seismic phases, is not possible for core-diffracted waves because of the rapid loss of high frequencies during diffraction. A linear regression through the times of the wave peak maxima is the common means of determining the apparent slowness (*18, 27*) [J. C. Mondt, *Phys. Earth Planet. Inter.* **15**, 46 (1977); A. Souriau and G. Poupinet, *ibid.* **84**, 227 (1994)], and this has been shown to be as reliable as using a multiwaveform cross-correlation [M. E. Wysession and E. A. Okal, *Geophys. Res. Lett.* **16**, 1417 (1989)].

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High-Resolution Holocene Environmental Changes in the Thar Desert, Northwestern India

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Sediments from Lunkaransar dry lake in northwestern India reveal regional water table and lake level fluctuations over decades to centuries during the Holocene that are attributed to changes in the southwestern Indian monsoon rains. The lake levels were very shallow and fluctuated often in the early Holocene and then rose abruptly around 6300 carbon-14 years before the present (^{14}C yr B.P.). The lake completely desiccated around 4800 ^{14}C yr B.P. The end of this 1500-year wet period coincided with a period of intense dune destabilization. The major Harrapan-Indus civilization began and flourished in this region 1000 years after desiccation of the lake during arid climate and was not synchronous with the lacustral phase.

The southwestern Indian monsoon is critical for understanding past global and regional monsoon variations (*1–3*). The few records of Holocene monsoon variations from the areas that border the Arabian Sea in southern Asia have been based on pollen assemblages associated with the deposits of Lunkaransar, Didwana, and Sambhar paleolakes from northwestern India (*4*). These records, although based on limited dating, have been used extensively in regional compilations, in analysis of relations between summer insolation and the monsoon, and in paleoclimatic models (*2–7*) as well as to determine the relations between paleoclimate and Indus Valley civilizations (*8, 9*). Here, we present more detailed Holocene chronology of Lunkaransar based on analyses of the lacustrine laminated deposits, age dating, and geochemical analyses.

Lunkaransar (*10*) is a small, closed, dry basin surrounded by dunes at the northeastern margin of the Thar Desert (Fig. 1). The basin receives input from groundwater and direct rain and no input from streams. The water table is currently 2.4 m below the dry lake bed, and this water is saline with a composition that includes Na, Ca, Mg, Cl, SO_4, and HCO_3. Incoming sediments are only eolian sand from local dunes and eolian clay silt dust (*11*). Normally, the lake basin is totally dry, but heavy rainfall can form a temporary pool of water that evaporates during the dry season.

Trenches were excavated into the lake bed down to a thick, hard, carbonate layer at a depth of 3 m. The sedimentology of the upper 240 cm above the water table (Fig. 2) was documented at submillimeter-to-millimeter scales in both the field exposures and in the continuous, overlapping box cores in the laboratory. We obtained 15 radiocarbon dates (Table 1). The sequence was divided into four zones (Fig. 2) on the basis of characteristics of the deposits. Zone 4, dated at 4800 ^{14}C yr B.P. to recent, has no primary laminar structure and contains mud cracks, silt, and sand; it is interpreted as a dry lake basin that episodically was inundated by ephemeral lakes. Zones 1 to 3 (Figs. 2 and 3) are composed of two types of thin beds: (i) silt- and clay-rich detritus laminae with carbonate and in some cases thin gypsum laminae at boundaries, and (ii) gypsum laminae with some thin silt and clay laminae. We separated the entire sequence into four sedimentary facies (II to V) according to the dominant type and the thickness of the various beds (Fig. 3E) and inferred relative water depths

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Field observations show that the maximum lake stage did not reach 5 to 7 m. The ability of the basin to sustain even this level (facies IV and V) through successive years varied significantly throughout the Holocene (Fig. 3E).

Thin-section and x-ray diffraction analyses indicate that the clastics are allochthonous silicate minerals (quartz, plagioclase, potassium feldspar, clays such as chlorite and mica, and some hornblende), carbonate minerals, and some gypsum. Gypsum is the only evaporite mineral detected. The clay fraction (<2 μm) includes illite-smectite, illite, chlorite, and palygorskite. The palygorskite is authigenic and is indicative of intense evaporation episodes (*12*) at pH $\approx$ 8.5.

The concentration of clastic grains in separate laminae and the parallel orientation of the platy and elongated minerals indicate that the clastic grains were derived from dust storms (*11*) and they settled in water. The gypsum laminae contain fine authigenic crystals and abraded, sand-sized gypsum crystals. The abraded gypsum grains are most common in facies II and were probably blown in from drying mudflats at the margins (*13*) of Lunkaransar lake during periods of low lake levels.

The rise and fall of the water table at Lunkaransar reflect the regional precipitation over the basin. A lake is formed in Lunkaransar when the water table rises above the surface. Our data show that between about

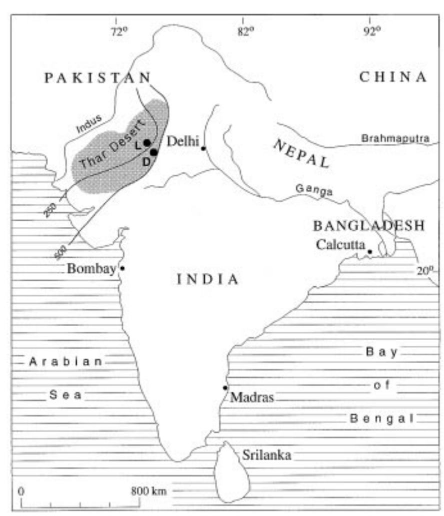

Fig. 1. Location map of Lunkaransar (L) and Didwana (D) dry lakes in the Thar Desert (shaded area) showing 250- and 500-mm/year isohyets.