

**for the reconstruction of post-Last Glacial Maximum climate history is discussed, and the need for developing a chronological database on this important archive of continental Holocene climate is recognized.**

THE Holocene palaeoclimatic history of the Thar Desert and its margins encompassing over 200,000 km<sup>2</sup> is of societal and environmental significance, and has a bearing on testing the response models of near surface systems to century and millennium scale climatic changes<sup>1</sup>. Previous workers have inferred past climatic changes from lake records in the Thar Desert<sup>2-7</sup>. These studies indicate heaviest summer precipitation between 10.8 and 10.0 Ka, fluctuating lake levels in the early Holocene, maximum lake levels between 7.2 and 5.6 Ka, and desiccation around 5.6 Ka. A dry phase at around 3 Ka is also inferred on the basis of aeolian/fluvio-aeolian<sup>8-10</sup> and lake records of Rajasthan and Gujarat<sup>11</sup>, and Haryana<sup>12</sup>. Model calculations for the Thar reveal that between 3.5 and 10 Ka, the summer rainfall was almost twice the present-day value and winter precipitation about 20% higher<sup>3</sup>.

Several lakes are present in the western part of India (Figure 1) and the lake deposits within them are of considerable palaeoclimatic significance because of their position along a rainfall gradient (600–200 mm), and their proximity to the Himalayan front, the Ganga Plain and the desert (Figure 2). Here we present the morphology of lakes/palaeolakes, associated landforms, nature of lacustrine deposits and their regional variability, along a 150 km NW–SE transect, in three precipitation zones, i.e. up to 300 mm, 300–500 mm and greater than 500 mm, from the Thar Desert to the Yamuna plains (Figure 2). Fifteen-pit sections (Figure 2) of the palaeolake deposits up to 3 m depths have been logged and about 10 well sections up to 10 m depths in the surrounding areas have also been studied.

The study area has three climatic zones from west to east (Figure 2). These are dry arid in Rajasthan (including the Nohar–Bhadra area), semi-arid in Haryana (including the Riwasa–Charkhi Dadri area) and sub-humid in Ganga Plain (including the Kotla Dahar area). The Haryana Plain shows the sharpest precipitation gradient compared to the Thar Desert and Ganga Plain. Meteorological data<sup>13</sup> of the three representative stations of these three zones are summarized in Table 1.

The Nohar–Bhadra area receives less than 300 mm rainfall annually, two-thirds of which is received during June–September. The mean temperature (42°C) is highest during May and lowest (5°C) during January. The Riwasa–Charkhi Dadri area receives 300–500 mm rainfall mainly during summer monsoon, i.e. June–September. The potential evapo-transpiration is 40 mm in December and 222.3 mm in June. The Kotla Dahar area has 600–700 mm rainfall, and the annual average temperature ranges between 18.8 and 31.7°C. A more exhaustive record of 1941–2002 from Nuh station shows a range of 300–1221 mm rainfall, with an average of 608.3 mm.

## Lake deposits of the northeastern margin of Thar Desert: Holocene(?) Palaeoclimatic implications

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**The understanding of past climates, particularly Holocene climate, changes in continental settings is significant for improving the predictive capability of models used for building future climate change scenarios. Continental sedimentary systems such as lake and river basins support large agricultural communities; even the desert margins support a substantial rural population. Therefore, understanding of the responses of these systems to future climate changes on decadal, century, and millennial scales needs to be strengthened in order to determine the varying limits of land, soil, water and vegetation resource structure on the demographic structure. In this context, we document the lake/pond deposits of the northeastern margin of Thar Desert along a rainfall gradient (200–600 mm) from west to east. The potential of the lake deposits and the associated sedimentary facies**

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Following the climatic trends, the geomorphic elements also show a systematic variation from west to east (Figure 2). The Nohar–Bhadra region is a desert erg characterized by dense aeolian landforms, dominated by relatively high-amplitude sand dunes and ridges with intervening sand sheets, and sparse depressions and deflation hollows. The elevation of the erg usually varies between 206 and 232 msl. Sand dunes are 5–25 m high and 1–10 km long. The dunes are stabilized, mainly longitudinal in form with northeasterly, easterly and rarely northerly orientations. These are overridden by small, younger active dunes of barchanoid, modified longitudinal and transverse forms oriented towards north, northeast, southeast and west. The erg surface gradually disappears along a northeasterly convex front passing along Anupgarh–Hissar–Riwasa line (Figure 2) close to the present 400 mm isohyet (20 years record). The domain is devoid of drainage.

The margin of the erg is surrounded by a 30–70 km wide semi-arid fringe (Figure 2), dominated by aeolian landforms. The sheets represent a surface of fluvial and aeolian deposits. Such surfaces have an elevation range of 190–225 msl. The dunes are 0.5–5 km long and 5–14 m high. They have longitudinal to barchanoidal base, and are overridden by longitudinal and transverse forms of subsequent generations. Their axis trends E–W and NE–SW, and subordinately along N–S and NW–SE. The criss-crossing of N–S and E–W ridges is common, and has given rise to complex shape patterns. The drainage is represented by a seasonal Ghagghar river originating from the Siwalik ranges in the north. Few relict, buried and abandoned segments of old

drainages are recognized in Hissar, Hansi and Sirsa areas, among which the palaeochannel of the Saraswati is the most significant<sup>14</sup>. Active lakes are absent.

The sub-humid domain is characterized by the presence of seasonal lakes and the appearance of drainage in an alluvial plain, which attains an elevation of 300 m in the north (near the Himalayan front) and 190 m in the south (near Nuh). The important lakes are Kotla Dahar and Sultanpur lakes in Gurgaon district (Figure 2), Dadanpur in Jhajjar district and Najafgarh in Delhi. Besides the short and seasonal northerly-flowing drainages of the northern Aravalli range, the perennial Yamuna river also flows southward from the Himalayan range.

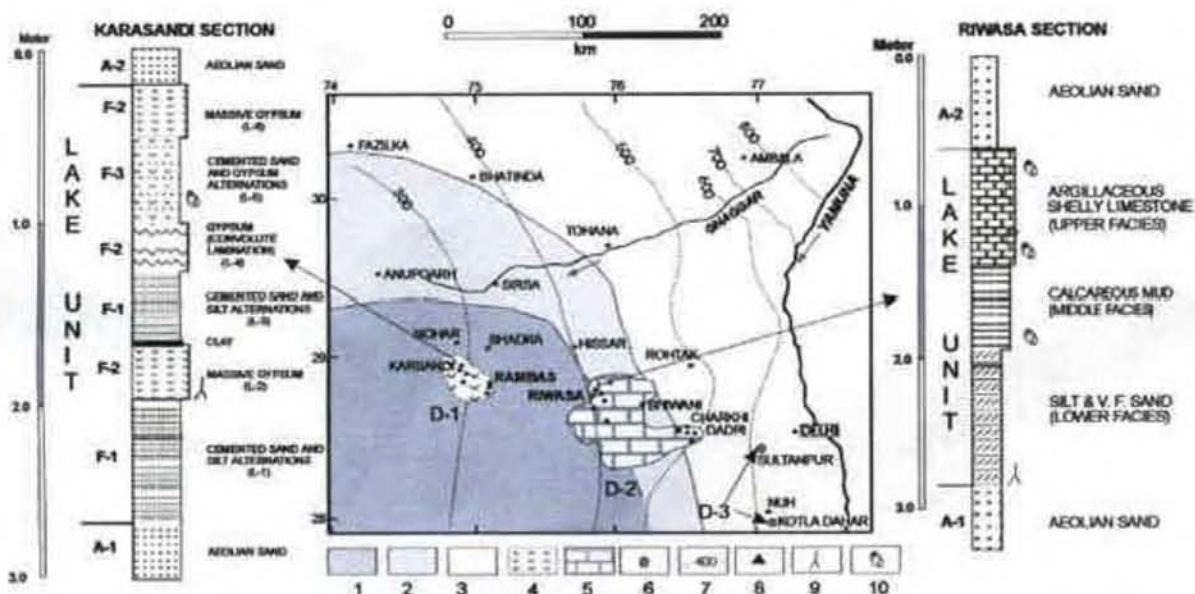
Three distinct groups of lake deposits, (D-1, D-2, D-3; Figure 2), each characterized by a typical lithology and morphology in each of the three rainfall zones have been recognized. The facies occur in association with desiccated planar surfaces, and as small lensoidal bodies in deflation hollows in different landform settings.

In the arid Nohar–Bhadra domain, the surface is made up of Late Quaternary (?) aeolian deposits occurring as dunes and sand sheets. A small volume of palaeo-lake deposits occurs as thin, isolated clusters of salt pan bodies in the deflation hollows. These hollows have older, high-amplitude stabilized dunes and ridges on the rim and younger, low-amplitude mobile dunes in the depressions (Figure 3a). The salt pan bodies are 0.30–2.4 m thick, few square metres to few hundred square metres in extent, and mostly semi-circular in shape. These deposits have been recognized south of Nohar (around Karasandi, Seorani, Nagrasari, Lalniya villages) and south-southwest of Bhadra (around Bhojka, Rambas and Melia villages) in Hanumangarh and Ganganagar districts, Rajasthan (Figure 2). Such deposits are characterized by laminated to interbedded gypsiferous sediments with few molluscan shells; these are underlain and overlain by aeolian sand. A typical section studied near Karsandi village (28°59′24.5″: 74°45′54.9″) is shown in Figure 2, in which two aeolian and one lacustrine unit have been demarcated. A-1 and A-2 are aeolian units consisting of brown, fine-grained, well-sorted sand that constitute the base and top of the salt pan respectively. Facies F-1 is dominantly detrital, consisting of alternating laminae and beds of cemented, brown, very fine sand and silt with gypsum. Facies F-2 is evaporitic in nature and consists of poorly laminated gypsum beds. In places, deformed and convoluted laminae in gypsum layers are observed (Figure 3b). Facies F-3 consists of detrital and evaporite sediments, and is represented by alternating sand and crystalline gypsum laminae with few gastropod shells occurring in the centimetre-thick sand laminae. The thickness of the lacustrine unit gradually reduces from west to east, attaining a reduced thickness of 0.40 m of fine-grained gypsum and sand near Rambas.

Geologically, the semi-arid domain is made up of Late Quaternary (?) aeolian deposits, with few inselbergs of rhyolites and granites in the western part, and alluvium



Figure 1. Location of important lakes in northwestern part of India.



**Figure 2.** Northeastern fringe of Thar Desert showing climatic zones, broad geomorphic elements and lake deposits. 1, Arid zone: High amplitude sand dunes; 2, Semi-arid zone: Medium amplitude sand dunes and sand sheets; 3, Alluvial Plain; 4, Sulphate-bearing lake deposits; 5, Carbonate-bearing lake deposits; 6, Detrital lake deposits; 7, Isohyet; 8, Pit section; 9, Root traces; 10, Molluscan shells.

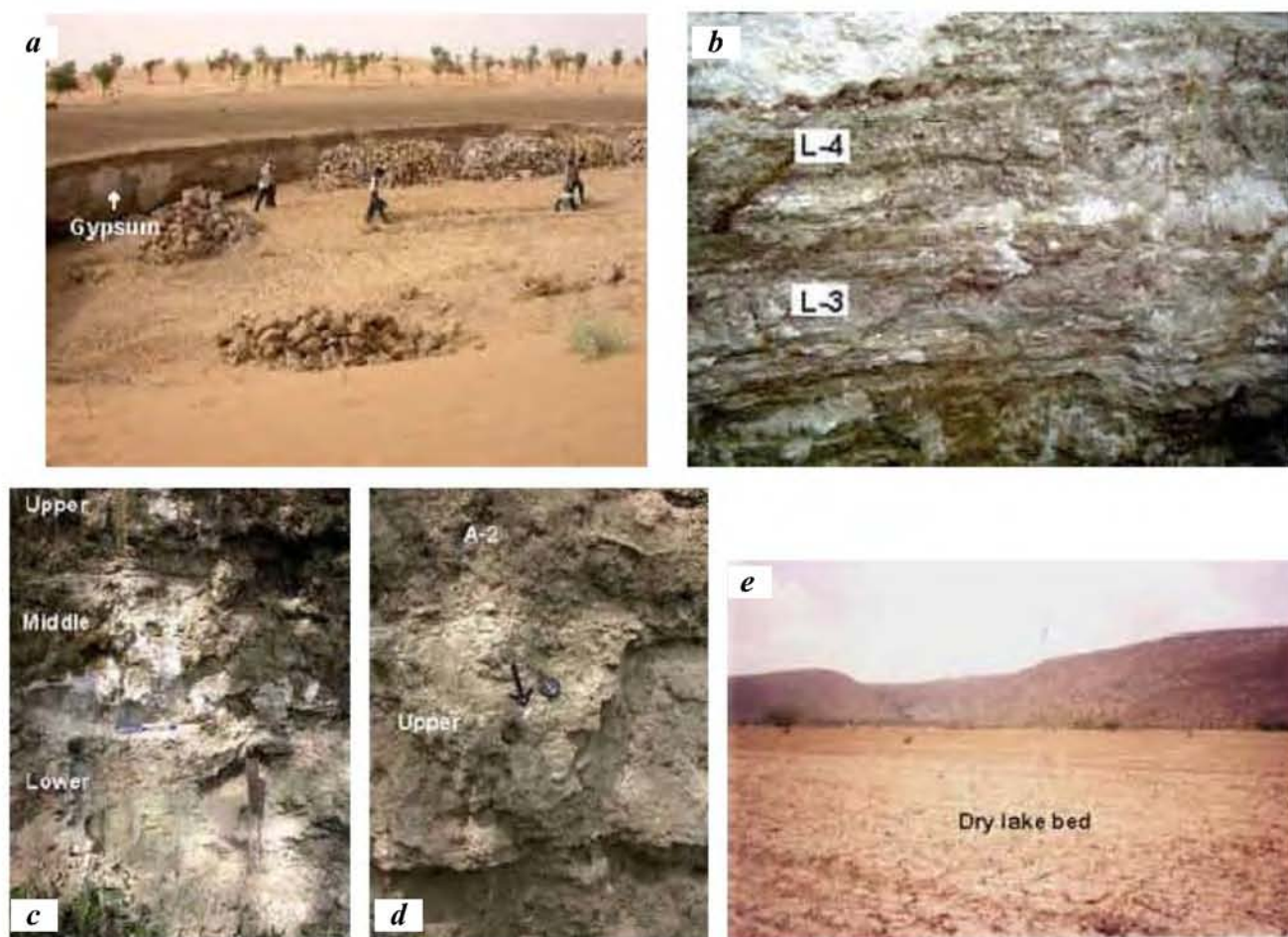
**Table 1.** Summary of climatic data of three representative stations (1931–60)<sup>13</sup>

	Ganganagar (arid)	Hissar (Semi-arid)	Delhi (Sub-humid)
Mean annual rainfall (mm)	296.3	446.0	714.2
Mean temp. range (°C)	17–32.9	17.4–32.8	18.8–31.7
Mean lowest temp. (°C)	0.3	0.8	2.7
Mean highest temp. (°C)	47.0	46.3	44.7
Humidity (%)	18–80	24–75	18–72

and aeolian deposits in the eastern part. Individual lake deposits have a spread of 200 m<sup>2</sup> to 10 km<sup>2</sup>. The Riwasa area shows four geomorphic units, namely inselberg, sand sheets, sand dunes and depressions (Figure 4 a). The palaeolake deposits of this semi-arid domain are abundant and scattered as small, stratified, lensoidal and sheet-like bodies of fossiliferous silt-clay and argillaceous shelly limestone in more than 2000 km<sup>2</sup> area of Bhiwani district, Haryana. In places, the argillaceous shelly limestone facies grades laterally into the calcrete facies occurring in the surrounding sand dunes. The 20–40 cm thick calcrete is dirty white to greyish, hard, relatively coarse-grained in comparison to the argillaceous limestone, and is devoid of shells. The undulating topography of Riwasa area gradually gives way to a gently sloping fluvio-aeolian plain towards the east, having poorly marked depressions with lake deposits. This topographic and lithologic change is accompanied by a marked reduction in the thickness of lake deposits from 2.5 m in Riwasa to 0.40 m in the Charkhi Dadri area. Based upon data from ten sections, three facies have been identified in the lake sequence in the Riwasa area. A representative litholog South of Riwasa village (28°47'08.2": 75°57'24.8")

is given in Figure 2. The lower aeolian sand unit (A-1) is brown, very fine-grained and well-sorted. Its upper part is harder, silty and grades into the lower facies of the lake unit without a sharp break. The lower facies of the lake unit consists of greyish to greenish coarse silt and very fine sand, with worm tubes and few gastropod shells. It is up to 0.80 m thick in the Riwasa area, but absent in the Charkhi Dadri area (i.e. Lohgarh, Khathiwas, Samaspur, Rawaldhi and Misri villages). It passes upward into a middle facies consisting of shell-bearing, off-white, soft calcareous mud. The upper facies is a hard, massive, argillaceous shelly limestone (Figure 3 c and d), which is 0.60–1.00 m thick around Riwasa and 0.15–0.30 m thick around Charkhi Dadri. The shells include eight genera of freshwater gastropods, thirteen species of mesohaline ostracods and two species of chara<sup>12,15–17</sup>. Near Charkhi Dadri, the upper facies with variable thickness has developed extensively. Near Shampur village, this upper facies is represented by a brecciated argillaceous shelly limestone, indicative of palustrine conditions<sup>18</sup>.

Lakes in the 500–700 mm rainfall domain are active shallow depressions that are flooded seasonally. Sand ridges



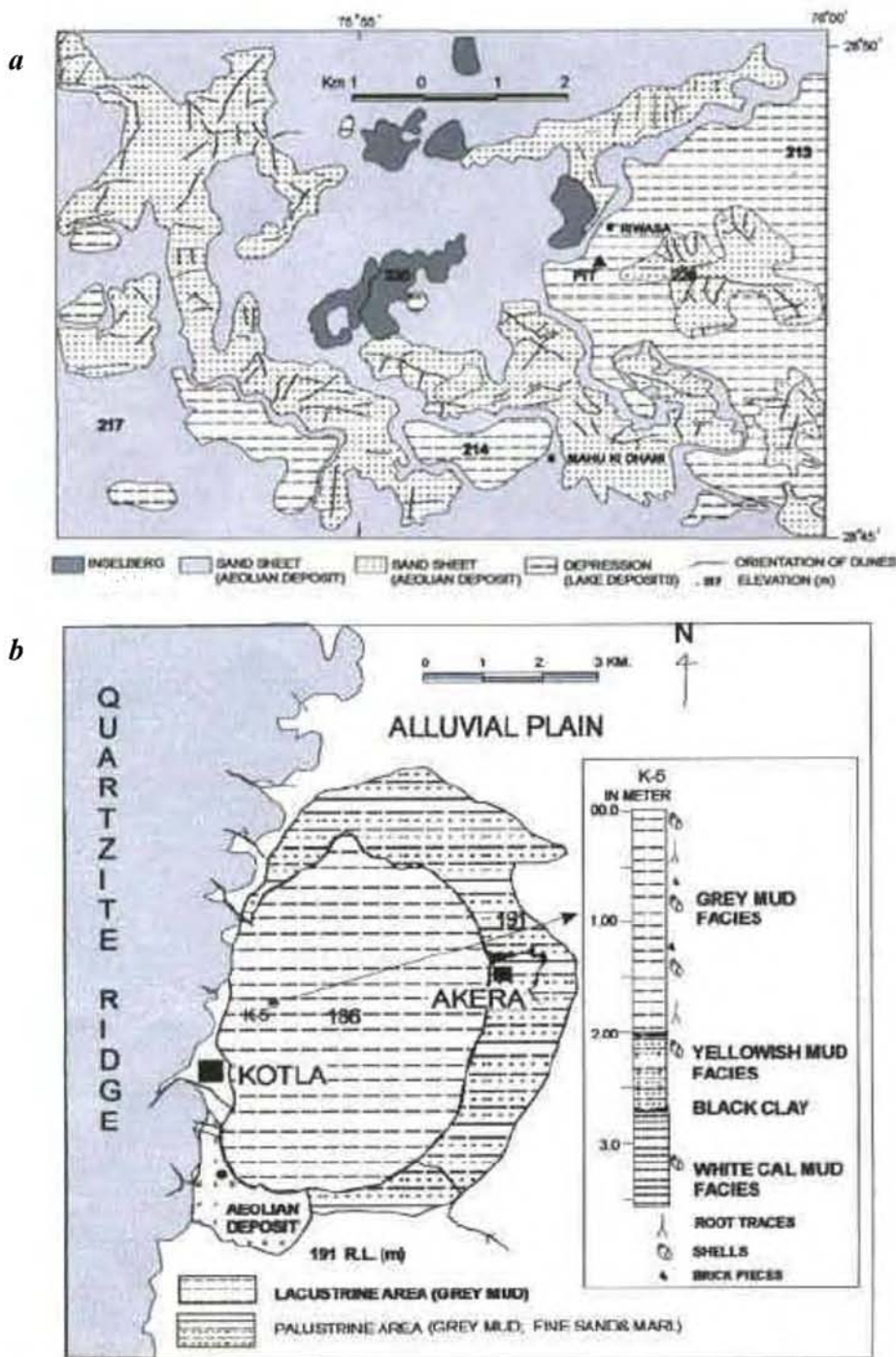
**Figure 3.** *a*, A partly sediment-filled deflation hollow near Sheorani village with older sand dunes at its rim and salt pan (gypsum quarry) underlying a ~50 cm thick aeolian cover in the middle. *b*, Closer view of part of the salt pan of Karsandi village showing gradational contacts of layers L-3, and L-4. Thickness of L-4 is 30 cm. *c*, Section of carbonate-bearing lake deposit south of Riwasa village, Bhiwani district showing lower facies (Lower), middle facies (Middle) and upper facies (Upper). *d*, Close-up of upper facies (argillaceous shelly limestone) below the upper aeolian unit (A-2). Note the gastropod shells near the lens cover. *e*, Panoramic view of dry Kotla Dahar lake. The Delhi Supergroup rocks are exposed on its western flank.

are present around Sultanpur lake, and a few mounds are recorded around the Kotla Dahar lake (Figure 4*b*). These deposits are made up of poorly stratified fine-grained detritus. The Kotla Dahar lake (Figure 3*e*) is a 5 m deep, closed, ephemeral lake spread over 20 km<sup>2</sup> (Figure 4*b*). It has +3.55 m thick lacustrine sediments (Figure 4*b*). The top part is a metre thick grey, hard mud facies with gastropod shells and gypsum crystals. It is underlain by 0.70 m thick, yellowish mud facies that has 2–5 cm thick streaks of black clay. The yellow mud facies is followed by white molluscan-bearing calcareous mud facies of undetermined thickness. All contacts are gradational.

Climate is one of the most important factors that controls the development of sedimentary facies in a lake because of the changes in its water level, spread, water chemistry and sediment supply<sup>19–21</sup>. As such, lake deposits are commonly used in reconstructing aspects of past hydrology, temperature and ecology<sup>22–25</sup>. The potential of lake deposits in the present study area for such determinations is high

because of their location in a desert fringe, which is sensitive to climate change. Although detailed chronological data of these sequences are not available, we suggest a tentative Holocene age on the basis of their field-association with the youngest geomorphic elements and the available preliminary radiocarbon chronological data<sup>12</sup> for the Riwasa area.

The lake environments based on the sedimentary facies associations in the three zones respectively, are summarized in Table 2. Sandwiching of the lake unit between the two aeolian units in the widely separated sections of Nohar–Bhadra and Riwasa areas signifies two phases of climate change from dry arid to wet and again to dry arid. In the arid region, wet conditions favour deposition of clastic layers, while dry conditions result in the shrinkage of water bodies and precipitation of salt layers<sup>20,21</sup>. Laminations in the detrital layers are due to variations in the detrital flux caused by variability in rainfall. The dominance of gypsum, with little or no carbonate precipitation in the evaporitic layers indicates extremely dry conditions.



**Figure 4.** Geomorphological units: *a*, Riwasa area, Bhiwani district. Lake deposits are confined to the depressions. *b*, Kotla Dahar lake area. (Inset) Lithosection of Pit K-5.

In the Riwasa area, the lower, fine-grained clastic facies represents gradual initiation of lake environment with high detrital influx. The middle shell-bearing calcareous mud facies indicates rise in water table and lake levels, and decrease in detrital influx due to reduced sediment supply. The upper argillaceous shelly limestone represents a lake-full stage in which biological productivity increased and calcium carbonate precipitated. White calcareous mud

at 2.75 m depth in the lake sequence of Kotla Dahar (Figure 4*b*) represents a lake-full stage. The overlying yellow mud facies suggests shallowing of the lake, while the upper grey mud facies with gypsum towards the top suggests ephemeral/seasonal nature of the lake.

In a regional context, variability in the nature of lake deposits from west to east, from sulphate to carbonate to detrital mineral phases corresponding to the present-day

**Table 2.** Depositional environments of the lake and associated aeolian sequences from arid, semi-arid and sub-humid zones

Nohar–Bhadra area	Riwasa–Charkhi Dadri area	Kotla Dahar area
A-2: Aeolian, arid condition	A-2: Aeolian, arid condition	
F-2 (L-6): Saline lake, dry condition	Upper Facies: Carbonate lake, biological productivity, negligible detrital input	Grey mud facies: Seasonal lake
F-3 (L-5): Moderately saline lake, fluctuating lake level		
F-2 (L-4): Saline lake, dry condition	Middle Facies: Carbonate lake, negligible detrital input.	Brown mud facies: Shallow lake
F-1 (L-3): Moderately saline lake, high detrital input		
F-2 (L-2): Saline lake, dry condition	Lower Facies: Freshwater lake, high detrital input	White calcareous mud facies: Perennial lake
F-1 (L-1): Moderately saline lake, high detrital input		
A-1: Aeolian, arid condition	A-1: Aeolian, arid condition	–

arid, semi-arid and sub-humid zones respectively, shows the rainfall gradient in the Holocene (?) followed the present pattern of decreasing rainfall generally from the east to the west. AMS radiocarbon dating and geochemistry of the lake sediments from Lunkaransar in Rajasthan suggest<sup>7</sup> a phase of shallow and fluctuating lakes in the early Holocene and lake-full phase between 6300 and 4800 <sup>14</sup>C yrs BP. The Didwana lake record shows more variability in the monsoon and slight delay in the formation of lakes compared to the Lunkaransar lake<sup>25</sup>. Also, it has been suggested<sup>26</sup> that the Sanai lake in the Ganga Plains, Uttar Pradesh went through a phase of expansion during ~10,000 to 5800 <sup>14</sup>C yrs BP (Early to Mid-Holocene). These authors have also recognized a dry spell and reduced monsoon activity during 5000–2000 <sup>14</sup>C yrs BP. For the Riwasa area, Bhatia and Singh<sup>12</sup> have suggested a lake phase between *c.* 5363 ± 110 and 3640 yrs BP, but this suggestion is based on an inadequate database of two conventional radiocarbon dates of argillaceous shelly limestone (marl). There is need to generate rigorous chronological data (AMS radiocarbon and luminescence) not only on the argillaceous shelly limestones which represent a part of the lake sequence, but also from the under- and over-lying aeolian as well as fluvial facies to reconstruct a detailed post-Last Glacial Maximum climatic history of this important region that borders major urbanized belts of northern India.

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## RESEARCH COMMUNICATIONS

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