A 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 palaeoclimatic evidence has been derived from locations well outside the distribution of Indus settlements. Here we report an oxygen isotope record of gastropod aragonite (δ18Oa) 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 δ18Oa 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, palaeoclimate 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 palaeoclimate 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 (δ18Oa) from paleolake Kotla Dahar. Our section (28°00'09"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 Rajkigarh 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-east, and alluvial plains to the north-east (Figs. DR1 and DR2 in the GSA Data Repository1). It is mainly underlain by Quaternary alluvium that acts as the principal groundwater reservoir and overlies the quartzite base- ment 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 km2, 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.

1GSA 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.

METHODS
A 2.88 m section of Holocene sediment was retrieved from a cut into the paleolake bed at Kotla Dahar. Weight percent CaCO3 was measured in bulk sediments by coulometric titration. Oxygen isotopes were measured on the
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 Suister, 1964). Owing to the paucity of whole shells in sediment horizons marking the δ18O 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 14C yr B.P.) than the overlying horizon at 170 cm (3710 ± 30 14C 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 δ18O transition and resumption of lake sediments at 170 cm is dated directly to be 3710 ± 30 14C yr B.P. Because the lithology of the section is the same below and above the δ18O 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 δ18O record from Kotla Dahar show three distinct phases representing different stages of the evolving lacustrine system (Figs. 2; Fig. DR12). The earliest deep-water phase (ca. 6.5–6.0 ka) is marked by the lowest δ18O, averaging ~2.3‰, and the highest CaCO3, averaging ~60% (Fig. 2). This phase is characterized by abundant fresh-water ostracod species (*Illyocypris, Darvinula*, and *Fabaecformiscandona*; 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, δ18O increases gradually to ~0.8‰ and CaCO3 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 δ18O increased abruptly from ~0.1‰ to 4.4‰ at ca. 4.1 ka, coinciding with a drop in CaCO3 to ~10% and disappearance of ostracods from the sediment. The δ18O averages 2.2‰ from 170 cm to the top of the section.

**DISCUSSION**

The δ18O, 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

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### Table 1. Age Analysis of Sediment Section from Paleolake Kotla Dahar

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

* A rejected date (Fig. DR8; see text footnote 1); R denotes replicated date. CAMS# = Center for Accelerator Mass Spectrometry number.
transient change in E/P that altered the steady-state lake water δ18O.

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 δ18O increase in Kotla Dahar coincides with a peak in dolomite-rich elolian 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 dating 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
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