland Norse (Zhao et al., 2022) and the ancient Andes (Arnold et al., 2021).

However, considerably less focus has been directed towards human responses in South Asia to northern hemisphere warming and cooling periods during historic periods over the last two millennia – e.g. the putative Roman Warm Period (RWP), Medieval Warm Period (MWP), Little Ice Age (LIA), despite these climatic events often being presented as global in impact (Fagan, 2002, 2005, 2009). The present research addresses this gap through analyses of botanical (macroremains and phytolith) and isotopic data spanning a chronology of around 2000 years at the site of Vadnagar, Gujarat (23°47′N; 72°39′E) (Figs. 1 and 2), a small urban centre of ~55 ha in the Medieval period that would have required a substantial agricultural hinterland to support it.

Historians have raised questions regarding climatic or environmental perturbations in South Asia and their relation to periods of drought with subsequent famines, particularly during the Mughal and colonial periods of the last 500 years (Damodaran et al., 2019; Maharatna, 1996; Mukherjee, 2019; Uberoi, 2012). Damodaran et al. (2019) argue that while there have been some attempts to synthesize records of El Niño Southern Oscillation (ENSO) variation, solar or volcanic forcing and historical accounts, reconstructing the complex relationship between climate variability and human responses requires a larger database of palaeoclimate and archaeological proxies that go beyond the instrumental record. Studies of high resolution speleothem records have attempted to link variability in Indian Summer Monsoon (ISM) precipitation with climate phases such as the LIA, MWP and RWP and considered these as drivers of dynastic succession in northern India (Kathayat et al., 2017). While these broad comparisons imply a causative relationship between climate, food production and political

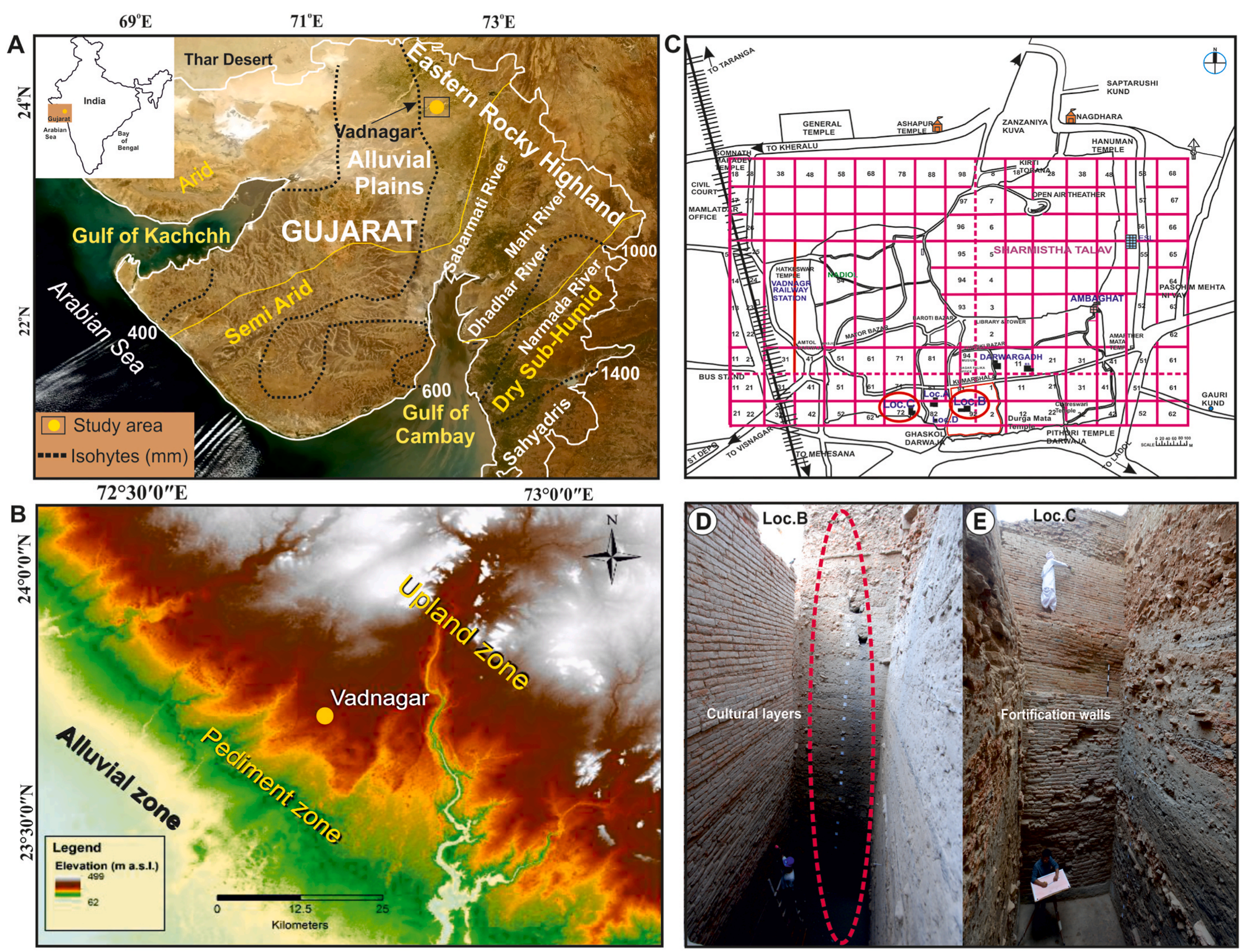

Fig. 1. (A) Map of Gujarat indicating location of Vadnagar. (B) Map of North Gujarat (C) Grid layout of excavated trenches at Vadnagar with Locality B and C circles in red. (D) Locality B showing layers of cultural deposits in 14.10 m deep cutting trench. (E) Locality C section along the fortification wall. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

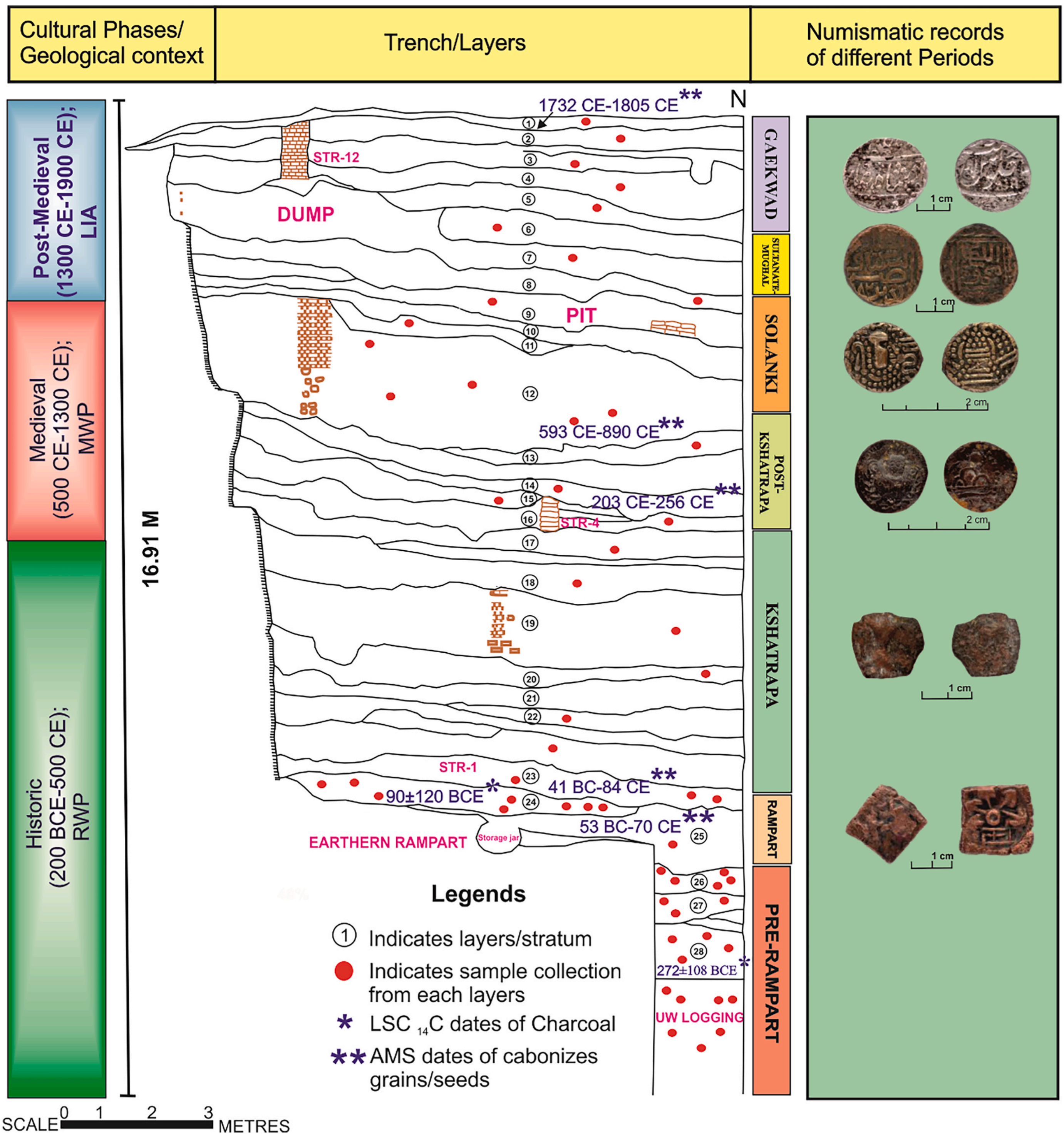

Fig. 2. Stratigraphy from Historic Phase to the Post Medieval phase of Trench YA1/72/85, Locality C, Vadnagar. Cultural phases, sample collection points and numismatic records of dynasties indicated.

continuity and change, we argue that these are best examined through site-specific studies, which may then inform broader historical syntheses. The case study at Vadnagar presents an opportunity for a detailed study of the relationship between climate and social-economic processes. We examine these relationships using isotopic and phytolith data representing a mixture of anthropogenic and climatic signatures at the site, as well as changing patterns of crop production in the macrobotanical record.

2. Study area

Vadnagar is located in the Mehsana District in the semi-arid uplands of northern Gujarat (Fig. 1), adjacent to a depression that is believed to be a palaeochannel of the Sabarmati River (Pokharia et al., 2021). The present course of the Sabarmati is around 15 km southeast of the archaeological site, and the Rupen River is around 4 km away. Rainfall is delivered by the summer monsoon, with an average of around 55 rain days generally between June and September and total precipitation of around 650 mm annually on average (Fick and Hijmans, 2017). Modern agriculture is dominated by summer season millet farming, with supplementary winter crops sown between November and April, aided by modern irrigation systems. The majority of the present day landscape is agricultural land, with some communities of dry deciduous forests composed of *Prosopis cineraria*, *Prosopis chilensis*, *Azadirachta indica*, *Acacia nilotica*, *Ailanthus excelsa*, *Holoptelia integrifolia*, *Salvadora oleoides*, *Ziziphus* sp., *Acacia tortalis*, and *Citrus aurantium* being the dominant arboreal vegetation community (Singh, 2013).

Archaeological excavations have been taking place at the site since 2014 first under the Directorate of Archaeology, Gujarat followed by the Archaeological Survey of India. Excavations have revealed archaeological deposits up to 24 m in depth (Agnihotri et al., 2021) with contexts dated by OSL and AMS to the 6th century BCE. Previous archaeobotanical studies (Pokharia et al., 2021) of deposits associated with Buddhist stupas at the site indicate an agricultural economy dominated by rice and pulses between the 1st century BCE and the 5th century of the Common Era (CE). The substantial archaeological remains as well as historical accounts from the Chinese Buddhist pilgrims Faxian and Xuanzang (Agnihotri et al., 2021) indicate the site has been a significant urban and monastic landscape for at least 2000 years. This long-term urban archaeological sequence is rare among excavated historic period sites in northern India.

The main excavated site is located adjacent to Sharmistha Lake, a semi-natural water body possibly originating from an oxbow lake prior to the diversion of the Sabarmati before being modified into a reservoir during the early occupation of the city (Ambekar, 2022). In addition to this resource, it has been argued that porous soil landscapes around the site have allowed easy access to groundwater (Agnihotri et al., 2021). In a survey of local water management structures, Ambekar (2022) reports 54 artificial waterbodies interlinked by canals within 10 km of the site, and based on related structural materials dated at least as early as the 1st century CE, argues that these abundant and complex water management systems allowed for long-term resilience of urban occupation at Vadnagar.

3. Materials and methods

3.1. Sampling and collection

74 samples totaling 3750 L of sediment (Fig. 2) were separated during excavations in 2017-18 from Trench YA1/92/73 at Locality B (Supplement 2 - F1) and Trench YA1/72/85 at Locality C (Supplement 2 - F2) at Vadnagar. Standard flotation techniques for archaeobotanical recovery followed (Pearsall, 2015), with buoyant carbonised and silicified plant remains (grains/seeds/fruits) recovered through a 30 mesh (0.5 mm) geological sieve. Dried samples transported for analysis at Birbal Sahni Institute of Palaeosciences, Lucknow, India. A total of twenty-nine sediment samples from the basal layer (29) to the top of profile in Trench YA1/72/85 at locality C were taken for phytolith and isotope studies (Fig. 2).

3.2. Chronology

Carbonised seeds and charcoal recovered through flotation were dated at Birbal Sahni Institute of Palaeosciences (BS), Lucknow, India, Direct AMS (D-AMS), USA, Physical Research Laboratory (AURIS), Gujarat, India and IsotoppechZrt.AMS 14C Lab (DeA), Hungary for ^{14}C measurements (Table 1; Fig. 3). Conventional radiocarbon ages were calibrated in OxCal v4.3.2 (Bronk Ramsey, 2009) using the IntCal13 calibration curve (Reimer et al., 2013). Calibrated ranges were compared with the ceramic, numismatic and other artefact assemblages recovered at the site to define the cultural sequence.

3.3. Laboratory analyses

Plant remains were examined under a Leica Z6AO stereoscope and sorted. The identification of carbonised grains/seeds was made using reference collection at BSIP, Lucknow, and published literature (Pokharia et al., 2011, 2017). Full absolute counts of plant taxa and ubiquity are presented in Supplement 1.

Stable carbon isotope ($\delta^{13}C_{SOM}$) ratios were determined on organic matter of sediments from cultural layers. Analyses were conducted using a Pyrocube Elementar elemental analyser and Precision Elementar EA-IRMS Isotope Ratio Mass spectrometer in continuous flow mode. For isotopic analysis, sediment samples were subjected to decalcification. Around 2 g of dried/homogenised sediment aliquots were treated with 10% hydrochloric acid (HCl) then dried overnight. Samples were subsequently washed several times with deionised water to remove any excess chloride ion. Samples were again dried in an oven at ~60° Celsius and re-powdered to obtain a homogenised sample. Data quality of measured C and $\delta^{13}C$ values was checked using a suite of in-house (laboratory) and international IAEA standards. Accuracy and analytical precision of measured $\delta^{13}C$ was better than 0.2‰. For the C component, analytical precision was found to be better than 3–5% (based on duplicate analysis). The isotopic data are reported using standard delta notations. C isotopic data were determined using the Vienna-PDB standard.

Phytoliths were extracted following standard techniques adapted from Piperno (2006). Ten grams of dried sediment was treated with hydrochloric acid (HCl) to remove carbonates, followed by hydrogen peroxide (H_2O_2) to remove organic content. Samples were washed with

Table 1
AMS and LSC ^{14}C dates of carbonised seeds and charcoal recovered from the archaeological site Vadnagar dated at Direct AMS (D-AMS-), USA, PRL (AURIS-), Ahmedabad, Gujarat, India, IsotopeechZrt.AMS 14C Lab (DeA-), Hungary and Birbal Sahni Institute of Palaeosciences (BS-), Lucknow, India (at 2 sigma (95.4%) probability) (all radiocarbon dates were calibrated in Oxcal.V.4.3.2

Trench/layer	Depth (cm)	Lab code	Source	14C date (yrs BP)	Calibrated Age (BC/CE) (with 2σ uncertainty)	Periodization based on traditional method	Cultural phase
YA1/92/73/3/1	60	DeA-26895	*Pennisetum glaucum*	192 ± 18	1732 CE -1805 CE	Gaekwad pd. (18th - 19th CE)	Post Medieval (1300–1900 CE)
YA1/92/54/12	600–610	AURIS-03702	*Oryza sativa*	1317 ± 79	593 CE – 890 CE	Post Kshatrapa Pd. (5th-10th CE)	Medieval (500–1300 CE)
YA1/92/54/14	710–720	DeA-26898	*Macrotyloma uniflorum*	1816 ± 20	203 CE-256 CE	Kshatrapa Pd. (1st - 4th CE)	Historic (200 BCE-500 CE)
YA1/72/85/1/23	1195–1215	D-AMS 032051	*Oryza sativa*	1966 ± 27	41 cal BC - 84 CE	Kshatrapa Pd. (1st - 4th CE)	
YA1/72/85/1/25	1295–1340	D-AMS 032047	*Oryza sativa*	1998 ± 29	53cal BC -70 CE	Rampart Pd. (2nd BCE - 1st CE)	
A1/33/94/2/24	1636–1705	BS-4093	Charcoal	2040 ± 120	90 ± 120 BCE	Rampart Pd. (2nd BCE - 1st CE)	
A1/33/94/2/28	1768–1781	BS-4099	Charcoal	2222 ± 108	272 ± 108 BCE	Pre-Rampart Pd. (Pre 2nd BCE)	

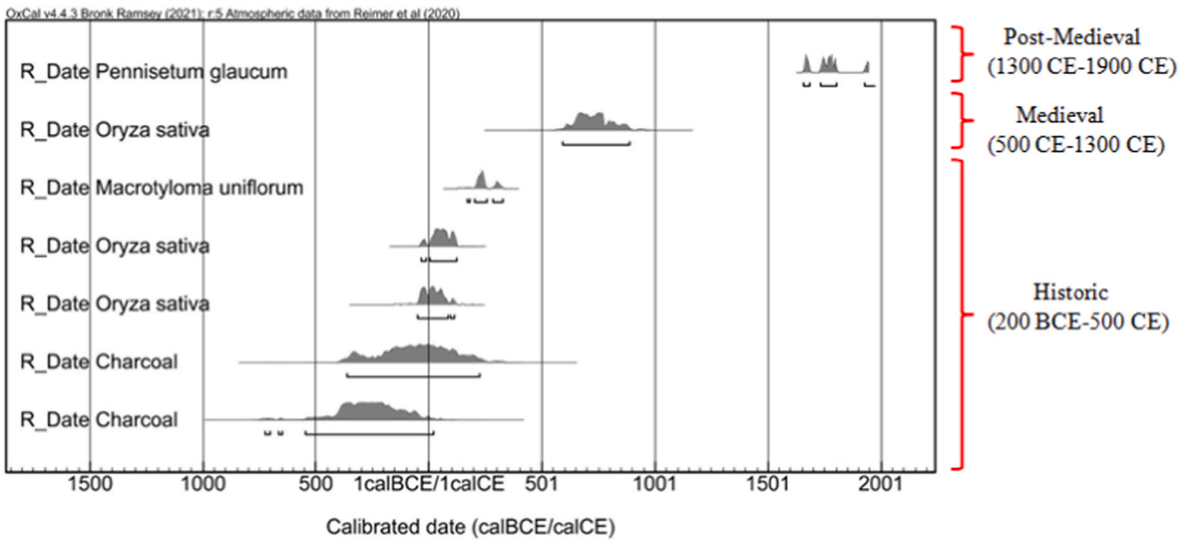

Fig. 3. Calibrated radiocarbon probability ranges.

distilled water and heavy liquid flotation was performed using a solution of cadmium iodide and potassium iodide at specific gravity 2.3. A minimum count of 400 phytoliths was achieved in most samples and phytolith morphotypes were categorised using standard classifications (International Committee for Phytolith Taxonomy (ICPT) et al., 2019). Photographs were taken on a Leica DM 2500 microscope (400 ×). Cluster analysis was performed using CONISS in Tilia (Grimm, 1987). A total of 19 phytolith morphotypes were identified, including grass and non-grass phytoliths. A humidity/aridity index or Iph (%) suitable for tropical environments was calculated based on the ratio of chloridoid type phytoliths to the sum of panicoid and chloridoid types. Typically an Iph value of <30% suggests humid conditions and a value of >30% suggests arid conditions (Twiss, 1992).

4. Results

4.1. Chronology of Vadnagar

Based on the radiometric dates (Table 1; Fig. 3) and archaeological materials, three broad phases comprising a number of historic or dynastic sub-phases have been identified: the Historic Phase I at the site ranges 200 BCE–500 CE comprising the Pre-Rampart to Kshatrapa sub-phases, the Medieval Phase II ranges 500–1300 CE (Post-Kshatrapa and Solanki sub-phases) and the Post-Medieval Phase III ranges 1300–1850 CE (Mughal and Gaekwad sub-phases). These find agreement with other published site chronologies (Agnihotri et al., 2021).

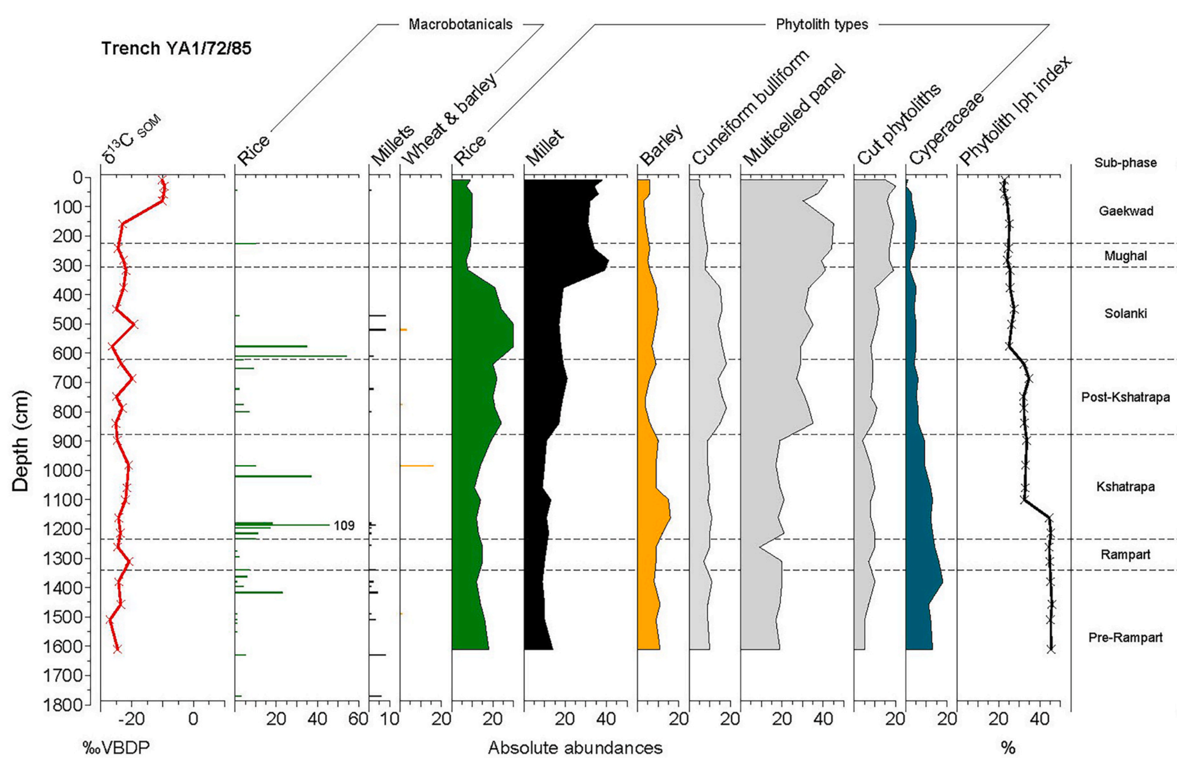

Fig. 4. Stratigraphic plot of $\delta^{13}C_{SOM}$, macrobotanical abundances, crop and Cyperaceae phytolith abundances, phytolith Iph index from Trench YA1/72/85.

4.2. Isotopic data

Sediment carbon stable isotope ($\delta^{13}C_{SOM}$) values display a large degree of variability from −27.0 to −9.3‰ with average value of −21.1‰ ±5.1 (Fig. 4). During the Historic and Medieval (ca. 200 BCE to 1300 CE) $\delta^{13}C_{SOM}$ values reflect a C_3 dominated environment with a mean value of −23.9‰±1.9. The Post-Medieval period (1300–1850 CE) is characterised by enriched values of −9.8‰±0.4, typical of a C_4 dominated agriculture.

4.3. Macrobotanical remains

A total of 562236 carbonised grains/seeds/fruits were recorded and identified (Supplement 1; Supplement 2 - Fig. 3). In general, the cultivated plants include both winter growing crops (barley - *Hordeum vulgare*, wheat - *Triticum aestivum/durum*, pea - *Pisum sativum*, lentil - *Lens culinaris*, and flax - *Linum usitatissimum*) and summer crops (rice - *Oryza sativa*, sorghum - *Sorghum bicolor*, pearl millet - *Pennisetum glaucum*, broomcorn millet *Panicum miliaceum*, foxtail millet - *Setaria italica*, mung/urd bean - *Vigna radiata/mungo*, horse gram - *Macrotyloma uniflorum*) The most common finds were rice and millets (especially *Pennisetum glaucum* and *Sorghum bicolor*), but finds also include other cereal crops, pulses, fibre crops, fruits and a few wild taxa. Detailed quantities of sediment floated and remains recovered from each sample are presented in Supplement 1. The density of cereal remains per litre of sediment is 0.36/L during the Historic Phase, 0.47/L during the Medieval Phase and 1245/L during the Post-Medieval phase.

In the Historic Phase I (200 BCE−500 CE) winter crops compose 4% of the total plant assemblage that was dominated by summer rice and pulses. Large-grained cereals (mainly rice) account for 95% in comparison with 5% for small-grained cereals/millets (Fig. 4; Supplement 2 - Figs. 4 and 5). During Phase II (500−1300 CE; MWP) large-grained cereals account for 85% whereas small-grained millets account for 15% (Fig. 4; Supplement 2 - Figs. 4 and 5). The majority of charred crop remains from these two phases are from Trench YA1/72/85 and are presented stratigraphically in Fig. 4.

The Phase III (1300−1850 CE), assemblage is dominated by charred caryopses of millets (97%), mostly *Pennisetum glaucum* and *Sorghum bicolor*. Mung bean (*Vigna radiata*) is also well represented in this phase (Fig. 5; Supplement 2 - Figs. 4 and 5). We note that these remains are primarily recovered from a deposit containing over 500,000 carbonised grains from Trench YA1/92/73 and are presented as a single context in Fig. 5.

4.4. Phytolith data

A total of nineteen phytolith morphotypes were identified (Fig. 6), excluding unidentified types. Throughout the profile the relative proportion of Grass Silica Short Cells (GSSCs) was dominant, followed by other grass and non-grass cells. Multicell panels including indeterminate leaf/culm panels from crops, and cut phytoliths were also recovered. Family-specific Cyperaceae phytoliths were also observed. The crop phytoliths include various millet, rice, wheat and barley type morphotypes indicating some agricultural provenance. Iph−humidity are presented in Fig. 4.

Phase I (200 BCE–500 CE) - Grass phytoliths dominate, ranging from 85 to 90%. GSSCs account for 45−52% with lower relative abundances bilobates (22−29%), cross (1.5−3%), saddles (8−10%), rondels (4−8%) and trapezoids (5–10%). The elongate psilate and elongate dendritic compose 5−8% and 8−9% respectively. Various crop phytoliths include millets, rice, barley, cut phytoliths range 17–20%. Cyperaceae phytoliths are highest in this zone, from 3 to 5%. The Humidity-aridity index or Iph% ranges 22−28%, the lowest in the record.

Phase II (500–1300 CE) - This is dominated by grass phytoliths from 86 to 91%, the highest in the whole profile. The GSSCs range between 41 and 50%, including bilobates (17–19%), cross (2–4%), saddles (10–11%), trapezoids (4−6%) and rondels (4−6%). Psilate and dendritic elongate types account for 8−9% and 5%–6%. Total crop phytoliths account for 26−30%, while rice type phytoliths were highest in this zone (5−8%). An increase in millet phytoliths was observed. The Humidity-aridity index was 32%–35%, slightly higher than the preceding zone.

Phase III (1300−1850 CE) - Grass phytoliths dominate as in Phases I & II (84−89%). GGSCs range from 35 to 39% including bilobates (12−16%), cross (2–5%), saddle (13–15%), rondels (2−4%) and trapezoid (3−4%) types. Elongates including psilate and dendritic types account for 8−12% and 4−5% respectively. Total crop phytoliths were highest in this zone (26−31%), especially millet types between 8 and

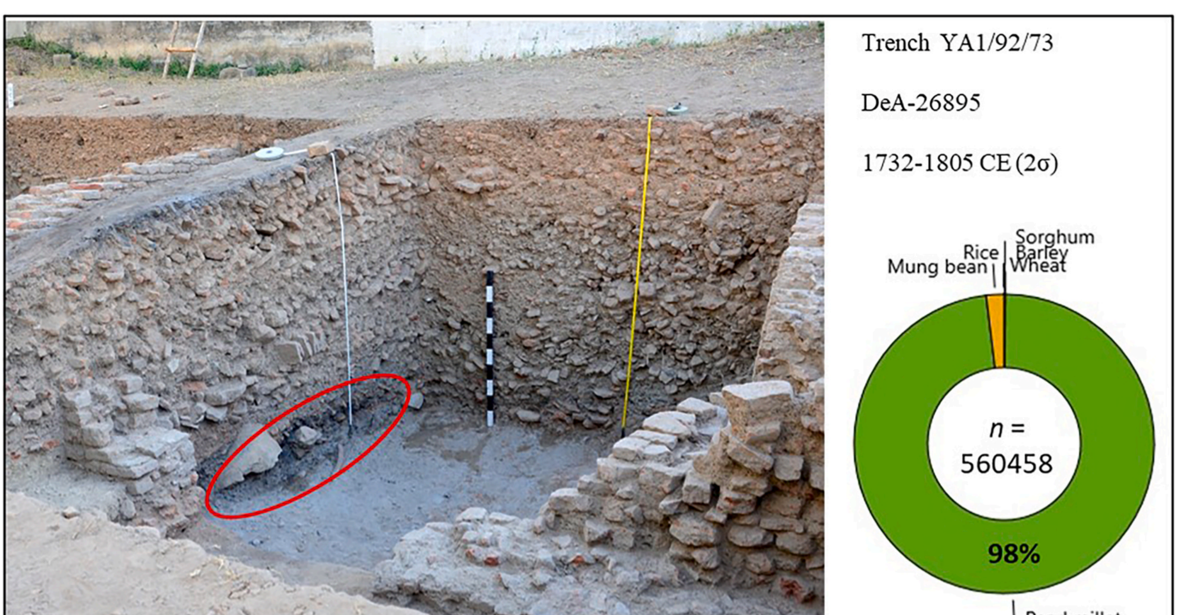

Fig. 5. Plant macroremain bearing context (circled in red), AMS date DeA-26895, and crop relative abundances from Trench YA1/92/73. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

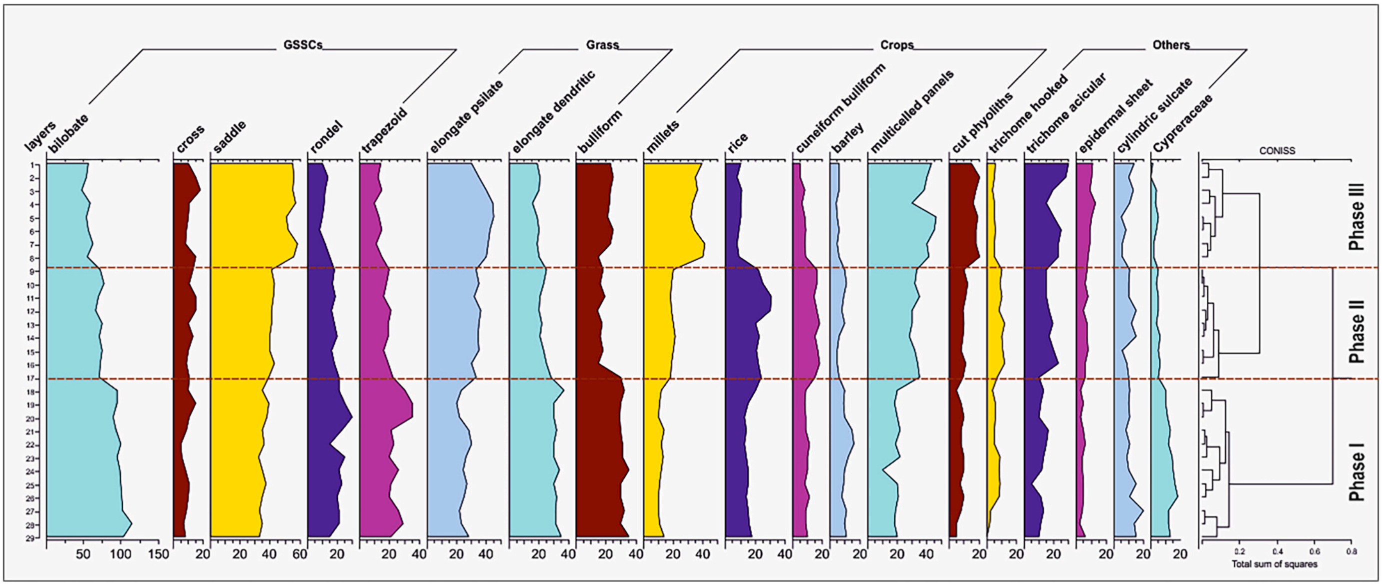

Fig. 6. Phytolith spectrum from Vadnagar (absolute abundances).

10%. Cyperaceae phytoliths were at their lowest abundance. The Humidity-aridity index was highest in this zone, ranging 44%–46%.

5. Discussion

5.1. Late Holocene climate in arid northwest South Asia

At present, there are few high-resolution palaeoclimatic records covering the past 3000 years in northern Guajarat. Pollen from the three uppermost (15 cm) samples from a Pariyaj Lake core (Raj et al., 2015) have been interpreted as indicating dry, winter precipitation dominated conditions over the last 3500 years, while at Wadwhana Lake (Prasad et al., 2014) multiple proxies from the upper 20 cm of sediment dated ca. 700 BCE – 700 CE have been interpreted as indicators of a warm humid climate. Due to the low sampling resolution of these studies we approach these interpretations cautiously. Two studies on organic carbon and sediment geochemistry from coastal Gujarat (Banerji et al., 2017, 2019) also indicate a warm humid climate and enhanced monsoon precipitation between ca. 1000 to 1500 CE, followed by an arid event between ca. 1600 to 1800 CE that the study authors correlate with the Medieval Warm Period and Little Ice Age respectively. Also in southern Gujarat, sediment size classes and variations in terrestrial and marine palynofacies have been interpreted as indicating warm humid conditions between ca. 600 to 1600 CE, with weaker monsoon precipitation indicated during the last 400 years (Thakur et al., 2019).

Pollen data from Mandovari lake at Chandravati in southern Rajasthan, around 80 km north of Vadnagar indicate a shift from tropical deciduous forests to drier open grasslands at around 1500 CE (Pokharia et al., 2020), interpreted as evidence of weakened summer monsoon precipitation, also correlated with the LIA. From archaeological contexts at Chandravati, a shift in phytolith abundances from Panicoid to Chloridoid grasses and a decline in Cyperaceae are indicators of increasingly arid conditions locally after ca. 1400 CE. These shifts are concomitant with a major change in relative abundances of crop plants among the macrobotanical assemblage, from large-grained winter/-summer cereals prior to 1400 CE to small-grained summer millets after this time.

Oxygen stable isotope ($\delta^{18}O$) records from Himalayan cave speleothems at Mawmluh (Kathayat et al., 2022) and Sahiya (Kathayat et al., 2017) have been interpreted as indicating Indian Summer Monsoon variation over the last 2000 years. At Sahiya (Kathayat et al., 2017), declining $\delta^{18}O$ values from ca. 250 to 500 CE are interpreted as weakening monsoonal precipitation, followed by an in increase until ca. 1000 CE, argued to be correlated with the Medieval Warm Period. A subsequent decline is correlated with the Little Ice Age at around 1600 CE. In the Mawmluh record (Kathayat et al., 2022), minima in $\delta^{18}O$ at around 1600 CE and another sharp decline lasting around 100 years from 1700 CE have been correlated with several periods of multi-decadal drought in the historic record and associated with the Little Ice Age.

Environmental signals in the phytolith data from Vadnagar are generally consistent with these regional climatic changes. During the Historic phase (200 BCE−500 CE), the relative proportion of Panicoid phytoliths was highest with Chloridoid types being the lowest, suggesting mesic vegetation around the site. Cyperaceae phytoliths were present in higher proportions in this zone, also indicating a warm and humid climate. An Iph value ranging from 22 to 28%, supports this interpretation and likely results from stable monsoon conditions.

In the following Medieval phase (500−1300 CE), a slight decrease in Panicoid phytoliths was seen and an increase Chloridoid phytoliths may represent a landscape with a higher abundance of arid adapted grasses. This change is reflected in an increase in Iph values at Vadnagar, ranging 32–35%. In the Post-Medieval phase (1300−1850 CE) further aridification is indicated by an increase in Chloridoid phytoliths and a decline in Panicoid phytoliths. Cyperaceae phytolith abundances remain below 10. Iph values around 44–46% suggest a further reduction of available moisture in the local environment.

The phytolith data generally represent a stepwise increase in aridity over the last 2000 years, with the arid conditions of the last 600 years especially consistent with regional palaeoclimate records indicating arid events identified with the Little Ice Age (Dixit and Tandon, 2016; Kathayat et al., 2017), however our data may also indicate lower levels of local humidity prior to ca. 1000 CE than is indicated by regional palaeoclimate records.

5.2. Droughts and famines in historical records

Drought in the Indian sub-continent is generally due to a failure (precipitation 2σ below long-term average) of the southwest monsoon. The drivers of failure are persistent atmospheric subsidence, with the EI Niño phase of the Southern Oscillations (ENSO) having the strongest relationship with drought (Kumar et al., 2006; Ummenhofer et al., 2011). ENSO driven summer drought has been correlated with historic reductions in summer grain production, with flow-on reductions in winter crops requiring carryover soil moisture (Selvaraju, 2003). Historical accounts of famines in India record 14 famines between the 11th and 17th centuries, 12 between 1769 and 1858, and 20 between 1860 and 1908 (Das, 1988). While noting the complex social, political and environmental factors in famines, Kathayat et al. (2022) closely correlate multi-year monsoon failure in speleothem proxy data and the instrumental record with climate events such as the Little Ice Age and relate these to historical records of mass mortality famines, urban abandonments and social instability. Conversely - synthesising palaeoclimate data, modelled past ENSO events and historical accounts, Damodaran et al. (2019) argue that while a number of crises during the 17th century in India were contemporary with arid conditions associated with the Little Ice Age, the authors question whether institutional or other historical factors played a larger role than environmental factors. The authors cite 19th century observations by Danvers and Campbell regarding late 18th century famines that describe disruption of labour patterns, institutional mismanagement and singular catastrophic environmental events as larger factors in regional famines than protracted environmental phases (Damodaran et al., 2019, p. 68). Similarly, Mukherjee (2019) cites Mundy's description of the diversion of food resources away from the general population and towards military expeditions during the Gujarat famine of 1630-32 to argue that institutional failings rather than environmental perturbations were major factors in widespread famine. These arguments contrast with an examination of the correlation between drought and famine in southern India during the British colonial period (Ray et al., 2021). Rather than acute single rain failures as the cause of social disruption, the study authors argue that protracted periods of sub-average ($1-3\sigma$) rainfall were greater factors in crop failure and famine.

Taking a longer term view, in a synthesis of historical archaeology in India, Dhavalikar (1999) characterises the period 400 to 1000 CE as a period of "second urban collapse" in northern India. It is argued that this is evidenced by abandonment of urban centres and dispersal of populations to rural hinterlands in the archaeological record, combined with historical accounts describing adverse climate conditions, crop failures and famines. The data in our study indicating long-term, gradual reduction in humidity through the Late Holocene, combined with an archaeological record of occupation and food production, presents an opportunity to assess human adaptation to protracted environmental change.

5.3. *Resilient agricultural strategies at Vadnagar*

The archaeological, botanical and sediment isotopic data at Vadnagar indicate an agricultural economy supporting long-lived and continuous urban occupation from the Historic to Post-Medieval period. Archaeological investigations have revealed that town-planning remained unchanged for around 1900 years, from about the first century CE to the nineteenth-century CE. This level of continuity of urban settlement and form is not only very rare in northwest India, but is rare in South Asia more broadly, and the results here are among the first presented for such extended urban continuity. We attribute part of this continuity of occupation to the development and use of selective agricultural strategies, including hydraulic infrastructure and administration, that were able to either adapt to or ameliorate climatic changes in the region.

The archaeobotanical assemblage from Vadnagar during Phase I (200 BCE−500 CE) and Phase II (500 −1300 CE) has a wide range of crop plants (Fig. 4; Supplement 1; Supplement 2), indicating a summer/winter cropping system comprising cereals such as barley (*H. vulgare*), bread-wheat (*T.* cf. *aestivum*), dwarf-wheat (*T. sphaerococcum*), rice (*O. sativa*), pearl-millet (*P. glaucum*), and sorghum-millet (*S. bicolor*). Leguminous crops are represented by field-pea (*P. arvense*), grass-pea (*L. sativus*), green-gram/black-gram (*Vigna* sp.), horse gram (*M. uniflorum*), *Lens culinaris* and *Lablab purpureus*, and additional crops including linseed (*Linum* cf. *usitatissimum*) and cotton (*G. arboreum/herbaceum)*. While Phases I and II at Vadnagar are composed of a mix of large-grained summer and winter cereals, the assemblages are still numerically dominated by the summer season, rice, and summer pulses. The higher relative abundances of large-grained cereals among the macrobotanical remains is also reflected in the crop phytolith assemblage during Phases I and II, with rice and barley morphotypes dominating the crop assemblage (Fig. 4). Through this period, $\delta^{13}C_{SOM}$ values varied ranged from −27.02 to −19.29‰ (mean −23.9‰±1.9) are interpreted as also indicating a C_3 dominated vegetation landscape. As we argue sediments in the Locality C habitational layers would have been derived from nearby arable fields, these variations most likely reflect agricultural patterns.

The dominance of large-grained cereal agriculture during this period – especially water demanding rice, despite the apparent reduction in available moisture evident in our phytolith data and other regional studies raises questions regarding technological or administrative adaptation that allowed the continuity of these cropping systems. The archaeological remains and epigraphs at Junagadh dam in southern Gujarat (Shaw and Sutcliffe, 2003) describe a "natural" reservoir converted to a larger dam through the construction of embankments dating to the first centuries CE. Epigraphic inscriptions from the Mauryan and Kshatrapa periods indicate the dam was maintained through Buddhist and later Brahminical patronage systems that drew on these earlier traditions (Shaw and Sutcliffe, 2003). From the 8th century CE onwards, stepwell (*vapi*) technology developed in southern India spread to arid regions of Rajasthan, Madya Pradesh and Gujarat (Pandey et al., 2003), while the *araghatta* or Persian wheel allowed the distribution of water from deep storage systems possible (Hardiman, 1998). The construction *vapi* and *araghatta* was typically undertaken through systems of Brahminical patronage, particularly during the Solanki dynasty in northern Gujarat where land subdivision and distribution during arid periods apparently allowed for agricultural diversification and expansion (Gupta, 2017). We may relate this historical and archaeological evidence to the higher abundances of water demanding crops in our archaeobotanical data from this period, arguing that crop selection, locally developed and adapted water management infrastructure, and complex institutional management may allow ongoing production despite apparent reductions in monsoon precipitation. Despite political changes during the Islamic period in north India, historical records indicate that patronage of water management systems was typically maintained, at least up until the British colonisation in the early 19th century (Hardiman, 1998; Jain et al., 2022).

During Phase III (1300−1850 CE), large-grained cereals (rice, wheat, barley) declined significantly in the macrobotanical assemblage, whereas small-grained millets (sorghum & pearl millet) dominated the agricultural produce with close to 100% relative abundance. However, the sheer abundance of *Pennisetum glaucum*. ($n > 500{,}000$) grains suggests that the archaeological context from which they were sampled was a food storage deposit, rather than deposited in ash or refuse as was likely in previous phases. This interpretation is supported by the modest quantities of sorghum ($n = 592$) and mung bean ($n = 10833$) from the same context, which can be expected when a storage feature is reused for a few subsequent crops. As a result, interpretation of this macrobotanical assemblage is difficult, however the abundance of drought resistant millets (*Pennisetum glaucum* and *Sorghum bicolor*) in the Post-Medieval period at Vadnagar suggests a strategic shift towards of drought-resistant summer crops, resembling similar shifts seen in Indus Valley Civilisation period sites in Gujarat in response to weakening monsoon precipitation during the early 2nd millennium BCE. (Pokharia et al., 2011, 2017).

As the millet macrobotanical remains are recovered from a single context in Trench YA1/92/73, we approach their interpretation with caution, however the phytolith and isotopic data in continuous sequence from Trench YA1/72/85 indicate that these changes are not confined to a single context but likely reflective of changes in crop production and processing more generally across the site. Within both Mughal and

Gaekwad (i.e. 16th–19th centuries CE) contexts, millet phytoliths dominate large-grained cereal types, while $\delta^{13}C_{SOM}$ values in the Gaekwad sub-phase shift from a minimum of −22.9‰ to a maximum of −9.27‰ (mean −12.4‰±5.25) that is the result of higher inputs C_4 plants, likely being millet crops. The shift from a rice dominated agriculture to one dominated by millets during the Gaekwad period seems to indicate that water availability rather than seasonality was a driver of agricultural adaptation around the site. This contrasts with other regional studies that indicate more balanced shifts in the agricultural package as a response to changing climate conditions (Pokharia et al., 2020; Thakur et al., 2019). The archaeobotanical data from these later contexts also mirror the present-day cultivation practices around Vadnagar and indicate that the development of this current system was a comparatively recent phenomenon, taking place within the last few centuries. While this shift may be attributed to more acute arid conditions associated with the Little Ice Age, Jain et al. (2022) note the disruption of patronage systems and obligations in relation to water management systems during the British colonial period in favour of revenue generating irrigation systems. During the Gaekwad period under British suzerainty, it is possible that these institutional changes exacerbated climate stressors leading to the expansion of arid adapted millets more suitable to rainfed cultivation.

6. Conclusion

The adaptability of the farmers around Vadnagar evidenced in the archaeological record here has implications for historians investigating the relationship between climate change, drought, and famine. While long-term environmental conditions were likely drivers of changing cultivation patterns around Vadnagar, this took place within an established subsistence and hydraulic tradition that was highly resilient to climatic fluctuations. The archaeobotanical data we present here, as well as other regional case studies (Pokharia et al., 2020) indicate that Indian farmers of the northwest arid zones were in the past able to accommodate or adapt to climate events of the last two millennia, expanding the agricultural package to capitalise on higher precipitation when available, able to shift to more arid adapted crops during periods of increased aridity and drought, and able to construct and manage hydraulic landscapes that helped to ameliorate the worst impacts of those fluctuations. Moreover, even when the administration of their hydraulic systems was impacted by Colonisation, local farmers were still able to adapt via shifts in cultivated crops – representing resilience against both climatic shifts as well as administrative changes. The parallels between regional developments in water management systems and the modification of Sharmistha Lake at Vadnagar indicate scope for future detailed study into the historic water management system in the city. While future climate change may be more pronounced than previous Holocene shifts, and may increase the likelihood of catastrophic events, we argue that variability among archaeobotanical datasets from sites where occupation was continuous through multiple, changed environmental conditions and administrative regimes provide useful insight into ways that these impacts may be reduced. A resilient response to future conditions would require considered management of water resources, labour, food production and distribution in northwest India.

CRediT authorship contribution statement

Anil K. Pokharia: Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing, Formal analysis, Data curation, Funding acquisition. **Himani Patel:** Investigation, Writing – review & editing. **Abhijit S. Ambekar:** Investigation, Writing – review & editing, Funding acquisition. **Michael Spate:** Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Deepika Tripathi:** Investigation, Formal analysis. **Shalini Sharma:** Writing – review & editing. **Rajesh Agnihotri:** Investigation, Writing – original draft, Formal analysis. **Keir M. Strickland:** Investigation, Writing – review & editing. **Lara González-Carretero:** Investigation. **Ravi Bhushan:** Investigation. **Alka Srivastava:** Investigation. **Ruchita Yadav:** Investigation. **A. Shivam:** Investigation. **Ankur J. Dabhi:** Investigation. **K.P. Singh:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.qsa.2023.100155.

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