Abrupt weakening of the summer monsoon in northwest India ~4100 yr ago

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ABSTRACT

Climate change has been suggested as a possible cause for the decline of urban centers of the Indus Civilization ~4000 yr ago, but extant paleoclimatic evidence has been derived from locations well outside the distribution of Indus settlements. Here we report an oxygen isotope record of gastropod aragonite ($\delta^{18}O_a$) from Holocene sediments of paleolake Kotla Dahar (Haryana, India), which is adjacent to Indus settlements and documents Indian summer monsoon (ISM) variability for the past 6.5 k.y. A 4‰ increase in $\delta^{18}O_a$ occurred at ca. 4.1 ka marking a peak in the evaporation/precipitation ratio in the lake catchment related to weakening of the ISM. Although dating uncertainty exists in both climate and archaeological records, the drought event 4.1 ka on the northwestern Indian plains is within the radiocarbon age range for the beginning of Indus de-urbanization, suggesting that climate may have played a role in the Indus cultural transformation.

INTRODUCTION

Holocene paleoclimate records suggest that Indian summer monsoon (ISM) variability occurred at centennial and millennial time scales (Gupta et al., 2003; Dixit et al., 2014), but the instrumental record (post-1871) is generally too short to document the full range of variability. Thus, paleoclimate studies are necessary to evaluate past changes in ISM intensity and their potential societal implications. Paleoclimate records indicate that a widespread aridification event occurred ~4.2 k.y. before the present (ka), an event that has been linked with the collapse of the Old Kingdom in Egypt, the Early Bronze Age civilizations of Greece and Crete, and the Akkadian Empire in Mesopotamia (Cullen et al., 2000; Marshall et al., 2011; Weiss, 2012).

Weakening of the ISM at that time is also proposed as a possible cause for the de-urbanization of the Indus Civilization (Staubwasser et al., 2003; Staubwasser and Weiss, 2006; Lawler, 2007; Berkelhammer et al., 2012; Clift et al., 2012; Ponton et al., 2012). The link between the climate event at 4.2 ka and cultural transformation in South Asia is equivocal partly because existing paleoclimate records are from areas outside the distribution of Indus settlements. Climate drying at ca. 5 ka has been inferred from the Thar Desert lakes (Enzel et al., 1999; Prasad and Enzel, 2006), but these Rajasthani lakes had divergent hydrology and climate histories throughout the Holocene (Wright, 2010), rendering the desert uninhabitable, as compared to the adjacent flood plains of the Indus River system. The archaeological evidence also suggests that the Thar Desert had no Indus settlements, but is flanked on three sides by Indus archaeological sites (MacDonald, 2009).

Here we report an oxygen isotope record of gastropod aragonite ($\delta^{18}O_a$) from paleolake Kotla Dahar. Our section (28°00′095″N, 76°57′173″E) is ~0.5 km southwest of the pit (K-5) described by Saini et al. (2005). The lake is located in northwestern India at the northeastern edge of the distribution of Indus settlements, ~160 km southeast of the Indus city site of Rakhigarhi and 75 km southwest of Delhi.

Today, the northwestern Indian plains are characterized by subhumid, semiarid, and arid zones, following the present pattern of decreasing summer monsoon rainfall from east to west (Fig. 1). Paleolake Kotla Dahar is situated in the subhumid region in the Mewat district on the southern edge of Haryana. The district has a quartzite ridge to its west, arid Rajasthan to the south-southeast, and alluvial plains to the north-northeast (Figs. DR1 and DR2 in the GSA Data Repository[1]). It is mainly underlain by Quaternary alluvium that acts as the principal groundwater reservoir and overlies the quartzite basement of the Delhi Subgroup (Geological Survey of India, 2012). Kotla Dahar occupies a topographic depression to the east of a northeast-southwest–trending quartzite ridge and there is another parallel quartzite ridge ~15 km southeast of the lake. Kotla Dahar is today a small, closed basin that floods seasonally (Figs. DR1 and DR2). During summer, seasonal streams from the hills west of Kotla Dahar flow toward the southeast and fill natural depressions. The lake was ~5 m deep and spread over ~20 km^2, with up to 3.55 m of lacustrine sediment fill (Fig. DR1; Saini et al., 2005).

The regional climate is classified as tropical steppe, semiarid with a mean annual temperature of 25.3 °C and ~600 mm of rainfall. Approximately 75% of the annual rainfall falls between June and September by the northwestward-moving monsoon depressions from the Bay of Bengal, and the remaining 25% comes from western disturbances from October to December (Khan, 2007).

We infer past hydrologic changes in the lake using $\delta^{18}O_a$ of the aragonitic gastropod *Melanoides tuberculata* (Fig. DR3) preserved in stratified lake sediment, and additional evidence from the relative abundance of ostracod taxa and percent $CaCO_3$. The $\delta^{18}O_a$ of the *M. tuberculata* shell is dependent on both the temperature and lake water $\delta^{18}O$ from which the aragonite was precipitated. We interpret changes in $\delta^{18}O_a$ as reflecting mainly the $\delta^{18}O$ of the lake water, because the observed changes (>4‰) are too large to be attributed to Holocene temperature change (>16 °C) alone. The seasonal range in $\delta^{18}O$ of rainfall is very large at New Delhi, averaging ~–7.5‰ during the summer monsoon and ~0.3‰ during the dry season (Bhattacharya et al., 2003; Fig. DR4). New Delhi receives 80% of its total annual rainfall during the summer from the Bay of Bengal, and given the proximity of New Delhi to Kotla Dahar, the major source of moisture to the lake during summer in the Holocene is likely to have been the same. Variation in the timing and intensity of the monsoon affects lake-water $\delta^{18}O$ by changing the rainfall $\delta^{18}O$ and by altering the relative hydrologic balance between evaporation and precipitation (E/P) in the lake catchment. An early monsoon withdrawal and/or a decrease in rainfall amount increases the annually mean weighted $\delta^{18}O$ of rainfall (Berkelhammer et al., 2012).

The oxygen isotope mass balance of a closed-basin lake is dependent on the $\delta^{18}O$ of the input (rainfall and groundwater) and E/P over the catchment (Gat, 1996). We interpret the increases in shell $\delta^{18}O_a$ to reflect a decreased contribution of summer monsoon rainfall, which in turn is the result of increases in the mean annual $\delta^{18}O$ of rainfall and reduced precipitation over the lake catchment. Conversely, the periods of increased monsoonal rainfall are marked by low shell $\delta^{18}O_{a.}$

METHODS

A 2.88 m section of Holocene sediment was retrieved from a cut into the paleolake bed at Kotla Dahar. Weight percent $CaCO_3$ was measured in bulk sediments by coulometric titration. Oxygen isotopes were measured on the

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[1] GSA Data Repository item 2014129, methods and materials, Figures DR1–DR12, and evaluation of hard-water lake error correction, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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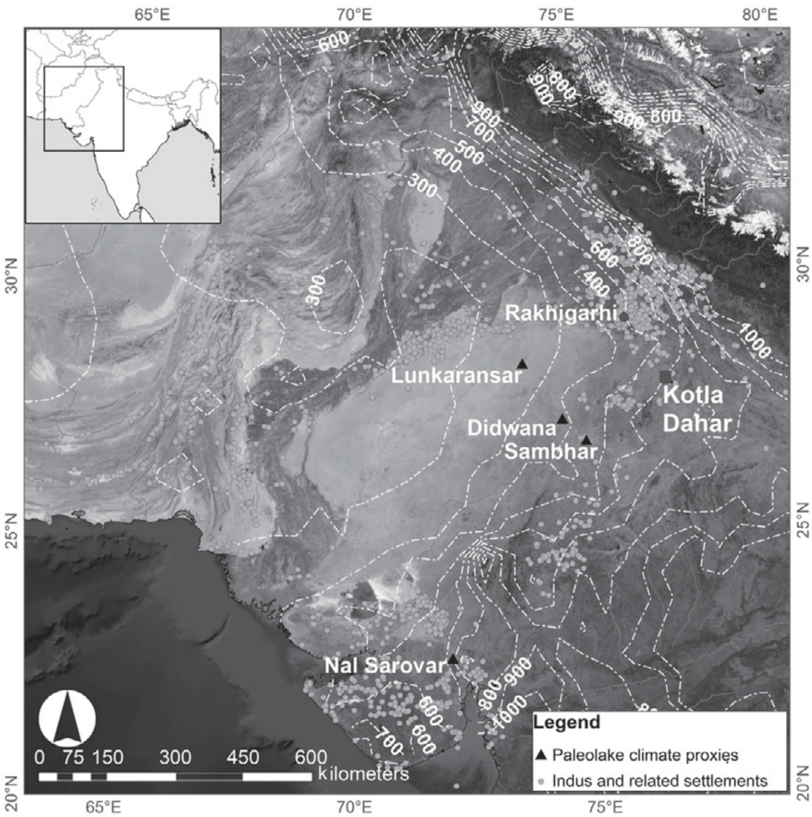

Figure 1. Location of paleolake Kotla Dahar (dark gray square) (28°00′095″N, 76°57′173″E), Haryana, India, and other climate proxies (black triangles) from Thar Desert. White dotted lines are isohyets (mm) between 1900 and 2008. Light gray dots indicate locations of pre-urban, urban, and post-urban Indus Civilization. Dark gray dot is nearest Indus urban center, Rakhigarhi. Satellite imagery was obtained from NASA's Earth Observatory (http://earthobservatory.nasa.gov/Features/BlueMarble/). Inset map shows location of main map in relation to limits of Indian subcontinent.

gastropod *M. tuberculata*. All carbonate isotopic results are reported in standard delta notation relative to the Vienna Peedee belemnite (VPDB) standard (for detailed analytical procedures, see the Data Repository).

The chronology of the stratigraphic section was determined by radiocarbon dating of gastropod shells and terrestrial organic material by accelerator mass spectrometry (AMS) at the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory (California, USA), and calibrated using OxCal v.4.1.63 and the IntCal09 data set (Reimer et al., 2009).

RESULTS

The chronology of the sediment profile for the past 6.5 k.y. was established using 8 AMS radiocarbon dates on gastropods and 1 organic sample (Table 1; Fig. DR5). Bedrock in the lake catchment is composed mainly of quartzite (Saini et al., 2005), suggesting a relatively small input of older radiocarbon in the lake water and a minimal hard-water lake error (Figs. DR6 and DR7; Table DR1; Deevey and Stuiver, 1964). Owing to the paucity of whole shells in sediment horizons marking the $\delta^{18}O$ transition at 170–175 cm, we attempted to date mixed gastropods shell fragments combined from depths at 180 and 185 cm. The resulting date was younger (3130 ± 30 ^{14}C yr B.P.) than the overlying horizon at 170 cm (3710 ± 30 ^{14}C yr B.P.), but subsequent X-ray diffraction analysis showed that the gastropod shell fragments, originally aragonite, had been diagenetically altered by calcite secondary overgrowths (Fig. DR8). We therefore discount this date on the basis of poor preservation. In an attempt to bracket the age of the transition horizon, we dated the nearest horizons above (170 cm) and below (202, 205, and 207 cm). The age of the end of the $\delta^{18}O$ transition and resumption of lake sediments at 170 cm is dated directly to be 3710 ± 30 ^{14}C yr B.P. Because the lithology of the section is the same below and above the $\delta^{18}O_a$ transition, the age of the beginning of the transition at 175 cm was calculated using a best fit line between 170, 202, 205, and 207 cm, yielding an age of ca. 4.1 ka, assuming no hard-water lake error (Fig. DR9).

The stratigraphic section and $\delta^{18}O_a$ record from Kotla Dahar show three distinct phases representing different stages of the evolving lacustrine system (Fig. 2; Fig. DR12). The earliest deep-water phase (ca. 6.5–6.0 ka) is marked by the lowest $\delta^{18}O_a$, averaging –2.3‰, and the highest $CaCO_3$, averaging ~60% (Fig. 2). This phase is characterized by abundant fresh-water ostracod species (*Ilyocypris*, *Darwinula*, and *Fabaeformiscandona*; J. Holmes, 2013, personal commun.; Fig. DR10) and a low abundance of gastropods. The boundary between the deep-water phase and subsequent shoaling phase is marked by a 5-cm-thick organic-rich layer from which charcoal was dated to ca. 6.4–5.8 ka (Table 1). Immediately above this charcoal layer, from ca. 5.8 to 4.2 ka, $\delta^{18}O_a$ increases gradually to ~0.8‰ and $CaCO_3$ decreases to ~37%. Sediments deposited during this period contain abundant, well-preserved gastropods (*Planorbidae*, *M. tuberculata*) that thrive in littoral environments and ostracods (*Cyprideis torosa*) that tolerate salinities as high as 60‰ (Heip, 1976) (Fig. 2). The $\delta^{18}O_a$ increased abruptly from –0.1‰ to 4.4‰ at ca. 4.1 ka, coinciding with a drop in $CaCO_3$ to ~10% and disappearance of ostracods from the sediment. The $\delta^{18}O_a$ averages 2.2‰ from 170 cm to the top of the section.

DISCUSSION

The $\delta^{18}O_a$ and faunal records suggest that a relatively deep fresh-water lake existed at the site from 6.5 to 5.8 ka. This interpretation is consistent with an early to middle Holocene strengthening of the monsoon documented in records

TABLE 1. AGE ANALYSIS OF SEDIMENT SECTION FROM PALEOLAKE KOTLA DAHAR

Depth (cm)	Laboratory number (CAMS#)	Material	Radiocarbon age (^{14}C yr B.P.)	Calibrated age (yr B.P.)	Error ($\pm 2\sigma$)
125	154770	Mixed gastropods	2255 ± 30	2250	93
135	154769	Mixed gastropods	1980 ± 30	1934	60
170	156264	*Melanoides tuberculata*	3710 ± 35	4040	110
170 R	156265	*M. tuberculata*	3745 ± 35	4040	110
(180–185)*	156263	Mixed gastropods	3130 ± 30	3353	88
202	161945	*M. tuberculata*	4300 ± 25	4894	64
205	161946	Mixed gastropods	4300 ± 35	4895	66
207	154771	Mixed gastropods	4250 ± 35	4760	109
228	153624	Charcoal	5320 ± 120	6076	316
287	157228	*M. tuberculata* shell fragments	5670 ± 30	6445	89

*A rejected date (Fig. DR8; see text footnote 1); R denotes replicated date.
CAMS#—Center for Accelerator Mass Spectrometry number.

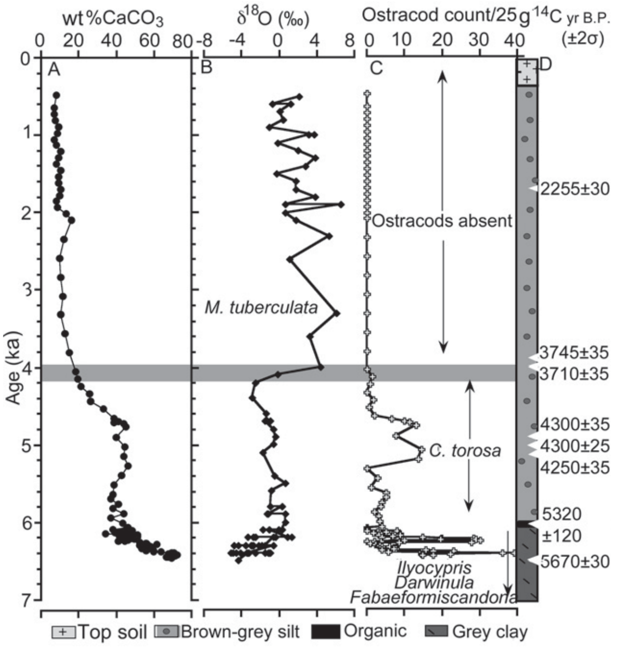

Figure 2. Weight percent (wt%) carbonate and $\delta^{18}O$ VPDB (Vienna Peedee belemnite, ‰) of gastropod *Melanoides tuberculata*, ostracod valve count per 25 g of sediment, and lithostratigraphy of section plotted against calibrated age (ka). White triangles denote levels of radiocarbon dates in ^{14}C yr B.P. Horizontal bar denotes climate transition at 4.1 ka.

from Oman, the Arabian Sea, and Thar Desert lakes (Fleitmann et al., 2003; Gupta et al., 2003; Prasad and Enzel, 2006). After ca. 5.8 ka, the increased abundance of *M. tuberculata,* the pulmonate gastropod *Planorbidae*, and the ostracod *C. torosa* indicates a progressive lowering of lake level and increasing salinity (Fig. 2; Fig. DR10). Furthermore, an increase in $\delta^{18}O_a$ and decrease in $\%CaCO_3$ suggest a gradual change toward higher E/P conditions between ca. 5.8 and 4.2 ka. This climate trend is consistent with a long-term Holocene decrease in ISM rainfall recorded in marine and speleothem records (Gupta et al., 2003; Fleitmann et al., 2003).

An abrupt 4‰ increase in $\delta^{18}O_a$ occurred at ca. 4.1 ka, documenting a sharp reduction in ISM intensity and increased E/P in the lake catchment (Fig. 2). The absence of ostracods from the sediments deposited following this transition indicates a shift to shallow, seasonal lacustrine conditions because *C. torosa* require permanent water to survive (Anadon et al., 1986). A similar drying event at ca. 4.0 ka was observed in a U/Th-dated Mawmluh Cave speleothem, in northeast India (Berkelhammer et al., 2012). The shift also coincides, within chronological error, with the monsoon weakening at 4.2 ka recorded in Arabian Sea sediments (Fig. 3C) (Staubwasser et al., 2003). Taken together, the records from Kotla Dahar, Mawmuluh, and the Arabian Sea provide strong evidence for a widespread weakening of the ISM across large parts of India at ca. 4.2–4.0 ka. The monsoon recovered to the modern-day conditions after 4.0 k.y. ago, and the event lasted for ~200 yr (ca. 4.2–4.0 ka) in this region. The step change at Kotla Dahar is not necessarily a permanent change in the local hydrology, but could instead represent a transient change in E/P that altered the steady-state lake water $\delta^{18}O$.

The cause of ISM weakening at ca. 4.1 ka has been related to large-scale tropical ocean-atmosphere dynamics, i.e., changes in the Indian Ocean Dipole (IOD) and El Niño Southern Oscillation (ENSO) (Fisher et al., 2008; MacDonald, 2009). Observational and modeling studies indicate that a positive IOD weakens the effect of ENSO on the ISM (Ashok and Guan, 2004). Abram (2009) suggested a shift in Indian Ocean climate to a more negative IOD state after ca. 4.3 ka. There is also evidence for a shift in ENSO variability in the Pacific beginning at ca. 4.2 ka, marked by a transition to stronger and/or more frequent ENSO events (Conroy, 2008; Toth et al., 2012). Thus, the ISM weakening observed in the Kotla Dahar and Mawmuluh records may have been related to the coincidence of a negative phase of the IOD coupled with increased ENSO variability (Berkelhammer et al., 2012).

Within the errors of the age models of the respective records (i.e., ±100 yr), the $\delta^{18}O$ increase in Kotla Dahar coincides with a peak in dolomite-rich eolian dust in the Gulf of Oman (Cullen et al., 2000) and a distinct dust spike in Kilimanjaro (Africa) ice cores (Thompson et al., 2002) (Fig. 3). These events have been linked to droughts in Mesopotamia and Africa, and coincide with the observed ISM weakening in South Asia. Evidence of aridification at 4.2 ka also comes from the Mediterranean Sea, Turkey, the United Arab Emirates, the Gulf of Oman, Tibet, Mongolia, and China (Weiss, 2012).

The estimated age of the onset of drier conditions at Kotla Dahar is ca. 4.1 ka, but we take the U-series age range of the speleothem from 4071 yr ago (±18 yr) to 3888 yr ago (±22 yr) as the most accurate timing of the monsoon weakening (Berkelhammer et al., 2012). The beginning of Indus de-urbanization is estimated at ca. 4.0–3.9 ka (Wright, 2010), but these

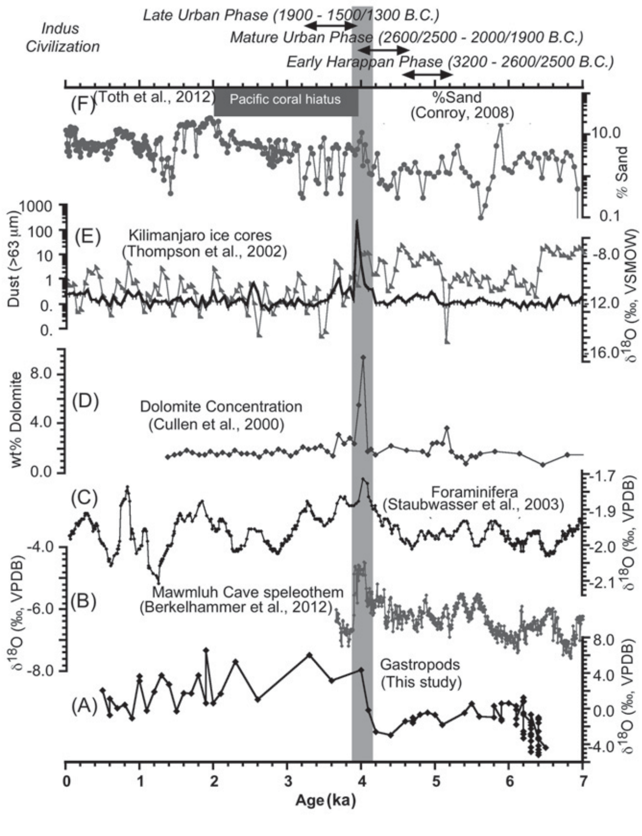

Figure 3. A: Gastropod $\delta^{18}O$ record from Kotla Dahar. VPDB—Vienna Peedee belemnite. B: $\delta^{18}O$ record from Mawmluh Cave speleothem in northeast India. C: $\delta^{18}O$ record of planktonic foraminifera from Arabian Sea. D: Dolomite concentration from Gulf of Oman sediment core. E: Ice core $\delta^{18}O_{SMOW}$ (Vienna standard mean ocean water) and dust (>63 μm) from Kilimanjaro, Africa. F: Percent sand in El Junco Lake, Galapagos Islands (proxy for El Niño events). Gray horizontal bar denotes reef growth hiatus in tropical eastern Pacific attributed to increased El Niño Southern Oscillation. Vertical bar at ca. 4.1 ka indicates inferred climate drying related to summer monsoon weakening. Indus cultural periods are shown at top.

archaeological dates have analytical uncertainties of ±40 yr and 110 yr (Shaffer, 1992; Staubwasser and Weiss, 2006), giving calibrated probability distributions of 150–310 yr. Therefore, assuming a small hard-water lake error, the resultant age of drying at Kotla Dahar is consistent with the suggested archaeological dates for the onset of Indus de-urbanization within dating uncertainties (Table DR1; Figs. DR5–DR9). Our paleoclimate record also provides indirect evidence for the suggestion that the ISM weakening at ca. 4.1 ka in northwestern India likely led to severe decline in summer overbank flooding that adversely affected monsoon-supported agriculture in this region (Giosan et al., 2012).

The 4.2 ka aridification event is regarded as one of the most severe climatic changes in the Holocene, and affected several Early Bronze Age populations from the Aegean to the ancient Near East (Cullen et al., 2000; Weiss and Bradley, 2001). This study demonstrates that the climate changes at that time extended to the plains of northwestern India. The Kotla Dahar record alone cannot fully explain the role of climate change in the cultural evolution of the Indus civilization. The Indus settlements spanned a diverse range of environmental and ecological zones (Wright, 2010; Petrie, 2013); therefore, correlation of evidence for climate change and the decline of Indus urbanism requires a comprehensive assessment of the relationship between settlement and climate across a substantial area (Weiss and Bradley, 2001; Petrie, 2013). The impact of the abrupt climate event in India and West Asia records, and that observed at Kotla Dahar, on settled life in the Indus region warrants further investigation.

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