

Paleoclimate History and Antiquity of Thar

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Abstract: The presence of climate-responsive landforms, namely lakes, aeolian and fluvial transported sediments termed sheetwash aggradations and relicts of pre-existing surfaces in the Thar Desert, have generated a wealth of paleoclimate information. Aeolian dynamism has dominated the past ~250 ka (kilo years before present) with episodes of aggradation at 17-13, 30-21, 70-60, 100-80, 140-130, 170-160 and ~250 ka. Most of these episodes were followed by extended periods of landscape stability and soil development, including redistribution of carbonates with in a stratigraphic context. The preceding period i.e., from ~250 to 600 ka was characterized by episodic sheetwash deposition. Deep sections show a stack of aggradations each generally with a discrete calcrete formation. Extensive spatial mobility of carbonates and pronounced pedogenic calcrete development suggest dominance of a distinctly semi-arid climate that was significantly wetter than the present. Relict surfaces are from ~600 ka to 1600 ka. Extraordinary landscape-scale mobility of carbonates is demonstrated by regoliths with massive carbonate enrichment and by the evolved nature of carbonate fabric. Both these attest to their extended antiquity and to a pronounced semiarid with possibility of even wetter episodes during this period. Summing up, studies suggest that for a major part of the past two million years this region enjoyed a semi-arid climate, significantly wetter than the present and that aeolian activity typical of a desertic environment appeared in a much later part of the of the Quaternary. Much has been learnt but scope exists for further refinement.

Key words: Thar paleoclimate, desert antiquity, calcretes in Thar, climate-responsive surfaces of Thar.

Presence of a Thar, a desertic tract, within a sub-continent gifted with a strong monsoon regime is an environmental peculiarity. However, when looked from the west, the region is an easterly limit of the vast mid-latitude desert belt from Sahara through Arabia and Iran. This fringe location makes Thar a potential area to record past extent and strength of monsoon wind circulation regime, the establishment of which is considered to be eight million years ago at least (Gupta *et al.*, 2004). Thar desert should experience an amelioration of its aridity and, shrinkage of its size whenever monsoon regime was strong and conversely, its weakening should have led to an accentuated aridity. Quite early in geomorphological investigations in Thar, it became apparent that sand dunes, a dominant landform in Thar, are stable with evidence of weathering and soil formation and those in vicinity of rocky outcrops are deeply incised. This was inferred to mean that the dune building had happened sometime in the past and possibly in a drier and windier climate than

the present and that their stability resulted from a subsequent climate amelioration (Pandey *et al.*, 1964). Discovery of Middle Paleolithic stone tools in obstacle dunes, off the western flank of the foothills of Aravalli Mountains, while confirming above suggested that this dune building happened at least tens of thousands of years ago (Allchin *et al.*, 1978). Disorganization of past drainage system in central Luni basin (Ghose, 1964) and westward shift and break up of proto-Saraswati drainage system up in the north suggested significant changes in hydrological regime (Ghose *et al.*, 1979; Kar and Ghose, 1984). Palynological and hydrological evidences collected from salt lakes 1970's (Singh *et al.*, 1974) showed also considerable fluctuations in lake levels and in composition of vegetation surrounding these lakes.

Since these studies a lot of investigational effort has gone into paleoclimate reconstruction in the region. Results of these studies have been extensively published (Singhvi 2004), and a recent review by Dhir and Singhvi (2012) provides an overview of the present understanding of the evolution of the Thar Desert. The present article is another effort with some dimensional elaborations.

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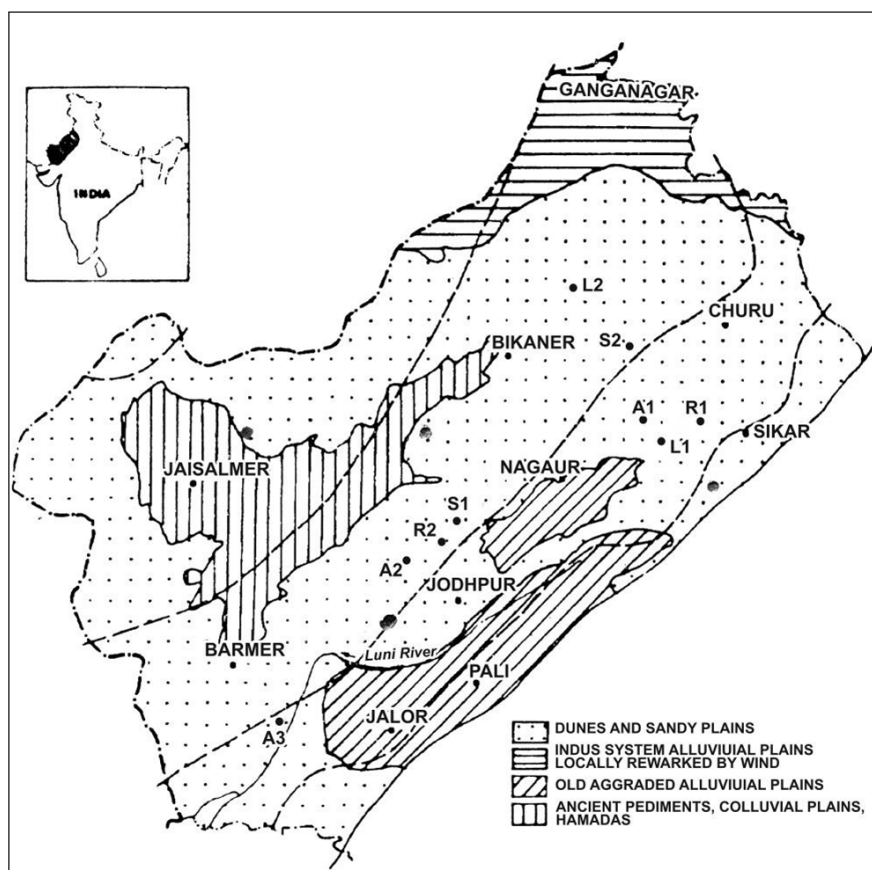


Fig. 1. Map of Thar showing a generalized distribution of present day surfaces (after Dhir *et al.*, 1994). Also shown is location of major investigated sites: Didwana Salt Lake (L1), Lunkarnsar Lake (L2); 16R Dune Section (A1); Chamu Section (A2); Khudala Section (A3); Nandia Khurd (S1), Sunari Section (S2); Ringan Section (R1); Anwana Section (R2).

Present Day Land Surfaces and their Paleo-Environmental Attributes

Aeolian landforms comprising dunes and sandy plains are the dominant surficial cover (Fig. 1). The other landforms are the younger alluvial plains up north, old aggraded alluvial plains in central and south-east and ancient, Early Quaternary or older surfaces in central and western Thar. Several salt lakes of various dimensions dot the entire desert. Amongst these Sambhar Lake in north-east is the largest. Geochemical, palynological and other studies of deep sediment cores in these lakes show that sedimentary deposition is stratified and also pollen-rich and thus has a potential in reconstruction of past environments.

Aeolian sediments mantle the surface, but with varying thicknesses (Dhir *et al.*, 1994). The sediments are moderately well sorted and this feature together with local mineralogical variations imply that these originated through

deflation of pre-existing landforms, including the then existing stream beds (Wasson *et al.*, 1983; Wadhawan, 1988 and Hema *et al.*, 1986). The sandy plains and dunes in the north-east with 400-500 mm rainfall show some weathering, distinct reddish brown coloration and deep leaching of carbonates and in the central (~300 mm rainfall) tract the sands are light brown and show an increase in carbonate content and secondary accumulations (nodules) with depth. In the westernmost and driest situations dunes are least weathered and are weakly gypsiferous (Dhir *et al.*, 2004). Thus, aeolian sands are a valuable proxy for paleoenvironmental studies. Their potential got a quantum jump with development of a luminescence dating method, which is able to provide chronology of a particular depositional episode. (Singhvi *et al.*, 1982). The younger alluvial plains in the northern most Thar are the southern limit of the vast alluvial plains that have formed by sedimentation from Himalayan and Siwalik hill

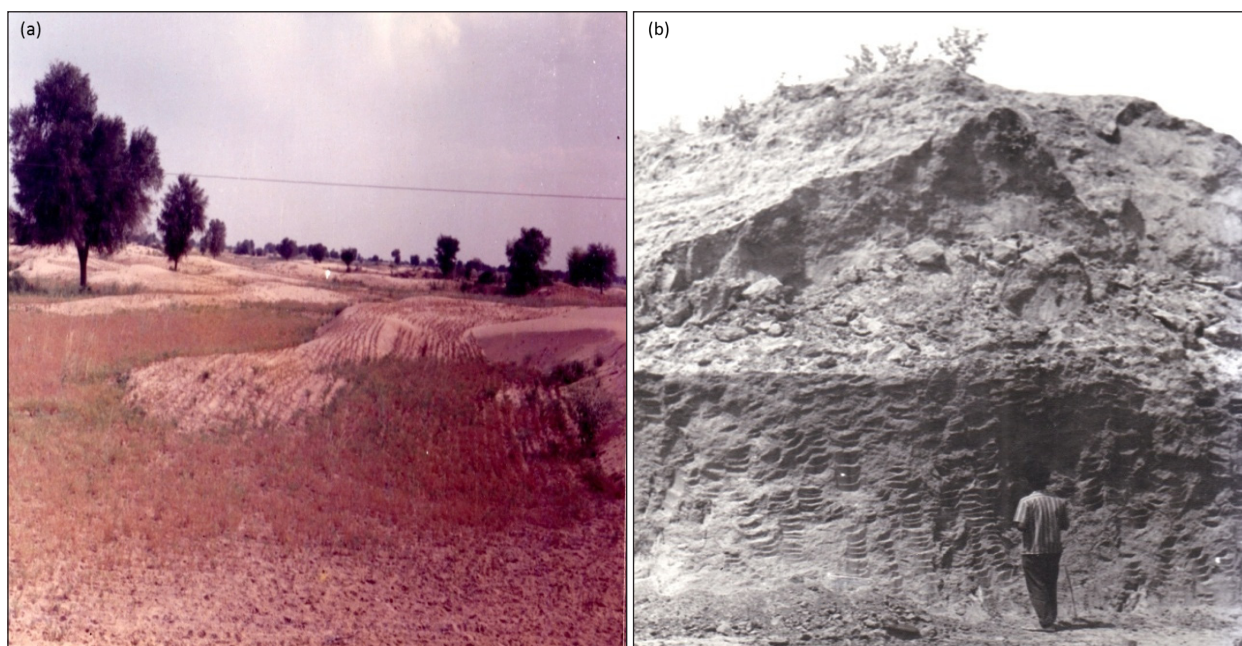


Fig. 2. (a) A view of younger alluvial plains. The surface sediments have been extensively reworked into sandy undulations and even low dunes; (b) Alluvial plains in transitional are seen encroached upon by Thar dune field sand.

ranges. Deep sections here show evidence of flood plains, channel and lacustrine sediments. These sediments in Thar and its contiguous areas has been extensively reworked by wind into low dunes and hummocks (Fig. 2a). In the transitional area with the Thar dune fields, these plains are seen overlain with exogenous sands (Fig. 2b). The soils are weakly developed due to sediments being of young ages and an arid moisture regime.

Old aggraded plains are a dominant landform in Luni basin and adjoining area to the north and also in parts of central Thar. Sporadic occurrence is also seen deep in the desert, where these lie buried under a variable thickness of aeolian mantle (Dhir *et al.*, 1994). The sediments are poorly sorted and show a mineralogy consistent with local rocks and surfaces, leading to their being termed sheetwash aggraded plains (Dhir *et al.*, 2004). Though the thickness of sediment cover can be a few hundred meters, but generally it ranges between 5 to 10 m. Kar (1988) and Bajpai (2004) have shown the control of tectonics on sediment thickness. Deep sections show a sequence of several aggradations with marked breaks and soil formation in between. Within the stretches of these plains, mounds of older alluvial formations occur (Fig. 3). These exposures comprise cemented, gravel-pebble

facies, indicating that these are channel facies of an older surface, associated plains of which have since been eroded away. These present a clear case of relief reversion and of the fact that there has been a change in base level of erosion in the past. The sheetwash aggraded plains host well developed calcretes and deep section show a stack of these.

Calcretes are generally typical of a semi-arid climate, as a drier climate restricts spatial and profile distribution of carbonates, whereas a wetter climate tends to push carbonates out of the landscape. Calcretes are a striking feature of sheetwash aggraded plains and also of several younger and older landforms. Effort to date these with U/Th methods were unsuccessful due to detrital contamination. Electronic spin resonance technique developed by Kailath *et al.* (2000) when used on phase constrained samples has been found workable. Great advantage with this method is its vast age range that extends to hundred of thousands of years and hence has the ability to cover entire Quaternary period.

Relict surfaces are widespread in central part of Thar, but isolated occurrences are seen elsewhere also. These occur in a variety of settings, most extensive of which is Bhojka-Pokran-Bap-Bikaner surface (Fig. 1) comprising pediments and boulder spread. Another is



Fig. 3. A positive relief feature in a sheetwash aggraded plain. Such features are an evidence of relief inversion due to selective erosion of surrounding, less resistant plains. It is an evidence also of change in base level of erosion.

Jayal Upland, which comprises braided stream deposits, originating from western lopes of Aravalli Mountains and got uplifted sometimes in Neogene. Thereafter the surface underwent a tectonic upliftment and erosion (Achyuthan and Rajaguru, 1997). It shows a ferricretisation of the boulder-gravel bed in its basal part while calcretization dominates the upper. They speculated a late Neogene to early Quaternary age for these developments. Besides above, there are also near surface rocky pediments, which depending upon lithology, show varying thickness of weathered zone and imprints of past environments.

Paleoclimate Evidence from Salt Lakes

Didwana and other salt lakes were investigated in early 1970 by Singh *et al.* (1974)

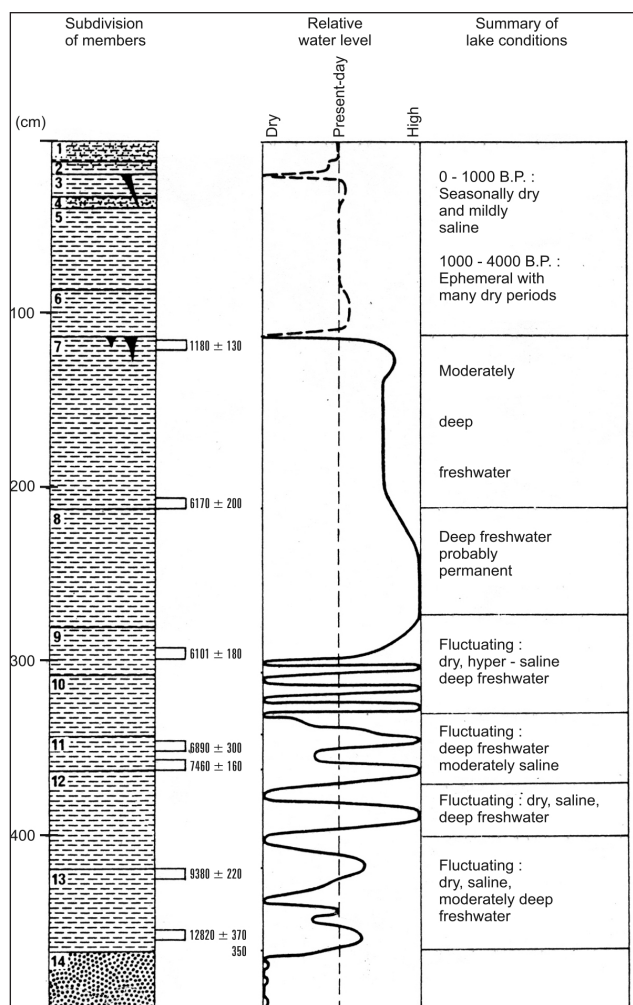


Fig. 4. Stratigraphy and paleo-hydrology of Didwana Lake (adapted from Singh *et al.*, 1990). The lake maintained a continuous, fresh water column between 6 to 4 ka BP suggesting a period of persistent ameliorated climate with a substantial contribution also of winter rains.

and they showed that a few meter thick pollen-rich sediments carried a history stretching over thousands of years. A little later Wasson *et al.* (1984), based on geochemistry and mineralogy of the Didwana Lake, deciphered hydrology, salinity conditions and reconstructed the climate over the past ten thousand years or so. They showed that hyper saline conditions prevailed at Last Glacial Maxima i.e. at about ~20 ka ago with little sedimentation of clastic sediments and the later started accumulating only after 13 ka. The subsequent period from 13 to 6 ka saw wide fluctuations in lake levels with occasional hyper saline conditions. A synthesis of these studies with improved chronology was presented by Singh *et al.* (1990). The lowest strata from ~4.5 m and below dated to 12.8 ka and older, showed dominance of a tree-less savanna and extremely low values of wet land vegetation suggesting thereby a very arid condition. The overlying strata dated to 12.8-9.3 ka showed appearance of shrub-savanna grassland and a representation of fresh-water plants in the pollen assemblage-all suggesting intermittent filling of lake. The succeeding 9.3-7.5 ka BP saw a further increase in fresh-water plants and weakening of halite salt deposition and thus showed a further improvement in rainfall though still with intermittent dry episodes as seen in the earlier phase. The period from 7.5-6.2 ka BP experienced most significant changes (Fig. 4). The pollens of *Calligonum*, *Ephedra* and *Aerva* sp. i.e., representatives of very dry zone vegetation almost disappeared and instead Graminae and *Artemisia* spp., became far more prominent, clearly suggesting a great improvement in environment with lake holding fresh-water all the time. After this period of improved rainfall, the lake level started declining, culminating in complete drying up of the lake by 4.0 ka BP i.e., showing onset of condition close to the present. A significant observation was the presence of *Artemisia* spp., a winter season plant, which was represented even during the early period of lake history and continued to maintain its presence throughout the period of improved rainfall, but disappeared totally with the onset of 4.0 ka aridity. From this Singh *et al.* (1990) also concluded that unlike the present, the winter rains were quite a significant component of the annual rainfall regime then.

Enzel *et al.* (1999) made even more rigorous study of a lake at Lunkaransar, 150 km to the

north-west of Didwana and provided centennial scale record of past rainfall. Their findings broadly corroborated the findings from Didwana Lake. These also confirmed a Mid-Holocene period of major climate improvement both from pollens and stable isotope composition. Only the duration of the high water level in the lake was shorter than that at Didwana, which is explainable since Lunkaransar lies in a drier setting compared to Didwana (Fig. 1). Like Singh *et al.* (1990), they also emphasized the strong presence of winter rain circulation and concluded that the perennial water regime could not have been possible otherwise in the high atmospheric moisture deficit regime of the location concerned. A study of other lakes by Deotare *et al.* (2004) and of Roy *et al.* (2008), while confirming the earlier results, showed that the lakes in the more arid west dried up nearly a thousand years prior to those in the eastern part of Thar. Roy *et al.* (2008) based on carbonate and evaporite minerals showed a period of enhanced aridity at 3.1 to 1.3 ka BP and some amelioration thereafter.

Pre-historic Cultures and Climate

An exquisite pre-historic culture, named Harappan/Indus/Saraswati flourished along the western margin of Thar. The Harappan archaeological sites, when discovered in the year 1931, lay along Indus River and its tributaries, but investigations since then have shown far greater concentration of these along the Ghaggar-Hakra River, the course of which mostly runs parallel to and a few kilometer to the east of Indus River and had an independent exit to Arabian Sea. However, presently this river is lying in a dysfunctional and highly disorganized form. This culture is subdivided into three stages, namely Early Harappan (3200 to 2600 BCE), Mature Harappan (2600-1900 BCE) and Late or Degenerate Harappan (1900 to 1600 BCE). Harappan civilization distinguishes by its well developed and diversified agricultural economy, society organization and art and culture, including a script. At its peak i.e. Mature Harappna enjoyed a high degree of affluence and agricultural surpluses that permitted long-distance trade, an outstanding urbanization and evolved social structure.

Archeological evidence suggests that Harappan civilization in its grand stage was largely a riverine culture based on inundation

farming and winter cropping comprising wheat, barley and peas (Madella, 2003). This meant a sustainable discharge and of sufficient magnitude of water flow that it could traverse through several hundred kilometer of desert to the middle and lower reaches of Ghaggar-Hakra River where the settlements were well concentrated then. Many archaeologists had believed that flow was perennial then and sustained by Sutlej and Yamuna rivers, which presently do not flow into Hakra. However, studies of Giosan *et al.* (2012) based on incision pattern in upstream region and of Clift *et al.* (2012) based on sediment dating and the mineralogy, suggest that the Yamuna River had abandoned its south-western course to Ghaggar about 50 ka in the past. Clift *et al.* (2012) further showed that Sutlej continued to flow into Ghaggar for long thereafter but shifted its course to become a tributary of Indus System well before 10 ka BP. Probably more rigorous studies are needed since with Sutlej severing its contribution, the flow from residual Ghaggar catchment alone, whatsoever the rainfall regime, could not have sustained a water regime so critical for the Mature Harappan Stage civilization, particularly in view of the strong evidence provided by Lake studies that rainfall had started declining from Mature Harappan Stage itself. A view reiterated also by Valdiya (2013). The impact of declining rainfall became specifically apparent during Late Harappan. It is certain that Ghaggar-Hakra did not carry any durable flow from ~2000 BCE as Late Harappan settlements sites are seen even on the bed of the river itself. Besides size of village settlements greatly declined during this period and the cropping pattern also focused on summer season crops, including millets (Madella and Fuller, 2006). Importantly, settlements of this time are seen shifting more to the higher rainfall tracts to the north and even crossing the then Yamuna to the Yamuna-Ganga Doab. All these cultural evidences clearly point to the fact that rainfall in the region markedly declined from 2000 BCE onward, an event in conformity with findings from Lake studies.

History of Aeolian Dynamism and Palaeoclimate

Degree of stability and soil morpho-genetic features, though weakly expressed, as also presence of Mesolithic tools on surface gave

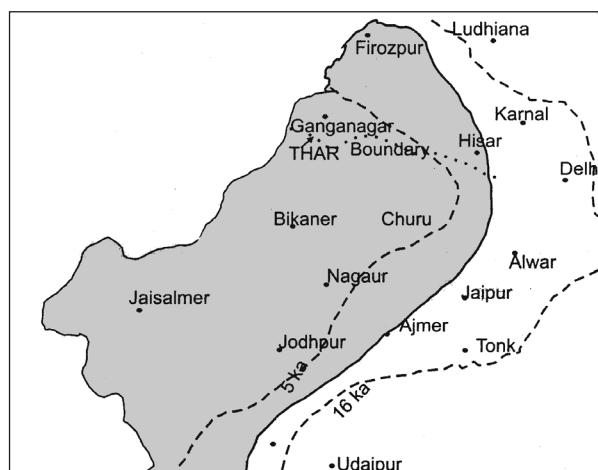


Fig. 5. Present (shaded area) and former extents of Thar Desert, namely at 5 ka and 16 ka (after Singhvi and Kar, 2004). The desert at 16 ka BP spread far beyond its present limits.

an idea that the sand dunes have been in place for a sufficiently long time, but assessments were not quantifiable and also amenable to subjectivity. Development of a luminescence dating method (Singhvi *et al.*, 1982) provided a method for direct dating of the age of deposition of sands. The ages are, directly on the minerals constituting the sands, robust and reproducible and have changed the way the desert studies have been done. Over time several improvements have been made in procedure and source of luminescence. This was followed by an extensive sampling of surficial aeolian sediments across the Thar. The results showed that sands could be as young as a few years to nearly 20 thousand years. The young ages were shown by fresh-looking sands whereas older ages were from stable dunes. Singhvi and Kar (2004) compiled these records and showed a much higher frequency of aggradation episodes for period 6 ka and older. From this they concluded that the period of major dune building in recent time had happened not at peak of Last Glacial Maxima aridity i.e. at ~21 ka, but thereafter between 17 ka to 11 ka, when monsoon winds were reestablishing themselves. This was also the period when desert features, namely the dunes, also spread to the east of Aravalli Mountains (Fig. 5).

Since then several deep sections have been studied for older records. Dhir *et al.* (2004) described a 12-meter deep section located in

central part of Thar. It comprises seven distinct lithounits (Fig. 6) which are discernible by fairly distinct breaks and are persistent laterally. Of these, one at the base is a cemented channel deposit made up of clastic gravels and transported calcrete nodules. The remaining six overlying units are in aeolian sands. The units II and III, dated respectively to ~250 ka and ~160 ka are somewhat poorly sorted sands compared to overlying ones and contain few large sized carbonate nodules. Unit IV is thick, very weakly pedogenized sand with nodules in its upper part. Six samplings at various depths showed an age range of 105 to 80 ka. Though dating results carry some degree of methodological uncertainty, apparent age reversion is a matter of detailed investigation. Unit V has a high concentration of nodules in aeolian sands and represents a zone of pedogenic carbonate accumulation, the upper solum of the profile having been denuded away. But elsewhere in lateral spread of this unit, complete profile exists. The aeolian sands are dated to ~60 ka. Unit VI, somewhat pedogenized and has chalky nodules in its lower half and has age of 28-27 ka. In its upper part the ages are 17-14 ka and this represents a separate aggradation, the intervening boundary of which has got obliterated by bioturbation (Dhir *et al.*, 2009).

The upper most unit comprises of fresh, recent sands.

Thus, the sequence is an assemblage of several aeolian aggradation episodes ranging in age from ~250 ka to present, most marked by period of stability and some soil formation manifest in profile redistribution of carbonate and formation of calcrete nodules. There is also some weathering of plagioclase and other minerals and neosynthesis of secondary minerals like palygorskite (Dhir *et al.*, 2009).

Misra and Rajaguru (1986) had earlier studied deep section in northern part of Thar and noted several aggradation units with calcrete features at several levels. They also showed for the first time the great antiquity of aeolian dynamism from presence of *in-situ* lower Paleolithic tools at the base and that of Middle and Late Paleolithic periods at upper levels. Subsequent refined dating by Achyuthan *et al.* (2007) and Singhvi *et al.* (2010) have firmed up a chronology based on thermo-luminescence measurements. The bottom unit with Early Paleolithic tools is dated to ~180 ka. Subsequent prominent aggradations are seen at 140, 125-110, 70 and 26-13 ka. Kar *et al.* (2001) studied a section in southern part of Thar on the bank of Luni River and showed that poorly sorted

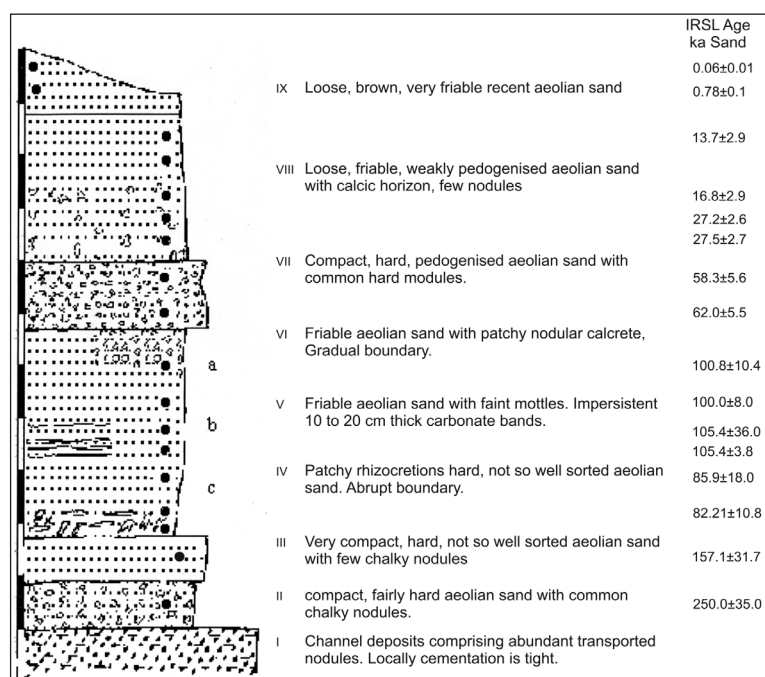


Fig. 6. Litholog of deep section at Chamu. The oldest aeolian episode (Unit II) has been dated at ~250 ka BP. A well developed nodular calcrete in Unit V is an evidence of a significant climate amelioration post-60 ka aeolian aggradation.

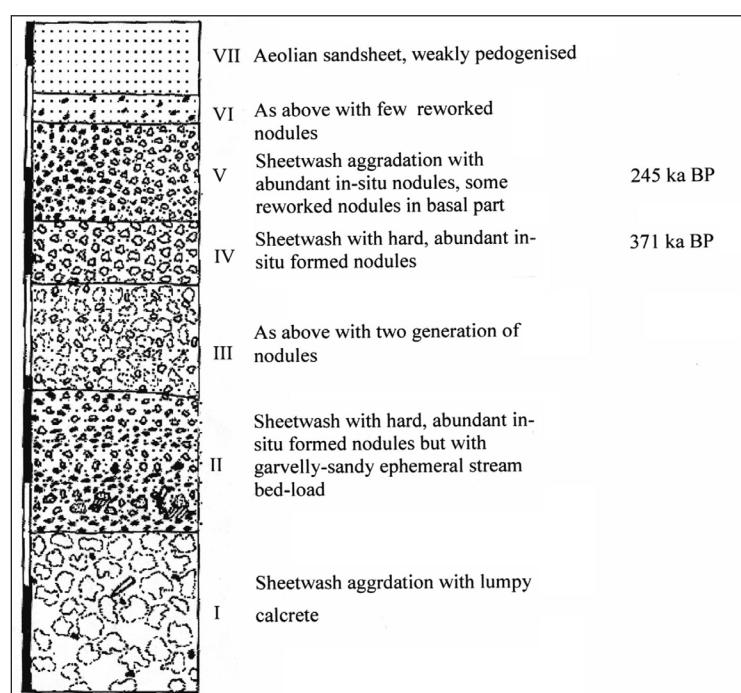


Fig. 7. Litholog of the deep section in sheetwash aggraded plains at Nandia Khurd. The top two lithounits are in aeolian sands. The remaining are in sheetwash aggradation, the upper most of which are dated to 245 and 371 ka BP.

sand at the base has an age of ~100 ka. The silty-sand layers between fluvial sands were dated to ~42 ka, whereas a thick, pedogenized aeolian sand unit at the top carried a date range of ~31 ka at the base and 19 ka in the upper part. They also recorded a channel activation phase between 70 and 30 ka.

Younger Alluvial Plains

This landform lies in the northernmost part of Thar (Fig. 1) and it is southern extension of the huge Indo-Gangetic Alluvial plains, which are a fast sedimenting basin with a huge

thickness. Soils on present day surface in Thar show a weak soil formation, manifest in profile redistribution of carbonate and minimum of *in-situ* chemical weathering and formation of secondary minerals. Studies of deep sections by Saini and Mujtaba (2009) in top 5-15 meters reveal that the last major alluvial aggradation activity, corresponding to much of the present day plains ended at ~20 ka. A second alluvial activity corresponding to Vedic Saraswati, happened during 6-3 ka, but on a much smaller scale. Saini *et al.* (2012) further showed that rivers had started experiencing a phase of

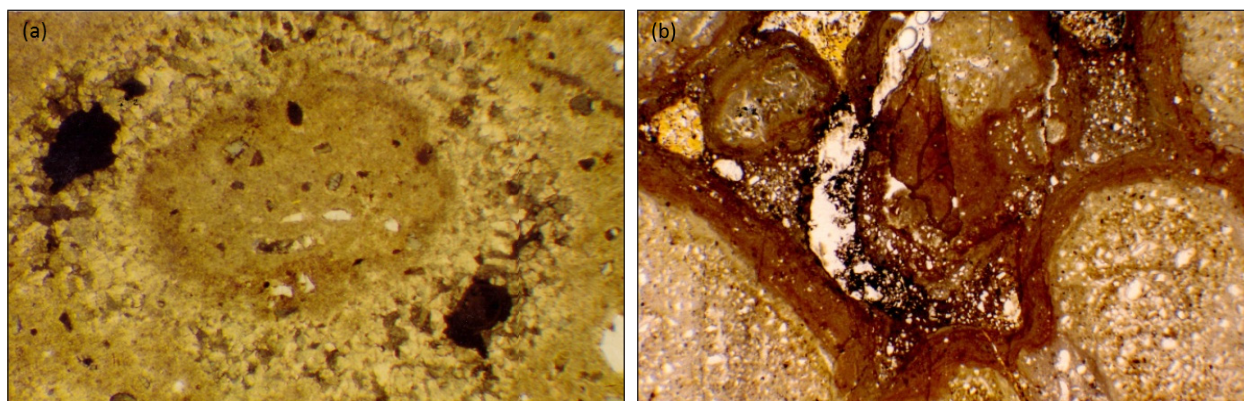


Fig. 8. (a) Photomicrograph of part of a nodule showing clotted micrite groundmass, spheroidal differentiation and shrinkage cavity, infilled with spar, (b) Laminar growth on joint surface of the hardpan at Sunari.

Table 1. ESR dating results from some of the lithounits in studied sections in sheetwash aggraded plains

Description of sample	Equivalent dose (Gy)	Dose rate (Gy ka ⁻¹)	Age (ka)
Banar IIIb-Nodule	105	0.92	114
Banar II-Nodule	320	0.94	340
Osian 2 III-Nodule	170	1.05	162
Osian 2 II-Nodule	300	1.08	278
Nandia Khurd VI-Nodule	260	1.06	245
Nandia Khurd V-Nodule	345	0.93	371
Sunari-Nodule under hardpan III	350	1.00	350
Sunari-Nodule under hardpan I	650	1.00	650

(Based on Dhir *et al.*, 2004).

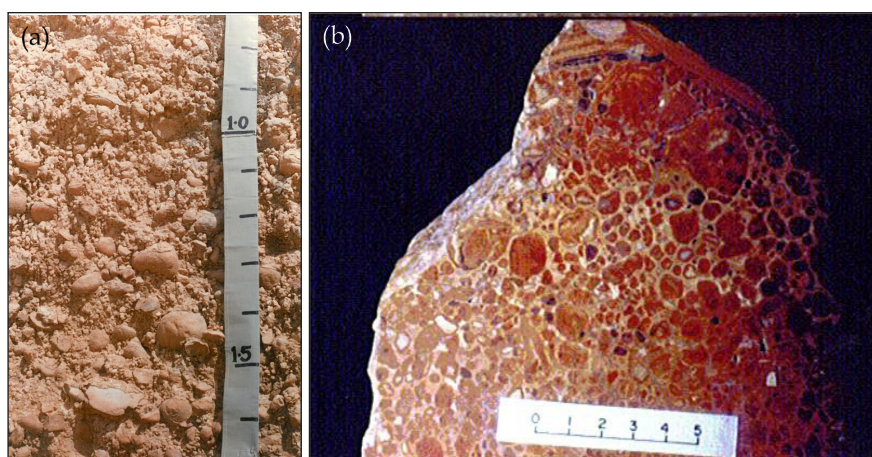


Fig. 9. (a) Disintegrating calcrete in Jayal Upland in gravely-pebbly deposits, (b) Slab section of the hardpan. Note the presence of pisoliths and lamellar calcretes, which are slow forming features and an evidence of large span of time over which the calcretes evolved. Presently these show several degradational features.

desiccation from ca. 28 ka and by 20 ka the drainage system became almost dysfunctional because of accentuating aridity. The period from 18 to 12 ka saw an aeolian deflation of the alluvial surfaces and formation of aeolian features. After a period of stability, the process reactivated, though on a smaller scale between 9 and 7 ka.

Evidence From Old, Sheetwash Aggraded Plains

The old aggraded plains are nearly level, extensive occurrence in Thar. The soils formed on these show fairly well-developed, zonal features typical of a semi-arid climate (Choudhary and Dhir, 1981). Deep sections, like those of aeolian sequences, show stack of several fairly distinct aggradation episodes, most with a well developed calcrete with minimum of overlapping features or overprinting. One such section, namely Nandia Khurd, is described and discussed. The section

lies in central part of Thar and comprises seven lithounits (Fig. 7). The top two units are aeolian sands, but the remaining five are sheetwash aggradations, each of half to one meter thickness. Unit I at the base comprises sandy loam matrix with frequent large lumps of calcrete. Unit II is texturally similar to Unit I but has well-developed centimetric sized hard carbonate nodules. In between are coarse, gravelly sediments with transported nodules that are interpreted as ephemeral channels deposit. Unit III is also sandy loam, but has both chalky and hard nodules, an indication of two generations of nodule forming process. Units IV and V are similar, but are separated by a distinct boundary. Units VI and VII comprise weakly pedogenized aeolian sands. Units IV (depth 270-200 cm from surface) and V (200 to 100 cm) were dated by ESR method at 371 and 245 ka, respectively. Three more sections were also examined and showed a similar architecture. Nodular features are exceedingly

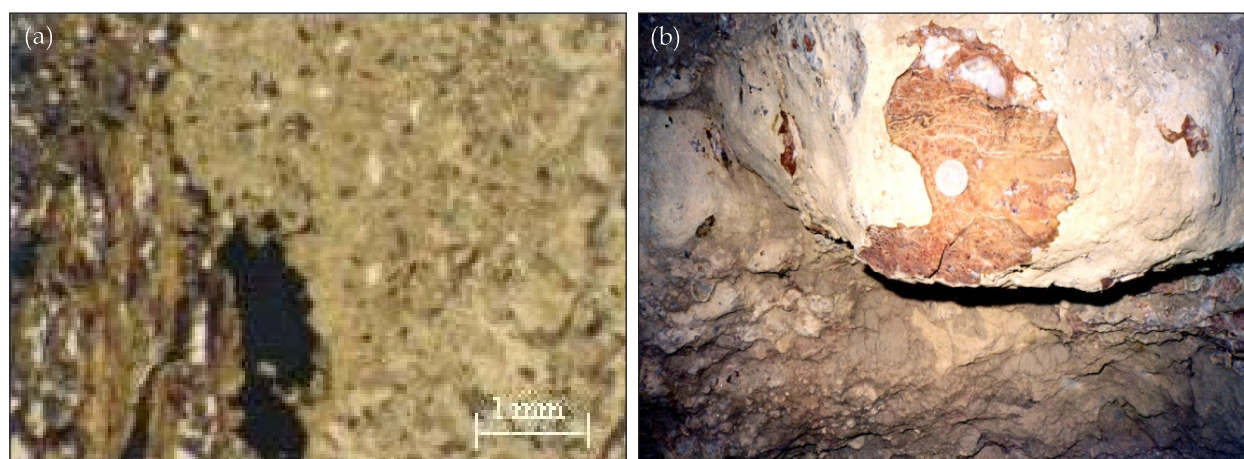


Fig. 10. Calcrete formed in regolith of biotite mica schist of Proterzoic age at Ringan (a) View of hard pan; note the laminal features; (b) Calcrete with vertical fabric formed by replacement of host mica schist by carbonate.

well developed and have a complex internal structure (Achyutahan and Rajaguru, 1998; Dhir *et al.*, 2004). Micrite groundmass is clotted in which host clastic grains are seen widely floating (Fig. 8a). At places the groundmass is reorganized into reddish brown, spherical domains. The host mineral grains, even the quartz grains margin is somewhat corroded and invariably have spar overgrowths. The shrinkage cavities are lined with spar also. Some

nodules are complex and formed by subsequent cementation of nodules. Sunari Section showed more advanced calcrete features in form of hardpan at several levels, joints in which were seen coated with laminar calcrete features (Fig. 8b). At places, the calcrete surface has a razor-sharp, planar boundary with over lying sediments and this feature is suggestive of the role of groundwater in enrichment of sediments with carbonate. The sheetwash aggraded plains have a huge amount of carbonate in form of calcretes and evidence suggests that much of this enrichment had taken place during the process of individual aggradation phase, the source being the calcareous rocks and degradation of pre-existing calcretes.

Table 2. ESR dating results of ancient calcretes

Description of calcrete	Equivalent Dose (Gy)	Dose rate (Gy ka ⁻¹)	Age (ka)
Ringan			
Hardpan	815	0.99	809
Nodule	910	0.96	876
Massive-vertical fabric	1050	0.88	1193
Anwana			
Hardpan	2325	1.5	1550
Breccia fill	900	1.5	600
Chalky	1200	1.5	900
Katoti hardpan			
Light red infill	850	0.95	850
Dark red groundmass	1850	1.2	1542
Ratau nodule lower	896	0.91	985
Nimbli Jodhan nodule lower	760	0.8	950
Badela upper nodule	465	0.83	560
Dhurila nodule	1200	1.05	1143
Lordian nodule	1150	1.12	1027
Chandrok nodule	855	0.84	1018
Badgaon upper nodule	810	1.18	686

Facility-constraint did not permit dating of all the lithounits in the studied sections and therefore only some of these could be dated. The results are presented in Table 1.

These show an age range of 650 to 250 ka, except for 160 ka in surface lithounit of Osian section. The age values are on calcrete features, which is a development subsequent to aggradation and hence actual aggradation could predate by a few thousand years. Nevertheless the results clearly suggest that sheetwash aggradations occurred in a time frame mostly of 600 ka to ~200 ka and that individual aggradation is a distinct episode and separated by a considerable time span, during which their surface was stable and soil formation and various diagenetic changes took place.

Evidence from Relict Surfaces

As mentioned earlier, these surfaces are largely out of the influence of the above described aggradation processes and several of these are remnant of surfaces that evolved in the long past geological history of the region. Achyuthan and Rajaguru (1997) described the Jayal upland stratigraphy and showed presence of ferricretes on ancient rock surface and of well-formed calcretes in near-surface conditions. Since calcretes are the most conspicuous morphological surficial feature in these and other relict surfaces and these are amenable to dating, these were studied at several locations (Dhir *et al.*, 2004). In Jayal upland and elsewhere also, the gravelly pebbly aggradations are deeply calcretized (Fig. 9a) and near surface the formation is fragmented and severely jointed. The hard pan in form of isolated boulders has a complex internal structure with advanced features like pisoliths and laminar growths which are slow to develop (Fig. 9b). These features are suggestive of large antiquity and of prolonged history of their evolution.

Relict surfaces also exist in form of regolith of ancient rocks. Of these, two sites were studied; one at Ringan in mica schist of Delhi Super group of Proterozoic (Dhir *et al.*, 2004) and the other Anwana section in Sonia Formation of Marwar Group, also of Proterozoic age (Sharma, 1999). The Ringan section possessed several calcrete facies namely nodular calcrete, massive, locally fragmented calcretes with vertically-oriented fabric and thick hard pan (Fig. 10 a,b). The regolith is characterized by comprehensive replacement of host rock by calcite. The individual features are dated to 1200 to 800 ka (Table 2). The Anwana section, nearly 9 meter thick, in sandstone possessed a large variety of calcrete forms such as brecciated nodular and nodular, box work and massive. There were abundant refilled dissolution channels, re-entrants, pisolithic and laminar features. Individual features are dated to 1550 to 600 ka.

Calcrete samples from other locations were subjected to dating and results are presented in Table 2. These reveal that the calcretes and their subsequent evolutionary feature have an age range of 560 to ~1600 ka, an antiquity going back to early Quaternary. Morphological

evidence suggests that this period experienced an outstanding spatial mobility of carbonates and its accumulation in near surface situation. The carbonate accumulations over time acquired several secondary features giving the calcrete milieu an extraordinary complexity.

Discussion and Synthesis

Preceding information has shown that Thar abounds in climate-responsive landforms spread over the entire Quaternary and investigation of these has permitted reconstruction of climate for the period of their development. The salt lakes because of their ability to hold an amplified response to climate change and preservation of floral, geochemical and isotopic proxies has given a fairly high resolution record. These clearly show that marked climate changes have occurred during the Holocene. At the beginning of Holocene, i.e. at about 10 ka BP, the rainfall was generally higher though with a large degree of fluctuations. And this situation with some modulation continued to prevail for next few thousand years. But the period from 6 ka to ~4 ka was particularly wet when lakes carried high water levels almost all through the year and over the years. Subsequent period to the present possessed a dry climate akin to present day situation. The period prior to Holocene was marked by a pronounced aeolian activity and formation of sand dunes and such other features. The last major sand spread and dune building in Thar happened between 17 ka to ~11 ka. This was also the period when desert spread to the north and east of its present limit. Chamyal *et al.* (2003) and Juyal *et al.* (2006) have reported evidence of aeolian activity of this period from northern Gujarat also. Saini and Mujtaba (2012) have presented similar information from adjoining Haryana plains as well. In other words this was indeed a period of widespread aeolian activity and hence of reduced rainfall and high wind regime. Available records from few deep sections show such aggradations to have occurred in the past during ~250, 170-160, 140-130, 100-80, 70-60 and 30-21 ka. Of these, aggradation activity of 30-21 ka and of 70-60 ka are also recorded from east of Aravallis (Chougankar *et al.*, 1999). But records of older aeolian episodes have not so far been reported from other areas adjoining Thar, particularly from northern Gujarat, where deep sections of comparable antiquity have been reported (Juyal *et al.*, 2006). Probably these

aeolian activities were not that widespread. However, while reporting the chronology of events, a few qualifications are needed. Firstly, though luminescence dating method provides a degree of reproducibility, the results always carry a degree of systematic error, which increases as the age of dated sample becomes greater; secondly, studies show that aeolian aggradation is not expressed uniformly at landscape scale and further that aggradation of a particular episode may get truncated or even totally deflated during a succeeding episode. Thus, all the episodes may not exist at any given site. Thirdly there is still a problem of age inversion in individual aggradations, reasons for which remain yet to be fully understood. Thus, a larger number of sections, than those studies so far, need to be examined in order to give a comprehensive chronology. Further, though, several investigators believe that aeolian activity is only ~250 ka old, it is quite logical that a more intense, strategic sampling may advance this antiquity to some extent.

Studies similar to Thar have been made in other deserts also. Juyal *et al.* (1998) in Arabian Desert showed oldest aeolian activity at ~230 ka and several episodes thereafter to the present and Preusser *et al.* (2002) from studies in southern Arabia related dune activity with low global sea levels or glacial periods and resultant aridity during the past 160 thousand years. Singhvi *et al.* (2012) compiled results from several studies in this region to show such aggradations at 165-130, 120-100 ka and then at ~70 ka. Episodic aeolian aggradations from ~80 ka onwards have been reported also from Australian and South African deserts (Singhvi and Porat, 2008). However, it is still too early to build up a global pattern and this is as much due to insufficiency of data as on account of varied response to a given global climate event (Singhvi and Porat, 2008).

Individual aeolian aggradation episode is followed by a period of stability during which some pedogenesis comprising a weak soil formation and profile redistribution of carbonates occurred. Presence of individual aggradation-related calcretes in deep sections is a clear evidence of this. A broad idea of duration of these episodes is provided by intervals between just mentioned aggradation episodes. Of these, the period from ~50 to 30 ka seems particularly conspicuous. This

is suggested by presence of perched water features in some deep sections. It is marked in neighboring northern Gujarat by more intense soil weathering, though in alluvial parent material context (Juyal *et al.*, 2003). It is interesting to compare the past climate fluctuations with present climate datum. The existing aeolian landforms behave as fairly stable features with the present day rainfall of 250 to 450 mm in much of Thar and the instability wherever it exists is not natural but due to intense biotic interference. Logically, periods of aeolian aggradation shown above ought to have a rainfall (and hence vegetation cover) substantially less, probably of the magnitude of 30 to 40% lower than the present. If we go by the analogy of last major phase of 17-13 ka, the wind regime has also to be stronger.

Sheetwash aggradation is a widespread surface in the region. Deep sections in these show an assemblage of several such episodes, each with discrete calcretes developed therein. Several sites with an extraordinarily strong calcrete development suggest that carbonate enrichment was aided also by a high water table, though pedogenic and vadose zone features dominate calcrete morphology. The calcrete nodules are hard and manifest a complex internal structure indicating episodes of carbonate dissolution and re-precipitation as also degradation of host clastic grains as well as neosynthesis. These suggest that conditions were near ideal for these processes to operate. Calcretes typically form in a semi-arid climate with a seasonality of rainfall; the rainy season creating conditions for solubilization of carbonate held in upper solum and its downward movement to the wetting front and the drying conditions thereafter causing a precipitation and growth as nodules or other such features (Gile *et al.*, 1966; Goudie, 1983; Tandon and Kumar, 1999). In fact Goudie (1983) posited a rainfall of 400-600 mm as optimum for a warm temperature zone for the purpose. Thus, all the three evidences, i.e. a sheetwash aggradation, presence of seasonally high water regime in landscape and conspicuous development of calcrete therein point to the fact that conditions during the period were dominated by a semi-arid climate. Stable isotope analysis of carbonate features is an established method to decipher rainfall-related vegetation, i.e. of C₃ and C₄ type vegetation cover. This

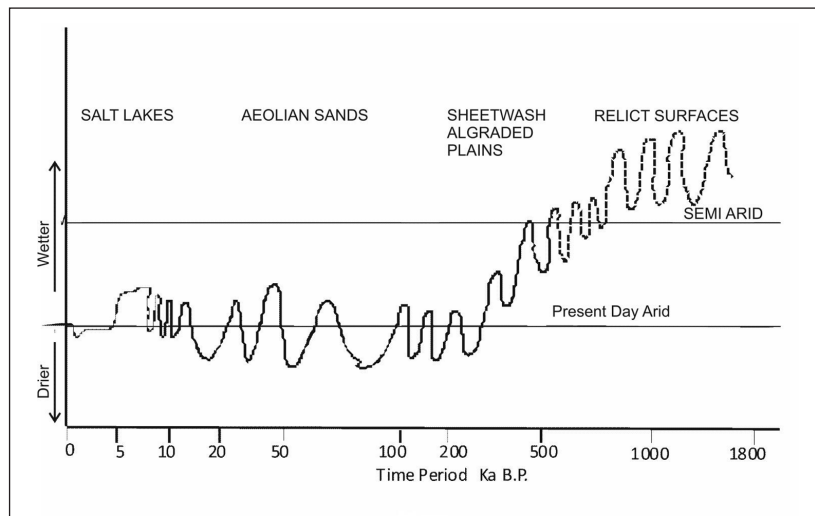


Fig. 11. Plaeoclimate scheme based on chronology of climate responsive features of various studied sites. Note that chronology scale is not uniform. For reasons given in text, chronology of climate fluctuations beyond 250 ka is approximate, but the trend is supportable.

analysis was performed on numerous samples of calcretes on alluvial plains and those from both younger and older surfaces. However, except from some young aeolian aggradations (Andrews *et al.*, 1999; Achyuthan *et al.*, 2007), values both of δC^{13} and of δO^{18} lay in a very narrow range and were thus not found helpful (Dhir *et al.*, 2004).

ESR data on these calcretes, though not exhaustive, suggest ages of ~160 to 350 ka BP with the bottom-most member in one of the sections being as old as 650 ka. These dates must be qualified. The ages are not of the aggradation episode, but that of the calcretes developed in these and hence aggradation must predate age by a few thousand years. Secondly, sheetwash aggradations are an outcome of braiding streams, mostly of second or third order drainage. Such drainages are also amenable to frequent shifting of their course. In this situation the aggradation at any given time can happen at one place whereas a neighboring one may be free of it. Because of this, a particular aggradation even at one location need not be present elsewhere and thus a synchronism cannot be expected across the landscape. But there is no doubt that the period of ~250 to 600 ka was indeed dominated by fluvial aggradation, which style is distinctly different from that of arid regime that succeeded it. Further, presence of remnants that occupy a positive relief in the present day plains is clear evidence that there existed still older alluvial aggradations, much

of which have since been denuded away. So, in fact aggradation activity could be older than what is suggested by studied sections.

Besides above, there are calcretes which are even older, lie in alluvio-colluvial parent material and owe their origin to high energy transport with a strong gradient that in all likelihood was aided by tectonism. The surfaces on which they occur have a positive relief form, due to denudation of the surrounding less resistant stratum. Additionally, there are calcretes in regolith of basal rocks. All these calcretes show advance stage features like hardpan that were later brecciated with concentration of lag on the surface (Dhir, 1995; Achyuthan and Rajaguru, 1998). Upon microscopic examination, these calcretes show features suggestive of repeated dissolution and re-precipitation that are manifest in pisoliths and lamellar growth. These latter features develop slowly and hence attest to their inferred antiquity. Some of these calcretes, including the latro-calcretes of Sundram and Pareek (1995) are in weathering crust of very ancient rocks. Absence of intensive studies on genesis and evolution of the landscape make difficult an interpretation, but the fact that the studied regoliths are hugely enriched by carbonates and the host rocks, like sandstone are profoundly transformed, suggest as much of an antiquity as of an environment that was conducive to huge mobility of carbonates. We interpret that climate during much of

the period was on wetter side of a semi-arid climate. Climate ought not have been humid, as believed by some, since in that case the calcretes could not have survived. ESR dating has shown that features of calcrete have ages from ~600 to 1600 ka. Though these values appear sensible, the data on individual calcrete feature need not be construed to mean a regional context. As regards climate at the transition from Neogene to Quaternary some information exists. Lukose (1977) reported alternating variegated clay and sandstone in Jaisalmer area, which he named as Shumar Formation. Achyuthan (1999) described ferricrete crust from the same stratigraphic situation. Such a lateritic crust has been recorded also at Jayal (Achyuthan and Rajaguru 1997) and by others in Bikaner and Jaisalmer area (Rakshit and Sundram, 1998; Sundram *et al.*, 1996). These were interpreted by them as a change from a humid tropical climate in Neogene to a dry climate later at the onset of Quaternary period.

Conclusions

Presence of a variety of landforms and investigational effort have brought out a fairly coherent information on climate history spanning over most recent period to ~2 million years. It has been shown that the period from present to ~250 ka BP was dominated by aeolian dynamism. This comprized fairly distinct episodes of aeolian aggradations that are separated by periods of climate amelioration and surface stability. During aggradation episode the climate is interpreted as both drier and windier than at present, whereas interlude of stability meant a condition akin to the present. Though climate variation is certain to have taken place, the data are not sufficient enough to compare with global or regional robust data based on polar ice cores or northern Arabian Sea cores. The period preceding it, i.e. from ~250 ka to ~600 ka was dominated by sheetwash aggradation and pronounced calcrete development in individual aggradation units. Both the style of aggradation, large spatial landscape mobility of carbonates and their transformation into exceedingly well-formed calcretes clearly suggest a climate that was less dry than at present or a typical semi-arid, but with high seasonality. The climate could not have wetter either as in that case carbonates ought to have been leached out of surficial crust. The relict

land surfaces often occur as isolated features and distinguish also by presence of high energy transported alluvial-colluvial sediments both these suggest tectonism-related relief changes to have played a role in landscape evolution. But the period was marked also by even a larger scale mobility of carbonates as marked by highly charged regoliths and alluvial aggradations. The climate then ought to be on the wetter side of a semi-arid rainfall range. Anderson and Prell (1993) had made a study on strength of summer monsoon rain for the past 350 ka and Gupta *et al.* (2005) a highly detailed account for the past ten thousand years, both based on marine sediments from northern Arabian Sea at sites off the coast of Oman. A correlation has also been attempted with established global records based marine and ice cores. Though the information derived from Thar shows a parrellism for last 20 ka period or so, but beyond that the relationship becomes problematic. Perhaps a far more rigorous sampling is needed to address the problem. Other situation could be relationship robustness of northern Arabian Sea monsoon with that of Thar. Presently, much of the summer monsoon rainfall comes from winds which move from central Arabian Sea eastward and recurve over eastern India to reach Thar and contribution of winds from northern Arabian Sea direct to the area is hardly any. For sand mobility and dune building, pre-monsoon wind intensity in terms of speed and duration are most critical. A relationship of this with monsoon behavior remains to be established. For the large preceding Quaternary period records from other parts of India or other deserts are few for a meaningful comparisons to be made. Various findings from Thar are summarized in Fig. 11. It must be added that this synthesis is based on currently existing evidence and is amenable to refinement and even modification from future and more rigorous investigations, scope for which exists.

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