Reconstructing the Climate Variability During the Last 5000 Years From the Banni Plains, Kachchh, Western India

Nisarg Makwana1, S. P. Prizomwala1, Archana Das1*, Binita Phartiyal2, Aashima Sodhi1,3 and Chintan Vedpathak1,3

1Institute of Seismological Research, Gandhinagar, India, 2Birbal Sahni Institute of Paleosciences, Lucknow, India, 3Research Scholar, Gujarat University, Ahmedabad, India

The climatic conditions during the beginning of the last 5,000 years have been discussed, debated, and documented from various parts of the Indian subcontinent, due to the human–climate interrelationship. In the present study, we report a multi-proxy dataset encompassing the widely used ~ geochemical and mineral magnetic proxies supported by radiocarbon and optical chronologies from the Banni Plains of the Rann of Kachchh, western India. Our results support the earlier observations of the prolonged wetter climatic condition synchronous with the mature phase of Harappan era which witnessed a short and intense arid condition at the terminal part of the mature Harappan phase. The climate system dramatically fluctuated during the last five millennia from pulsating between relatively arid (4,800–4,400 years BP, 3,300–3,000 years BP, and at 2,400 years BP) and relatively humid phases (>4,800 years BP, 4,000–3,300 years BP, 1900–1,400 years BP, and 900–550 years BP). The multi-proxy dataset shows a gradual strengthening of the monsoonal conditions from the Banni Plains during the late Harappan phase. Apart from this, the high sedimentation rate (>1 mm/yr) recorded from the Banni Plains suggests it can be tapped as a robust archive to reconstruct multi-decadal to centennial climatic events spanning the Holocene epoch.

Keywords: paleoclimate, Banni plains, middle to late Holocene, Kachchh, Harappan civilization 2

INTRODUCTION

Southwest Indian monsoon has a high socioeconomic impact as it plays a key role in delivering annual rainfall (nearly 80%) in the Indian subcontinent (Anderson et al., 2010; Berkelhammer et al., 2010). An understanding of the variability of Indian summer monsoon (ISM) rainfall for the Holocene epoch is vitally required to assess the speculated link between the climate deterioration and the decline in ancient civilization. The mid-Holocene, in particular, has witnessed several changes in climate with abrupt short events recorded globally as well as in the Indian subcontinent (Lamb, 1985; Bianchi and Mc Cave, 1999; Anderson et al., 2010; Sanwal et al., 2013; Quamar and Chauhan, 2014; Ngangom et al., 2016). Prasad et al. (2007), Prasad et al. (2014 b) reported wetter climate during the 5.5 to 2.8 ka BP from the lacustrine environments of Mainland Gujarat. Similarly, Laskar et al. (2013) reported subhumid climatic conditions from fluvial sediments of the Mainland Gujarat region. The period between 2.8 and 1.3 ka has reportedly experienced arid conditions from the lacustrine and fluvial records of Mainland Gujarat (Laskar et al., 2013a; Prasad V. et al., 2014; Sridhar et al., 2014a). Raja et al. (2019) reported paleoflood activity during 4,773 cal yr BP from the Parsons Valley Lake, Tamil Nadu. Consequently, the mid-to-late Holocene tend to have recorded various centennial
scaled abrupt climatic variations. However, studies documenting the climatic variations on the centennial to decadal scale are still limited and need to be looked upon (Binanchi and Mc Cave, 1999; Gupta et al., 2003; Sinha et al., 2007; Chauhan et al., 2009; Makwana et al., 2019).

The Great Rann of Kachchh (GRK) in western India is a semi-enclosed basin and a dominantly depositional microenvironment, and hence the paleo-mudflats of Rann have proven to be useful to decipher past climatic oscillation in different timescales (Pillai et al., 2017, 2018; Basu et al., 2019; Makwana et al., 2019). The recent efforts have hinted that the Rann sediments remain a treasure trove for reconstructing Holocene paleoclimate (Ngangom et al., 2016; Pillai et al., 2017, 2018; Basu et al., 2019; Makwana et al., 2019; Sengupta et al., 2019; Sarkar et al., 2020). The Rann of Kachchh is believed to be a Holocene sediment depocenter (Maurya et al., 2013) and also has been a hotspot of mature and late Harappan occupation, which believed to be a riverine and trade-oriented civilization during 7000 BP to 3900 BP (Gaur et al., 2013; Sarkar et al., 2020). Large urban centers of mature Harappan settlements flourished along the Indus and Ghaggar-Hakra rivers (Possehl, 2002), and were considered to have abruptly ended around 3,900 years BP (Possehl, 2002). Also, the mid-Holocene climatic changes are coincident with the appearance of highly organized and urbanized civilizations from the Afro-Asiatic monsoonal region such as Egypt, Mesopotamia, Indus-Saraswati, and in northern China regions that form the bulk of the deserts today (Brooks, 2006; Prasad V. et al., 2014). However, the reasons for the decline of these civilizations, viz. abrupt climate change, sea level fluctuation, or reduction of natural resources, are still a question of debate for the researchers (Galili 1988; Staubwasser et al., 2003; Wright et al., 2008; Giosan et al., 2012; Dixit et al., 2014, 2018; Das et al., 2017; Sengupta et al., 2019).

Some of the intriguing questions regarding the paleoclimatic conditions, particularly, in the Kachchh region of western India are as follows: 1) What were the paleoenvironmental conditions that existed in the Banni Grassland during the middle-to-late Holocene? 2) How did the climatic fluctuations change since the mature Harappan times? In light of this, the objective of the present study is to reconstruct the past climatic events from the Banni Plains and explore their nature/boundary conditions during the last 5,000 years using a multi-proxy dataset.

**STUDY AREA**

The GRK is a unique and intriguing vast salt encrusted flat land, which is an E–W trending subbasin and occupies almost half of the area of the seismically active Kachchh paleo-rift basin (Burnes, 1834; Glennie and Evans, 1976; Biswas, 1987). The Banni Plain is a part of the extensive low-level hyper arid saline tract of the Great Rann that occupies the northern part of the seismically active Kachchh paleo-rift basin. The Banni grassland happens to be only the inhabited part of the Great Rann due to the fact that it occurs at the highest elevation and is free of present-day marine submergence (Roy and Merh, 1981). Large parts of the Banni get submerged during monsoon under a thin sheet of water by rainfall and rivers from the Kachchh mainland in the south.

The present study site BKR (23°32'48.12"N and 69°40'30.36"E) is situated in the central to the northern part of the Banni Plains (Figure 1). The Banni Plains and the GRK are covered by the quaternary deposits mostly comprising silt and clay sediments and considered as Holocene depocenters (Gupta, 1975; Maurya et al., 2013; Khonde et al., 2017a; Makwana et al., 2019) of three distinct sources, viz. Indus source from north, Aravalli in east, and Kachchh Mainland in south (Maurya et al., 2013; Khonde et al., 2017a, b). It experiences a hyper-arid to arid climate with annual rainfall less than 30 mm per year (Figure 1). However, till now there are limited data pertaining to the paleoclimate, provenance, and the nature of sediment comprising the Banni Plain. With an aim to study the evolution of these majestic landscape features, which probably beholds vital insights on middle-to-late Holocene climatic fluctuations, a shallow trench from the paleo-mudflat of the Banni Grassland has been investigated. Trench is 5.5 m deep (BKR site) and located on Bhuj-Khavda road (Figure 1) in the Banni Plains. Geomorphologically, the study site is surrounded by higher Banni surface with an elevation varying from 4 to 12 m asml. The elevation of the trench site was 4.4 m above the present day mean sea level (msl) measured based on a D-GPS survey. The studied site is away from any human settlement, which assures negligible to nil anthropological effect.

**ANALYTICAL METHODS**

**Sediment Geochemistry**

$\text{Al}_2\text{O}_3$, $\text{Fe}_2\text{O}_3$, and $\text{TiO}_2$ are the major components of the aluminosilicate phase group and are useful to deduce the post depositional weathering and paleoenvironmental condition that prevailed in the region (Nesbitt and Young, 1982; Agnihotri et al., 2003; Tyagi et al., 2012; Das et al., 2017). Similarly, the ratio of $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ and CIA (Chemical Index of Alteration) has been used to measure the chemical weathering intensity in the region (Nesbitt and Young, 1982; Buggle et al., 2011; Pillai et al., 2018). The natural samples in the near-shore and marine-influenced environments may contain CaO content, originating from marine organisms. Hence, the samples collected from the field were treated with 1 N HCl until the CaO fraction was removed. These decarbonated samples were then used for estimating CIA, which represents the detrital content, originating due to the chemical weathering in the source region. A total of 55 samples were collected from the BKR site and dried at 50°C, crushed, homogenized, and sieved to <63 μm size. A part of this fraction was used for the analysis in XEPOS HE XRF instrument at the Institute of Seismological Research, India. The analytical precision of major oxide was better than 5% and that of trace elements was better than 10% (Das et al., 2017; Makwana et al., 2019).

**Mineral Magnetic Measurements**

Environmental magnetic properties of sediment samples were measured using standard rock magnetic methods (Walden et al.,
Selected samples were oven-dried and packed, ensuring no movement of magnetic minerals in nonmagnetic plastic bottles of 10 cm$^3$ for analysis. In the present study, we have measured magnetic susceptibility ($\chi$), anhysteretic remnant magnetization (ARM), and isothermal remnant magnetization (IRM) at Birbal Sahni Institute of Palaeosciences, Lucknow, India. Low magnetic susceptibility ($\chi_{\text{LF}}$) was measured using a Bartington MS2B dual-frequency susceptibility meter at 976 Hz frequency. Samples were first demagnetized by using the AF demagnetizer, and then anhysteretic remnant magnetization (ARM) was calculated in a steady 0.05 mT field superimposed over decreasing alternating field (AF) up to 100 mT using the alternating field demagnetizer, D-2000 AF demagnetizer. The remnant magnetization of all ARMs and IRMs was measured using a AGICO JR-6 dual speed spinner magnetometer. Isothermal remnant magnetization (IRM) was measured at forward fields of 20 and 1000 mT and backward fields of $-20$, $-40$, $-60$, $-100$, and $-300$ mT using ASC scientific impulse magnetizer. IRM measured at 1 T field was considered as saturation isothermal remnant magnetization (SIRM). The S-ratio is indicative of the ferrimagnetic vs. anti-ferrimagnetic minerals, and the value close to one corresponds to the dominance of the ferrimagnetic minerals. S-ratio is often used as paleo-monsoonal proxy calculated using the formula $\text{IRM}_{0.3} / \text{SIRM}$ (Basavaiah and Khadkikar, 2004).

AMS C-14 Dating
AMS is a modern and more efficient radiocarbon dating method for younger time frames to measure long-lived radionuclide that occurs naturally in environment. We have used two different samples of handpicked foraminifera from unit 2 to estimate the age of sediment deposition. Foraminifera tests were separated out from the samples and sent to Poznan Radiocarbon Laboratory, Poland, for AMS $^{14}$C dating. For both the uncalibrated ages, we used a marine reservoir effect ($\Delta R$) of $-8 \pm 37$ from northern Arabian Sea, as it was the closest possible value available from the studied point and represented similar semi-enclosed environment (Dutta et al., 2001). We used the latest available online CALIB 8.2 program for Marine13 dataset (Stuiver et al., 2018). Calibrated ages are expressed as calendar years over a 2$\sigma$-error range (95.4%).

RESULTS
Stratigraphy and Chronology of the BKR Trench
Based on the visual observations of sedimentological, textural, structures and variation in color, the entire succession was divided into three major litho-units (Table 1). At the BKR trench site, the bottommost exposed unit is a 70-cm-thick sticky dark bluish clay horizon (unit-1), followed by a 330-cm-thick brown silty clay deposit (unit-2). The foraminifera tests were collected from this unit, which yielded a calibrated AMS $^{14}$C age of 3,157–3,520 cal yr BP (median value: 3,339 ± 181 cal yr BP).

| Litho-units | Thickness (in cm) | Textural class                  |
|-------------|-------------------|--------------------------------|
| Unit-3      | 170               | Clayey silt horizon with faint laminations |
| Unit-2      | 330               | Silty clay horizon             |
| Unit-1      | 70                | Sticky dark bluish clay horizon |

FIGURE 1 | Digital elevation model of Kachchh showing the location of the study area and trench site in Kachchh.
and 3,833–5,032 cal yr BP (median value: 4,432 ± 600 cal yr BP) (Table 2) at depth of 2.3 and 4.1 m, respectively, from the top of the trench surface. Unit-2 is overlain by 170-cm-thick clayey silt dominated horizon with faint laminations, that is, Unit-3 (Figure 2). Owing to the lack of datable material and negligible amount of foraminifers, the bottom age of 4,432 ± 600 cal yr BP shows a wider error scatter, due to mixing of foraminifer tests from two adjacent samples. Hence, due to the lack of available chronology, we assumed a relatively uniform sedimentary sequence in Unit-2 to extrapolate two ages, that is, 4,800 years BP and 3,035 years BP on the basis of the sedimentation rate between the dated depths.

**Major Oxide Concentration and Their Elemental Ratio Variation**

The concentration of major oxides and trace elements along with their ratios were studied and based on significant deviations in statistical parameters; a total of three relatively arid and four humid phases of paleoclimatic conditions are deduced (Supplementary Table 1).

**Zone 1**

Zone 1 encompassing the concentration variation of Al₂O₃, Fe₂O₃, and TiO₂ from 14.33 to 15.62%, 4.75 to 5.48%, and 0.73 to 0.80%, respectively. The oxide ratios of K₂O/Al₂O₃, Na₂O/TiO₂, CaO/TiO₂, and Fe₂O₃/TiO₂ varied from 0.17 to 0.19, 1.58 to 2.56, 11.34 to 12.52, and 6.50 to 6.91, respectively. Similarly, the elemental concentration of Sr and Ca varied from 202 to 211 ppm and 6.3 to 6.7%, respectively. The ratios of Zr/Al varied from 15.1 to 21.0. The values of weathering intensity CIA varied from 82 to 85 (Supplementary Table 1).

**Zone 2**

Zone 2 shows the concentration of Al₂O₃, Fe₂O₃, and TiO₂ varied from 13.9 to 15.2%, 4.2 to 5.4%, and 0.76 to 0.81%, respectively. The oxide ratios of K₂O/Al₂O₃, Na₂O/TiO₂, CaO/TiO₂, and Fe₂O₃/TiO₂ varied from 0.17 to 0.19, 1.6 to 2.1, 11.3 to 12.8,
and 5.6 to 6.7, respectively. Similarly, the elemental concentration of Sr and Ca varied from 207 to 223 ppm and 6.4 to 6.9%, respectively. The ratios of Zr/Al varied from 19.0 to 223 ppm and 6.4 to 6.9%, respectively. The ratios of Zr/Al varied from 19.0 to 26.5. The concentration of Sr and Ca varied from 179 to 205 ppm and 6.4 to 6.9%, respectively. The ratios of Zr/Al varied from 16.5 to 16.7%, 4.5 to 6.9%, and 0.78 to 0.86%, respectively. The oxide ratios of K2O/Al2O3, Na2O/TiO2, CaO/TiO2, and Fe2O3/TiO2 varied from 0.16 to 0.18, 1.7 to 2.1, 12.0 to 13.4, and 5.8 to 6.7, respectively. Similarly, the elemental concentration of Sr and Ca varied from 179 to 205 ppm and 6.5 to 6.8%, respectively. The ratios of Zr/Al varied from 16.5 to 20.2. The values of weathering intensity CIA varied from 82 to 85 (Supplementary Table 1).

Zone 4
Zone 4 suggests the concentration of Al2O3, Fe2O3, and TiO2 varied from 143 to 153.4%, 4.1 to 5.1%, and 0.71 to 0.76%, respectively. The oxide ratios of K2O/Al2O3, Na2O/TiO2, CaO/TiO2, and Fe2O3/TiO2 varied from 0.16 to 0.18, 1.7 to 2.1, 12.0 to 13.4, and 5.8 to 6.7, respectively. Similarly, the elemental concentration of Sr and Ca varied from 204 to 218 ppm and 6.3 to 7.3%, respectively. The ratios of Zr/Al varied from 11.5 to 12.2, and 5.6 to 7.9, respectively. Similarly, the elemental concentration of Sr and Ca varied from 161 to 216 ppm and 6.3 to 6.9%, respectively. The ratios of Zr/Al varied from 11.5 to 12.2, and 5.6 to 7.9, respectively. Similarly, the elemental concentration of Sr and Ca varied from 161 to 216 ppm and 6.3 to 6.9%, respectively. The ratios of Zr/Al varied from 11.5 to 24.8. The values of weathering intensity CIA varied from 83 to 89 (Supplementary Table 1).

Mineral Magnetic Variations

Zone 1
Zone 1 shows the magnetic susceptibility (χLF) values varied between 1.18 × 10^{-8} m^3/kg and 1.97 × 10^{-8} m^3/kg, while the values of SIRM and χarm varied between 1.23−1.84 and 1.45 × 10^{-5}−5.88 × 10^{-5}, respectively. The increasing concentrations of χLF: SIRM, and χarm are indicative of the ferrimagnetic mineral signals. However, decreasing concentration of these parameters implies dominance of the anti-ferrimagnetic minerals within the section. Values of the S-ratio varied from 0.62 to 0.74, indicating the presence of low coercivity minerals (Supplementary Table 2).

Zone 2
Zone 2 shows the magnetic susceptibility (χLF) values varied between 1.55 × 10^{-8} m^3/kg and 1.56 × 10^{-8} m^3/kg, while the values of SIRM and χarm varied between 1.51–1.67 and 2.61 × 10^{-5}–3.60 × 10^{-5}, respectively. Values of the S-ratio varied from 0.63 to 0.66 (Supplementary Table 2).

Zone 3
Zone 3 suggests the magnetic susceptibility (χLF) values varied between 1.46 × 10^{-8} m^3/kg and 1.87 × 10^{-8} m^3/kg, while the values of SIRM and χarm varied between 1.39–2.16 and 2.82 × 10^{-5}–10 × 10^{-5}, respectively. Values of the S-ratio varied from 0.60 to 0.74 (Supplementary Table 2).

Zone 4
Zone 4 suggests the magnetic susceptibility (χLF) values varied between 1.82 × 10^{-8} m^3/kg and 1.88 × 10^{-8} m^3/kg, while the values of SIRM and χarm varied between 2.17–2.19 and 8.5 × 10^{-5}–8.9 × 10^{-5}, respectively. Values of the S-ratio varied from 0.76 to 0.77 (Supplementary Table 2).

Zone 5
Zone 5 suggests the magnetic susceptibility (χLF) values varied between 1.66 × 10^{-8} m^3/kg and 1.86 × 10^{-8} m^3/kg, while the values of SIRM and χarm varied between 1.98–2.19 and 7.10 × 10^{-5}–8.50 × 10^{-5}, respectively. Values of the S-ratio varied from 0.73 to 0.74 (Supplementary Table 2).

Zone 6
Zone 6 suggests the magnetic susceptibility (χLF) values varied between 1.56 × 10^{-8} m^3/kg and 1.58 × 10^{-8} m^3/kg, while the values of SIRM and χarm varied between 1.76–1.79 and 5.71 × 10^{-5}–6.12 × 10^{-5}, respectively. Values of the S-ratio varied from 0.75 to 0.77 (Supplementary Table 2).

Zone 7
Zone 7 suggests the magnetic susceptibility (χLF) values varied between 1.68 × 10^{-8} m^3/kg and 2.37 × 10^{-8} m^3/kg, while the values of SIRM and χarm varied between 1.91–2.76 and 6.82 × 10^{-5}–12.8 × 10^{-5}, respectively. Values of the S-ratio varied from 0.76 to 0.78 (Supplementary Table 2).
DISCUSSION

Approach: Role of Geochemistry and Magnetic Minerals in Paleoclimatic Reconstructions

The concentration of various oxides and elements is often derivative of weathering processes acting in the catchment of the basins. Major elemental concentration in sediments, mineral magnetics, and grain size often reflects the source of the origin, which were being used as effective proxies to demonstrate the intensity of chemical weathering, climate changes, and precipitation variations in the region (Staubwasser and Sirocko 2002; Yancheva et al., 2007; Tyagi et al., 2012; Clift et al., 2014; Das et al., 2017; Pillai et al., 2018; Ruifeng et al., 2020). The ratios like Na2O/TiO2, CaO/TiO2, and Fe2O3/TiO2 can be used to infer the changes in the paleoenvironmental condition (Pillai et al., 2018; Makwana et al., 2019). Increased values of Fe2O3/TiO2 with lower values of Na2O/TiO2 and CaO/TiO2 suggest increased precipitation, owing to the depletion of mobile elements like Ca and Na during erosion triggered by enhanced monsoon (Muhs et al., 2001; Kotlia and Joshi, 2013; Minyuk et al., 2013; Pillai et al., 2018). Hence, we assess the higher values of oxides like Al2O3, Fe2O3, and TiO2 along with K2O/Al2O3 and CIA (Chemical Index of Alteration) to mimic the enhanced monsoonal strength (Buggle et al., 2011; Pillai et al., 2018; Makwana et al., 2019). Similarly, concentration of magnetic minerals and their mineralogy have widely been used as surrogate to study the strength of the ISM (Basavaiah and Khadkikar, 2004; Warriar and Shankar, 2009). Magnetic susceptibility (χ) is controlled by the concentration and the grain-size distribution of ferromagnetic minerals and is strongly sensitive to variations of the local climate and constitutes an accurate proxy record, along with other parameters (Thompson and Oldfield, 1986; Phartiyal et al., 2003). The cumulative response of major oxide, elemental, CIA, and mineral magnetic properties is often touted to be a robust indicator of weathering intensity and is considered as a surrogate for reconstructing monsoonal strength (Warriar and Shankar, 2009; Prasad et al., 2007; 2014; Makwana et al., 2019).

Climatic Variability in Banni Plains Since the Mid-Holocene

Kachchh region in the western India experiences an arid climate and has attracted tremendous attention for its tectonic attributes (Chamyal et al., 2003). However, the landscape and its modulation with climatic forcings during the Holocene have been least explored (Pillai et al., 2017, 2018; Basu et al., 2019; Makwana et al., 2019; Sengupta et al., 2019). Our results reveal several alternate phases of wet and dry paleoclimatic conditions during the last five millennia from the Banni Plains (Figure 3).

Prior to 4,800 cal yr BP (Phase I)
The zone is marked by higher CIA values and other major elemental proxies, suggesting a higher chemical weathering under the relatively humid climatic regime (Figure 4). This is further indicated by the higher concentration of detrital components such as Al2O3, TiO2, and Fe2O3 vs. reduction of Na2O/TiO2, CaO/TiO2, Zr/Al, CaO, and Sr (Peterson et al., 2000; Luckge et al., 2001; Kotlia and Joshi 2013; Pillai et al., 2018). Thus, collectively, the geochemical proxies indicate a strengthened monsoonal condition and intense chemical weathering at period prior to 4,800 years BP in the Banni Plains region. The mineral magnetic proxies which provide information about the type and concentration of magnetic grains transported in the catchment (Oldfield et al., 1994) also support the inferences drawn from the geochemical data. The lower values of χr in phase one signify strengthened monsoonal condition, which leads to higher erosion and weathering that lowered the concentration of magnetic minerals. The values of the S-ratio also suggest a combined anti-ferro to ferrimagnetic mineral assemblage with dominance of ferrimagnetic minerals in phase I. The complied results of multi-proxies recommend the deposition of sediments that occurred under the relatively humid climatic condition in phase I (i.e., period prior to 4,800 years BP).

Thakur et al. (2019) based on palynological study form Harshad, western Saurashtra, reported a higher ISM precipitation during the 5,400 to 5,100 years BP period. Similar observations were also made by Kathayat et al. (2017) from the composite Sahiya d18O record from the Himalayas. Higher CIA and enhanced precipitation at 5.1 ka during the mature Harappan phase have also been reported by Ngangom et al. (2016) from the nearby Eastern Great Rann of Kachchh. A similar, wet phase of ISM was recorded by Parsons Valley Lake, Tamilnadu, southern India (Raja et al., 2019).

4,400–4,800 cal yr BP Period (Phase II)
The zone is marked by abrupt changes to lower CIA values and other major elemental proxies, suggesting a weaker chemical weathering under arid climatic conditions (Figure 4). This abrupt aridity around 4,400 years BP has been one of the most discussed, although debated, causative factor for the deurbanization and decentralization of Harappans as a community that was primarily thriving on river-based resources (Staubwasser et al., 2003; Madella and Fuller, 2006; Dixit et al., 2014, 2018; Sengupta et al., 2019). Several studies have shown that the brief phase of aridity experienced in western India as well as the Himalayas led to the drying of water resources and speculated that this might have led the Harappan migrations to explore alternate water resources and settlement to smaller centers (Madella and Fuller, 2006). Based on our proxy data, which shows excessive deficient moisture conditions during this period (4,400–4,800 years BP), we support the earlier view that the prevalence of drought-like conditions affected the deurbanization of the Harappan settlement from the Western India.

Period Between 4,400 cal yr BP and 3,300 cal yr BP (Phase III)
Phase III is marked by fluctuating but an overall increasing value of mineral magnetic parameters, higher concentration of major, and lower ratios of geochemical proxies. An increase in CIA
hints an enhancement of chemical weathering signifying higher precipitation, which is also reflected in increasing concentration of major oxides such as Al₂O₃, Fe₂O₃, and TiO₂ (Anderson et al., 2004). A significant increasing trend is also noticeable in the ratios of K₂O/Al₂O₃ and Fe₂O₃/TiO₂ with lower concentration of Na₂O/TiO₂ and CaO/TiO₂ (Figure 4). Mineral magnetic parameters, that is, χlf and S-ratio, showed progressive decrease and thereafter increase in phase III, which indicates fluctuating but overall gradual increased precipitation/monsoon (Figure 4). Similar results of enhanced monsoonal strength have also been reported by Pillai et al. (2017, 2018) from the Banni Plains during 4,600 and 2,500 years BP. This period was the initiation of deurbanization of the mighty Harappan civilization, which was marked by the migration of Harrapans from the well-established centers to other sites, owing to water source scarcity (Ponton et al., 2012; Dixit et al., 2014, 2018; Pokharia et al., 2017). On the contrary to this, recently, some studies have demonstrated change in farming pattern and other means for survival of the ancient settlers despite the aridity (Sarkar et al., 2020; Pokharia et al., 2017; Singh et al., 2018).
Period Between 3,300 cal yr BP and 3,000 cal yr BP (Phase IV)

The period from 3,300 years BP to 3,000 years BP experienced a relatively drier climate with reduced CIA values and abruptly decreasing concentration of major oxides such as Al₂O₃, Fe₂O₃, and TiO₂. The relative content of CaO, Sr, and Na₂O/TiO₂ increases as these mobile elements remain at the site due to the lack of hydrolysis. Prasad et al. (2014a) from the Wadhwana Lake in alluvial plains of Gujarat reported a short phase of low precipitation during 3,238–2,709 cal yr BP. Similar arid conditions are also reported from Rann sediments in northwest of the present site by Ngangom et al. (2016).

Contrastingly, Pillai et al. (2017, 2018) reported the period from 4,600 to 2,500 years BP as the period of enhanced monsoonal strength, owing to the coexistence of C4 and C3 vegetation along with geochemical composition of sediments due to chemical weathering. Recent studies from the Bednikund Lake, Himalayas, based on mineral magnetics, organic geochemistry, and grain size assemblages, also suggested an enhanced monsoonal strength during 3,380 and 2,830 cal yr BP. (Rawat et al., 2021).

Period During the Last 3,000 years (Phases V, VI, and VII in BKR Trench and BB Trench)

Makwana et al., 2019

The depiction of last three millennia has been done based on phases V, VI, and VII of BKR trench and previously reported BB trench from the northwest of the Banni Plains (Makwana et al., 2019). As we do not have age control on the top section of BKR, we only report that the phases V and VII show signs of strengthened monsoonal condition with enhanced values of CIA and associated geochemical proxies, whereas on the contrary, phase VI shows a relatively dip in CIA values and other oxides, hinting at a weaker chemical weathering, that is, arid climatic conditions.

On the contrary, the period from 2,900 years to 1900 years from BB trench site also supports an overall fluctuating to arid climatic condition with peak of that aridity around 2,400 years BP (Makwana et al., 2019). Pillai et al. (2018) from Luna core reported arid climatic condition during 3,000 to 2,500 years BP. Similarly, Quamar et al. (2021) studied a lacustrine sequence from central India and based on the pollen study reported a decline in strength of ISM during 3,000 to 2,600 years BP period. Similarly studies from the mudflats of Diu, Gujarat, are suggestive of the arid conditions during 2,640–1930 cal yr BP (Barnerjee et al., 2017). This is in agreement with a long drought in the Thar desert, India, between 3,600 and 2000 years BP (Bryson and Bryson, 1996; Enzel et al., 1999).

The period from 1900 years BP to 200 years BP shows three phases of prominent arid/humid climatic conditions (Makwana et al., 2019). These periods of arid/humid conditions coincide their timing with globally known events like the medieval climatic anomaly (MCA). These events have also been reported from regional archives in the past (Gupta et al., 2003; Sinha et al., 2007; Ngangom et al., 2012; Rajamanickam et al., 2017; Rawat et al., 2021). All the fluctuations from arid to humid climatic conditions during the last three millennia are abrupt in nature with sharp changes in proxy data (Figure 3). Previously, Makwana et al. (2019) reported a sedimentation rate of 1–2.2 mm/yr from the BB trench in the northwestern Banni Plains. The present BKR trench based on two AMS ¹⁴C ages yields a sedimentation rate of 1.6 mm/yr during 4,432 to 3,339 cal yr BP period. The high sedimentation rate from BB and BKR trenches (>1 mm/yr) also aids this endeavor. Despite the poor chronological control, the presence of abrupt arid and humid periods during last two millennia is suggestive of Banni Plains being capable of being used as potential archive for studying climatic reconstructions.

CONCLUSION

Based on the multi-proxy dataset from the Banni Plains of the Kachchh region spanning last 5,000 years, the salient findings are as follows:

1. The periods from 4,800 to 4,400 cal yr BP are marked by abrupt drier climatic conditions in a multi-proxy dataset, which has also been reported by several other studies from the regional archives owing to the initiation of synchronous urbanization of Harappan settlements. This is followed by a period from 3,300 to 3,000 cal yr BP and around 2,400 cal yr BP with pronounced aridity in the Banni Plain region.

2. The relatively humid climatic conditions were observed during >4,800 cal yr BP, 4,400 to 3,300 cal yr BP, 1900 to 1,400 years BP, and 900–550 years BP in the multi-proxy record. The late Harappan phase envisaged in the present study shows an intriguing gradual strengthening of the monsoonal intensity.

3. Based on preliminary results, the Banni Plains as an archive shows a high sedimentation rate, that is, >1 mm/yr, which suggests it can act as a robust archive which can be tapped to be an excellent sedimentary record to reconstruct multi-decadal to centennial climatic events spanning the Holocene epoch.

Future studies from Banni Plains with relatively deeper information could likely aid in reconstructing the dynamics of the region spanning the entire Holocene epoch, as the present study validates the archiving potential of Banni sediments for reconstructing short and long spells of paleomonsoonal conditions.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.
The paper was written by NM and AD. The idea was conceptualized by NM, AD and SPP. The magnetic results and data was worked upon by BP, CV and AS contributed in field investigation and laboratory analysis. SPP supervised the work and edited the paper.

**ACKNOWLEDGMENTS**

We thank DST, Government of Gujarat for funding. Director General ISR and Director BSIP are thanked for permission to publish this work and encouragement. The study forms part of Ph.D thesis of NM. We convey our grateful thanks to Gaurav Chauhan for his assistance in field. We thank SAIF, BSIP for providing infrastructural facilities. We thank two anonymous reviewers and Editor for their constructive comments, which improved the earlier version of the paper.

**SUPPLEMENTARY MATERIAL**

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.679689/full#supplementary-material
Thompson, R., and Oldfield, F. (1986). *Environmental Magnetism*. London: Allen & Unwin, 227.

Tyagi, A. K., Shukla, A. D., Bhushan, R., Thakker, P. S., Thakkar, M. G., and Juyal, N. (2012). Mid-Holocene Sedimentation and Landscape Evolution in the Western Great Rann of Kachchh, India. *Geomorphology* 151-152, 89–98. doi:10.1016/j.geomorph.2012.01.018

Walden, J. (1999). "Remanence Measurements," in *Environmental Magnetism: A Practical Guide*, Technical Guide No. 6. Editors J. Walden, J. P. Smith, and F. Oldfield (London: Quaternary Research Association), 63–88.

Warrier, A., and Shankar, R. (2009). Geochemical Evidence for the Use of Magnetic Susceptibility as a Paleorainfall Proxy in the Tropics. *Chem. Geology* 265, 553–562. doi:10.1016/j.chemgeo.2009.05.023

Wright, R. P., Bryson, R., and Schädel, M. (2008). Water Supply and History: Harappa and the Beas Regional Survey. *Antiquity* 8, 37–48. doi:10.1017/S0003598X00096423

Yancheva, G., Nowaczyk, N. R., Mingram, J., Dulski, P., Schettler, G., Negendank, F. W., et al. (2007). Influence of the Intertropical Convergence Zone on the East Asian Monsoon. *Nat. Lett.* 445 (7123), 74–77. doi:10.1038/nature05431

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Publisher’s Note:** All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.