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Linking Holocene drying trends from Lonar Lake in monsoonal central India to North Atlantic cooling events

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We present the results of biogeochemical and mineralogical analyses on a sediment core that covers the Holocene sedimentation history of the climatically sensitive, closed, saline, and alkaline Lonar Lake in the core monsoon zone in central India. We compare our results of C/N ratios, stable carbon and nitrogen isotopes, grain-size, as well as amino acid derived degradation proxies with climatically sensitive proxies of other records from South Asia and the North Atlantic region. The comparison reveals some more or less contemporaneous climate shifts. At Lonar Lake, a general long term climate transition from wet conditions during the early Holocene to drier conditions during the late Holocene, delineating the insolation curve, can be reconstructed. In addition to the previously identified periods of prolonged drought during 4.6–3.9 and 2.0–0.6 cal ka that have been attributed to temperature changes in the Indo Pacific Warm Pool, several additional phases of shorter term climate alteration superimposed upon the general climate trend can be identified. These correlate with cold phases in the North Atlantic region. The most pronounced climate deteriorations indicated by our data occurred during 6.2–5.2, 4.6–3.9, and 2.0–0.6 cal ka BP. The strong dry phase between 4.6 and 3.9 cal ka BP at Lonar Lake corroborates the hypothesis that severe climate deterioration contributed to the decline of the Indus Civilisation about 3.9 ka BP.

1. Introduction

The increasing demand for reliable climate projections due to the challenges related to global warming calls for enhanced investigation of the relationship between climate change and its effect on the environment. To assess future interaction between climate and environment, it is necessary to understand their interactions in the present and past. But, while modern observations are increasing rapidly and cover almost the whole world in high spatial and temporal resolution, the identification and investigation of suitable sites for palaeoclimate reconstruction is more difficult and requires great effort. Hence, several regions still lack a sufficient cover of investigated areas to help the scientific community in reconstructing the past climate and its influence on the former environment. One of these regions is India, which highly depends on the annual rainfall delivered by the Indian summer monsoon (ISM). This meteorological phenomenon affects a human population of more than one billion and is highly sensitive to climate change. In order to assess and to interpret potential future modifications of the Indian monsoon system, the knowledge of Holocene monsoon variability, its extremes, and their underlying causal mechanisms is crucial. And while terrestrial palaeorecords are available from the northern Indian subcontinent and the Himalayan region (Gasse et al., 1991, 1996; Enzel et al., 1999; Denniston et al., 2000; Thompson et al., 2000; Bookhagen et al., 2005; Prasad and Enzel, 2006; Clift et al., 2008; Demske et al., 2009; Wünnemann et al., 2010; Alizai et al., 2012), the number and length of comparable records from central and south India are limited (Yadava and Ramesh, 2005; Caner et al., 2007; Sinha et al., 2007; Berkelhammer et al., 2010). To address this issue, we have investigated the Holocene sedimentation history of Lonar Lake from central India with a special focus on centennial scale palaeoclimate reconstruction.

Based on mineralogical, palynological, and biogeochemical investigations on the ca. 10 m long sediment core, the longest, well dated palaeo-climate archive from India's core monsoon zone, S. Prasad et al.

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(2014) reconstructed the broad, Holocene climatic development of the Lonar Lake region, identified two millennial scale dry phases, and discussed the stability of the ISM–El Niño Southern Oscillation (ENSO) links and the influence of shifts in the position of the Indo Pacific Warm Pool (IPWP) on the prolonged droughts in the ISM realm. Here we present stable carbon and nitrogen isotope data from S. Prasad et al. (2014) as well as new data from amino acid, sediment composition, and grain-size analysis and interpret them with respect to centennial scale, Holocene climate variability and its tele-connections with the North Atlantic climate.

Bond et al. (2001) hypothesised a connection between North Atlantic cooling events and cosmogenic nuclide production rates, the latter indicating small changes in solar output. Additionally, they found virtually synchronous “quasi-periodic” ~1500 year cyclicity in both their palaeorecord and nuclide production rates. Thus, they postulated a reaction of climate to small changes in solar output, which would not be limited to the North Atlantic region but which would affect the global climate system (Bond et al., 2001). Correlations between the high and the mid latitude climate, as reconstructed from Greenland ice cores (Stuiver and Grootes, 2000; Johnsen et al., 2001) and ice-rafted debris in North Atlantic deep sea records (Bond et al., 1997), and the low latitude tropical climate have been found in various climate reconstructions (Haug et al., 2001; Gupta et al., 2003; Hong et al., 2003; Dykoski et al., 2005; Wang et al., 2005; Fleitmann et al., 2007; Koutavas and Sachs, 2008) supporting the assumption that different climate systems react to the same cause, like solar output variation (Bond et al., 2001; Soon et al., 2014) either independently or via tele-connections. However, since many palaeoclimate investigations concerning the correlations between tropical climate and North Atlantic climate were carried out in peripheral ISM regions (Hong et al., 2003; Fleitmann et al., 2007), these records could not indicate if the change in moisture availability was exclusively linked to an alteration in monsoonal summer rainfall rather than to altered winter westerly precipitation. Lonar Lake is one of the very few natural lakes located in the core monsoon zone in central India, and it is fed exclusively by precipitation of the Indian summer monsoon and stream inflow that is closely linked to monsoon rainfall (Anoop et al., 2013b). Additionally, available precipitation data from the region close to Lonar Lake indicate a good correlation with the all India rainfall record of the last century (1901–2002). Correlation between the all India rainfall record (ftp://www.tropmet.res.in/pub/data/rain/iitm-regionrf.txt) and the annual precipitation data of the meteorological stations in Buldhana, Jalna, Hingoli, and Washim (http://www.indiawaterportal.org/met_data/) varies between 0.62 and 0.69 ($p < 0.001$), making Lonar Lake a key site to investigate the connection between Indian monsoon strength and its connection to North Atlantic climate change.

2. Study site

Lonar Lake is a closed basin lake situated at the floor of a meteorite impact crater that formed during the Pleistocene (~570 ± 47 ka) on the Deccan Plateau basalts (Jourdan et al., 2011). The lake is located at Buldhana District in Maharashtra, central India at 19.98° N and 76.51° E (Fig. 1). The meteorite crater has a diameter of ca. 1880 m, and the almost circular lake covers an area of about 1 km^2. The modern crater floor is located at ca. 470 m above sea level, which is around 140 m below the rim crest elevation. The inner rim wall is fairly steep with slopes of 15–18° in the east and up to ~30° in the west and southwest (Basavaiah et al., 2014).

Lonar Lake is located in the ‘core monsoon zone’ of the Indian summer monsoon (Gadgil, 2003). The southwest monsoon from June to end of September is characterised by strong winds and brings in average rainfall of ~700 mm. Precipitation during December to April occurs only in rare cases. The temperature can exceed 40 °C before the onset of the monsoon and declines during the monsoon phase to an average of approximately 27 °C. The post monsoon from October to February is characterised by relatively low temperatures at an average of 23 °C

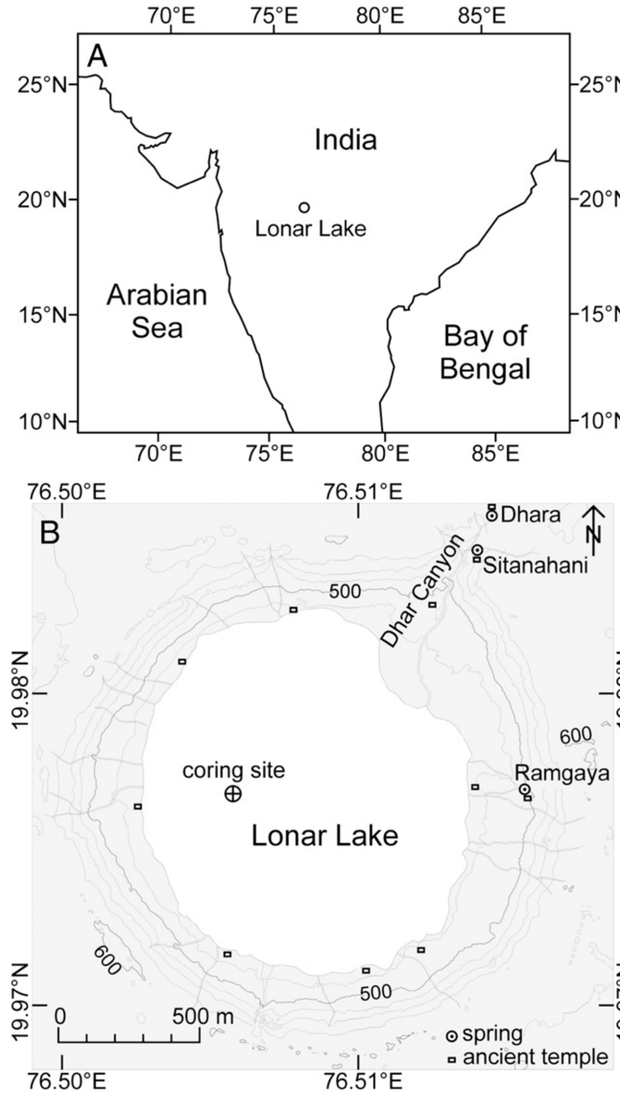

Fig. 1. A: Regional overview and location of Lonar Lake. B: Study area showing the coring site.

(http://indiawaterportal.org/met_data/). The lake is fed by surface runoff during the monsoon season and three perennial streams that are closely linked to monsoon rainfall as indicated by tritium dating (Anoop et al., 2013b). Two of them, the Dhara stream and the Sitanahani stream are entering the crater from the northeast. They have formed the Dhara Canyon, an erosive incision, and have built up an alluvial fan into the lake. Today this fan is used for agricultural plantation. The Ramgaya stream, the third stream feeding the lake, springs from the inner crater wall and enters the lake from the eastern shore. Nowadays the three streams are diverted towards the Dhara fan to irrigate the agricultural fields. Water discharge is only conducted by evapotranspiration; no outflowing stream is present and no loss due to seepage occurs as the lake level is below the local groundwater level (Nandy and Deo, 1961).

The modern lake is ca. 6 m deep, brackish, alkaline, and eutrophic with permanent bottom water anoxia (Basavaiah et al., 2014). The eutrophication promotes phytoplankton blooms especially during and subsequent to the monsoon when nutrients are washed into the lake. The algal assemblage is primarily made up of cyanophyceae (Badve et al., 1993). Thermophilic, halophilic, and alkalophilic bacteria in numbers of 10^2 to 10^4 viable cells/ml (Joshi et al., 2008) and methanogenic archaea (Surakasi et al., 2007) were reported from Lonar Lake. The lake lacks most zooplankton species and higher organisms. The zooplankton community within the lake consists of ciliates, culicid larvae, and rotifers (Mahajan, 2005). Only few exemplars of the ostracod *Cypris*