The Thar Desert and its antiquity

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For long, widely divergent views (based on isolated pieces of historical evidence or broad geological evolution of the subcontinent, notably the rise of the Himalayas in mid-late Miocene), had prevailed regarding origin and antiquity of the Thar Desert. Studies of the past few decades have since provided a wealth of new information on landform styles, evolutionary processes and palaeoclimate history with chronometric and isotopic constraints. Salt lakes, dunes and calcrete-bearing alluvial aggradations have been the focus of interest. This review synthesizes the multidisciplinary work to present the state of the Thar during the Quaternary period.

Studies on salt lakes have provided high-resolution palaeoclimate records, but of the past ~ 15 ka BP only. Strong aeolian activity is a characteristic of the latest 200–300 ka period and is marked by several episodes of greater aridity, strong wind regime and sand dynamism followed by periods of stability implying climate amelioration and some pedogenesis. However, the preceding mid and early Quaternary periods are marked by alluvio-colluvial and sheetwash aggradations with pronounced, well-evolved calcretes therein. These findings strongly suggest that for much of the Quaternary period, the Thar region enjoyed a semi-arid climate and the desertic conditions came to dominate much later.

Keywords: Calcretes, desert, dunes, electron spin resonance, palaeoclimates.

THE Thar Desert is a vast tract covering over 4000 sq. km in the northwestern part of the Indian subcontinent and it stretches from the western fringes of Aravalli Mountains to the Indus River (Figure 1). Much of it has a rainfall of 100–300 mm, though the eastern end of the arid zone as currently defined lies to the east of the 400 mm mean annual rainfall contour. Existence of such a desertic terrain in a subcontinent gifted with a strong monsoon regime is an anomaly heightened further by the fact that a region in the east at the same latitudes of the Thar is one of the wettest regions in the world. This situation has provoked some thinking on the origin and cause of aridity in the Thar Desert region. Krishnan[1] opined that the present pattern of rainfall must have set in when the Himalayas rose high enough to become an obstruction, thereby causing the establishment of a monsoon regime. However, the general lowering of temperatures during the Pleistocene Ice Ages must have kept Rajasthan moist till perhaps subrecent times. Stable isotopes and other studies have since shown that this event occurred at ~ 7 million years ago[2,3]. Roy and Pandey[4] also attributed a large antiquity to the Thar on the ground that it constitutes the eastern end of the great Saharo-Arabian mid-latitude desert belt that owes its existence to the anti-cyclonic, subsiding dry continental air regime. The eastward extension of this regime gets constrained by the strong monsoon winds. Several meteorologists have suggested that the shallowness of the monsoon current and the anti-cyclonic circulation do not allow the clouds to grow and precipitate, despite the presence of precipitable water in the region[5,6]. They further suggested that the occasional spells of heavy rainfall or even floods happen here whenever depressions developing over northern Bay of Bengal move into the area. However, such events are rare.

In contrast, Wadia[7] posited a post-glacial aridity for Central Asia, including the Thar Desert. Piggot[8] and several others used the presence of flourishing Harappan and subsequent civilizations within the Thar some 5000 to 2000 years ago as an evidence of a recent origin of the Thar Desert. The mention in the scriptures of a mighty river in the Thar in the Vedic times and the same as a dying river later reinforced this view further. However, some researchers have questioned this cultural–climate relationship on the ground that the pre-historic civilizations were distributed along rivers in the area and a shift in their course could itself lead to collapse of a culture[4,9]. Ravetry[10,11] as quoted in Allchin *et al.*[12] (p. 34), used passages from Moslem chronicles to suggest a mediaeval period for the origin of this desert. Bryson and Barreis[13] advocated a more younger age for the Thar by attributing its formation to rainfall prevention by dust in the atmosphere originating from degradation of landscape caused by intense biotic pressure. Thus, till recently widely divergent views prevailed regarding the antiquity of the Thar – some making it a recent phenomenon and some as old as the Miocene.

Early studies on Quaternary geology and landform

The occurrence for a couple of years of strong, dust-laden winds in the early 1950s and fears of a northward spread of the desert brought the Thar desert into national focus.

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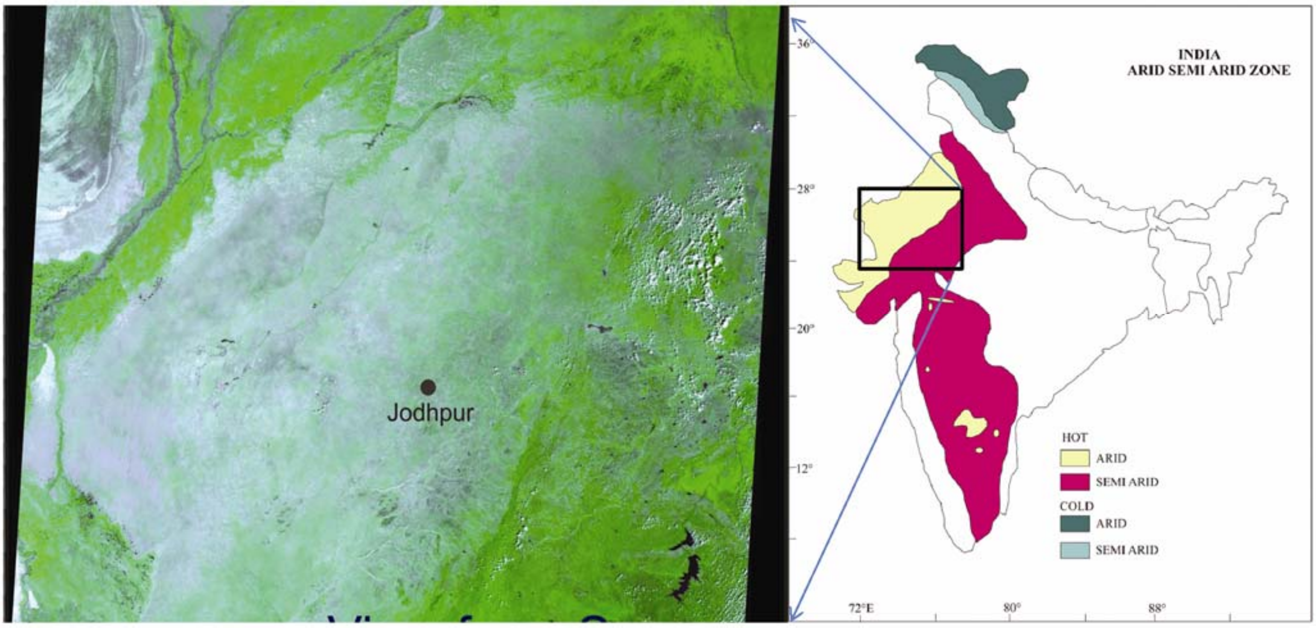

Figure 1. (Left) An IRS-FCC image of the Thar Desert. (Right) The limits of arid and semi-arid regions of India and the location of Thar in a regional context.

This led to the organization of a national symposium on the Thar by the then National Institute of Sciences of India (now Indian National Science Academy) in 1952 which attracted leading professionals of the day. The concluding remarks of its then President S. L. Hora are worth reproducing: 'Though Governments have started taking some action already, I wonder if any one knows precisely what Rajputana Desert is, how it came into existence, what is its present behaviour and why is it spreading, if it is spreading at all. I have failed to get a proper answer either from geographers or geologists or even from biologists and archaeologists. Every one has replied that we know very little about this Desert and what little we know cannot form a basis for planning for immobilization of this desert'[14].

The period that followed witnessed a large scientific and developmental effort to understand the natural resources and to develop and implement new technologies for amelioration of the desert. In the process, a wealth of information on landforms, soils, climate characteristics and ecology of the desert was generated. Dunes are a characteristic feature of the region and have a variety of forms. Most of these appear stable, well vegetated and with some pedogenesis. Some in the west were shifting and currently forming. Thus came their classification as dunes of old and new cycles[15]. Allchin[16] reported the presence of rolled lower Palaeolithic tools in the basal colluvio-aeolian sediments in the dunes and from the presence *in situ* of middle Palaeolithic tools in the upper aeolian sheets concluded that aeolian activity ought to be at least about 50,000 years old. Goudie *et al.*[17] showed that in the past, the limit of the Thar had extended far to the east from its present confines and defined a dune shift of 350 km between regions of past and present areas of dune activity. Extensive geo-archaeological studies by the Deccan College Team and detailed excavation by them near Didwana showed an entire sequence of tools from early to upper Palaeolithic[18]. The tools occurred *in situ* in dune sands and thus suggested the antiquity of aeolian dynamism to a few hundred thousand years. The source of this huge body of sands has been debated extensively. Wadia[7] had opined Rann of Kachhchh and Arabian Sea coast as a source, however, the absence of a fining trend down wind and spatial mineralogical variation of sand suggested a local origin[19]. Some researchers have suggested that contemporary aggradation surfaces, principally alluvial formations were the principal source of sand[20–22].

Geomorphologic studies revealed also the existence of several other landforms, apart from dunes. Ghose[23] showed that old aggraded alluvial plains were a dominant landform in the central Luni Basin. Other surveys by Central Arid Zone Research Institute (CAZRI), ICAR, Jodhpur have since shown the presence of this landform well beyond this Basin in the north and west of Jodhpur through Nagaur to Didwana and beyond, where these lie either as exposed or under a cover of aeolian sands. Dhir *et al.*[24] further suggested that these alluvial sediments occupy considerable thickness in the region and that the aggradation was episodic. Besides, these are somewhat poorly sorted, indicating thereby a short-distance transportation of sediments, mainly as a sheetwash[24]. Rakshit and Sundram[25] used bore-hole logs to infer thick alluvial aggradation in the present-day Bikaner–Churu area. In the southern part of the Thar, Wadhawan[26] and Kar[27] considered alluvial aggradation as the base of Quaternary, followed thereafter by a succession of alluvial–aeolian sediments. In the Luni Basin, the thickness of this alluvial aggradation presented a vast range, from over 300 m to just a few metres. This was attributed to repeated tectonic movements leading to horst and graben structures followed by an accelerated aggradation of poorly sorted sediments[28,29].

Analysis of aerial photos revealed existence of an integrated prior drainage system that presently lay dysfunctional and disorganized[30,31], clearly implying that there were period(s) in the past when the rainfall was substantially higher than today. Subsequent work using remote sensing tools revealed the presence of a palaeo-drainage system all over, including the most arid districts of Jaisalmer and Bikaner[32–34].

The disappearance of the legendry Saraswati River has been a subject of great interest. Remote sensing studies revealed several courses of a river at various points of time[31,35,36]. One of the earliest courses of a Himalayan drainage lay in the southerly direction to flow through the present Luni, with the latter being a tributary of the former[31,35]. Though the disorganization and abandonment of various drainage systems was mostly due to climate deterioration, the changes of stream courses were mainly an outcome of tectonics-induced geomorphic processes[33]. Bakliwal and Wadhawan[37] also emphasized the role of tectonics in basement configuration and development of aggradation basins all through the geological history, including the Quaternary.

Aside from the dunes, calcretes are the second most striking features in the Quaternary sediments in the Thar Desert[38]. Calcretes are secondary carbonate accumulations that form in near-surface sediments/bedrocks. Most of these form as a result of leaching of carbonates present in the solum or those added by aeolian accession and their precipitation at depth that is determined by the mean depth of the wetting front[39]. Calcretes also originate through ponding or groundwater enrichment or in lacustral settings. The calcretes are particularly well formed in soils of alluvial aggraded plains and show mostly a characteristic nodular form[40]. In young aeolian sediments these occur as powdery form or as ill-formed nodules, whereas those on ancient surfaces are highly evolved[38,41,42]. Rakshit and Sundram[25] identified gritty valley calcretes in the present-day Bikaner–Churu area, whereas Sundram and Pareek (unpublished data) identified the so-called laterocalcretes, i.e. calcretes that show evidence of post-formation impregnation with iron oxides. Dhir *et al.*[24] describe several deep sections with bands of calcrete at various levels and interpret these as repetitive episodes in the past aggradation of sediments with large hiatuses followed by pedogenesis and calcrete formation. Several calcrete exposures today lie as positive relief elements in the landscape. Such a relief inversion occurs due to contrast in resitance to erosion. Less erosion-resistant upper soil and sediments, including nodular calcretes therein, are eroded away and leave behind calcrete with a positive relief[38,43]. In the Nagaur–Sikar area of the central Thar Desert, well involved calcretes occur in the weathering zone of near-surface basal rocks. The foregoing suggested that several episodes of aggradation and calcrete development took place during the Quaternary, at times followed by denudation such that the older calcretes served as a feed material for the development of younger calcretes. Several sites in the aggraded alluvial plain show 2–3 m thickness of calcrete under a thin solum. These possess an almost razor-sharp boundary with the solum, and this situation lead researchers to conclude a role of groundwater in the enrichment of surficial sediments and their subsequent differentiation into massive and nodular forms under a vadose (the water-unsaturated zone between surface and water table) or pedogenic environment[38,42].

The Thar Desert is dotted with several salt lakes or playas. Though small in their spatial extent, these playas are distributed all over, from the foot of the Aravalli Mountains to the more desertic western part of Bikaner and Jaisalmer. Ghose[30] ascribed their occurrence to the point of confluence of drainage systems but subsequently suggested that blockage by aeolian sands could also be a possible cause[44]. Since then, other factors like deflation hollows or tectonically subsiding basins have been suggested[45–48]. The lakes are highly saline and a few in the west are gypseous. The sedimentary columns of these lakes comprise stratified strata dominated by silts and clays with various salt species and carbonate lenses, thus attesting to a fluctuating environment in the process of their development. These have proved to be a fertile landform in building palaeoclimate, as discussed in the following.

Chronometry studies of landforms and palaeoclimate interpretations

Singh *et al.*[49] made pioneering studies on several of the salt lakes. Wasson *et al.*[50] worked on the geochemistry and mineralogy of Didwana Lake to reconstruct the history of hydrological and salinity changes and to interpret past climate. A synthesis of these studies with improved chronology appeared a little later[51] and showed a large amplitude change in lake hydrology. The lowest strata from ~ 4.5 m and below was dated to 12.8 kyrs ^{14}C BP, and pollen analysis showed dominance of a treeless savanna and extremely low wetland vegetation, suggesting a dry climate. The overlying strata dated to 12.8–9.3 kyrs ^{14}C BP showed the appearance of shrub–savanna grassland and a representation of freshwater plants in the pollen assemblage – all suggesting infilling of the lake, though intermittently. The succeeding periods at 9.3–7.5

and 7.5–6.2 kyrs ^{14}C BP saw a further decrease in the pollen of typical arid zone taxa, and a significant appearance instead of *Graminae* and *Artemsia* species, clearly suggesting an improvement in the environment with the lake holding freshwater all the time. After this, the water regime in the lake declined further with the lake drying up completely around 4.0 kyrs ^{14}C BP. A significant model-based finding was that early Holocene had a sizeable contribution of winter rainfall, thus showing that western disturbances were more vigorous and had penetrated far into the south. Enzel *et al.*[52] made a study of a lake at Lunkaransar, ~ 140 km to the northwest of Didwana, and provided centennial-level record of rainfall. Their findings broadly corroborated the results from the Didwana Lake, including the mid-Holocene period of major climate improvement. However, the duration of the high water level in the lake was shorter than that at Didwana, thereby showing that a gradient of climate such as exists from east to west presently also existed in the past. From a comparison of mineralogical assemblage of several of the lakes, Roy *et al.*[53] showed persistence of this gradient for the period from 3 to 1 ka.

The last three decades have seen the emergence of significant chronometric data using luminescence dating of aeolian landforms (pioneered by the Physical Research Laboratory (PRL), Ahmedabad; Singhvi *et al.*[54]), and most of this work has been summarized by Singhvi and Kar[55]. Preliminary U series dating of carbonates in the earlier described deep aeolian sequence of Misra and Rajaguru[18] near Didwana showed ages of around 150 ka for the middle Palaeolithic tool-bearing aeolian sands and over 390 ka for the lowest stratum with Lower Palaeolithic tools[56,57]. Though the findings advanced the antiquity of aeolian activity a deal, the ages were considered as suggestive only because of serious contamination problem. Using luminescence dating Singhvi *et al.*[58] provided a direct estimation of the aeolian sands (thereby constraining the multiple hiatuses/pedogenesis) and reported younger ages for the middle Palaeolithic at around 80–100 ka. They also provided a time-frame for the various Palaeolithic tool-bearing strata. In the same rainfall zone as the Didwana section but in the south-central part of the Thar, another old aeolian sand sequence at Chamu gave an age of ~ 160 ka near the bottom of the section. This was followed by an aggradations[59] at ~ 90 ka and then at ~ 60 ka. This latter aggradation at ~60 ka distinguished by a more prominent calcrete development therein than that in the older or younger episodes, hence suggesting a substantially enhanced rainfall regime, though still with a high degree of seasonality. Aeolian aggradations at 60–50 ha and those at ~ 25 ka found herein were also reported from several other locations[60–65]. Another, even more ubiquitous aeolian aggradation was seen at 15–11 ka by Singhvi and Kar[55]. This made them to attribute major growth of the present-day high dunes to this particular time-period. They also concluded that maximum aeolian dynamism occurs not at the peak of aridity at Last Glacial Maximum (LGM), but a couple of thousand years thereafter when the monsoon winds pick up as a run-up to the post-LGM climate amelioration, while the landscape is still unstable because of inadequate vegetation cover. It was also shown that the Thar at this ~ 15 ka period had spread far to the east of its present limit and the same shrunk by ~ 200 km during the period of ameliorated climate at 5 ka BP (Figure 2). Minor episodes of aeolian accumulation occurred[66] at 5.2, 2.0 and 0.8 kyrs. An important finding of Kar *et al.*[67] was the acceleration of dune migration rates in areas where vegetation cover had been compromised due to human activity.

Chronolgy of calcretes

Dating of calcrete was a major challenge and pioneering studies at PRL and IIT Mumbai led to the development of the electron spin resonance (ESR) technique for dating the formation event of calcretes[68]. Dhir *et al.*[69] provided the relevant stratigraphic and petrographic details and further showed that the sheetwash aggraded plain calcretes developed during 250–370 kyrs with a sample dating to 650 kyrs. The calcretes on other surfaces, which are stratigraphically considered to be older, showed a range of ages with prominent formation episodes at ~ 600, 800–900, 1000–1200 kyrs. The oldest date was 1550 kyrs. The older calcrete sites include alluvio-colluvial buried pediments, the Jayal Ridge (late Neogene–early Quaternary according to Achyuthan[70] and others on weathering crust of schists (Pre-Cambrian Delhi Supergroup) and Sonia Formation (Proterozoic Marwar Supergroup; Dhir *et al.*[71]). Importantly, the findings showed that calcrete formation episodes occurred on several occasions throughout the mid and early Quaternary.

Discussion

Because of their ability to provide amplified response to climate change and preservation potential of vegetation, geochemical and isotopic proxies, the salt lakes have provided a high-resolution record which shows that marked climate (rainfall) changes occurred during the Holocene. Early Holocene was less dry and mid Holocene experienced marked wetness followed by a progressive desiccation, thereafter leading to the present-level of aridity at ~ 4 ka ^{14}C BP. The aeolian records show aggradations at ~ 160, 100–90, ~ 60, ~ 25 and 17–13 kyrs. Several of these have been recorded in the Thar margin in northern Gujarat[63–65], thereby suggesting that aeolian dynamism then had spread to areas presently beyond the limit of the Thar. In the Didwana sequence, Singhvi *et al.*[58] also observed that the time between successive dune accretions ranged from 22 to 15.8 kyrs, with a mean of 19 kyrs, which appears consistent with the precessional

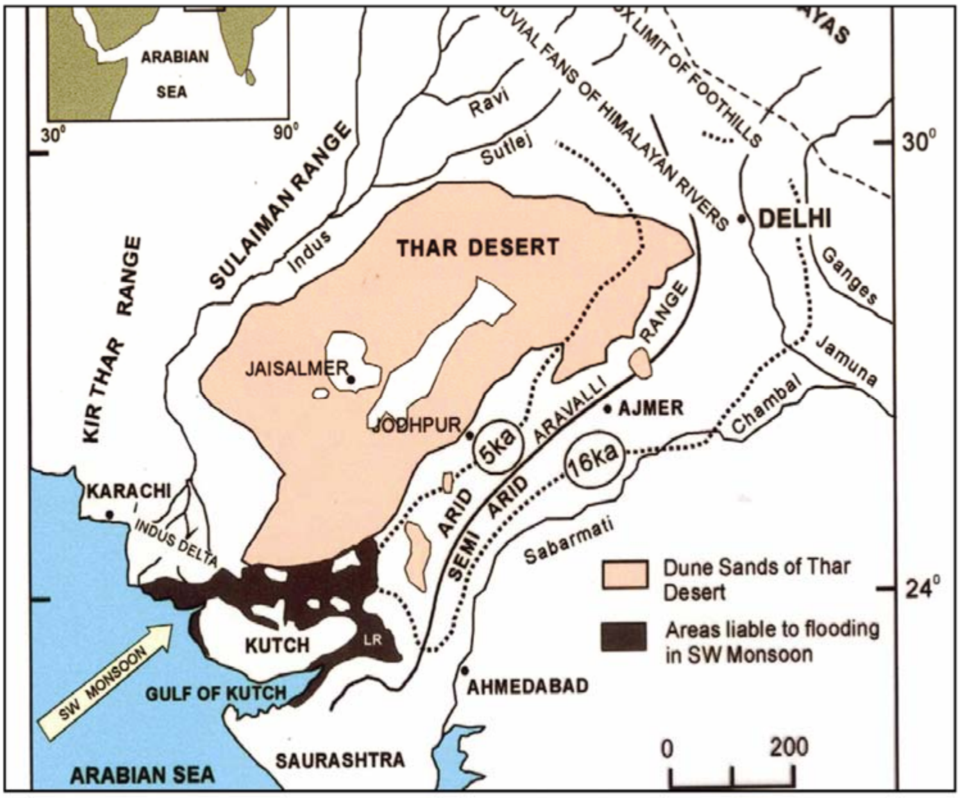

Figure 2. Past extensions of the Thar Desert. The contours are drawn based on luminescence dates and extrapolation between regions. Figure drawn by A. Kar, Central Arid Zone Research Institute, Jodhpur.

control on aeolian activity, an aspect which if confirmed, has important ramifications. Further, from a collation of luminescence ages, Singhvi and Kar[55] concluded that the peak of aeolian activity was not at the maximum aridity during LGM, but thereafter when the monsoon winds started as a run upto a period of climate amelioration and remains so till the monsoon rains induced-vegetation impeded sediment transport. Thus only a time window is available for the sands to accrete and be preserved. This was contrary to the conventional view of peaking of aeolian activity at the peak of LGM and the implication of this is the fact that the desert albedo changes at the height of glacial maximum were not as accentuated as has been considered so far. The narrow time window of dune accretion provides a possibility of constraining conditions of monsoon-related winds in the past 200 ka.

The wet periods enabled landscape stability due to increased cover of vegetation and resulted in pedogenesis and calcrete formation. At times in the process of succeeding aeolian aggradations, the pre-existing soils got eroded away leading to truncated profiles or total stripping. It is interesting to note that three sites in the Thar gave consistent results on the periods of dune aggradation and quiescence. This implies a regional behaviour[55,59,71], Minor time lags in these arise due to local factors. Though, like salt lakes, the aeolian records have provided a detailed insight into palaeoclimate of the Thar, the period spanned by these is so far restricted to ~200 kyrs only, which is a fraction of the ~2.6 million long Quaternary period.

The Thar Desert abounds in several old landscapes with well-formed calcretes therein and dating of these has enabled to fill this major gap. One of these surfaces is the sheetwash aggraded plains described earlier. Deep sections in these show several aggradation episodes with discrete calcretes developed within each. Several sites with an extraordinarily strong calcrete development show that carbonate enrichment was also aided by a high water table. Pedogenic and vadose zone features dominate calcrete morphology and imply a seasonality of the water table regime. ESR ages of these calcretes are ~160 to 350 kyrs, with the bottom-most member of one section showing an age of 650 kyrs. Calcretes typically form in a semi-arid climate with a seasonality of rainfall; the rainy season creating conditions for solubilization of carbonate held in the upper soulm and its downward movement with the advancement of wetting front and the drying conditions thereafter causing a precipitation of these[39,72–74]. In fact, Goudie[39] posited a rainfall of 400–600 mm as optimum for a warm temperature zone. A drier climate restricts the mobility of carbonates. This is seen from the Thar, where the post-LGM dunes show minimal to a modest profile distribution of carbonates only. A climate wetter than semi-arid on the other hand, leaches out the carbonates from the soil profile. Thus, 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 ~ 200–500 kyrs were dominated by a semi-arid climate, and this was distinctly different from the arid regime that succeeded it.

Besides the above, there are calcretes which are even older and lie both in regolith of near-suface rock exposures and in a variety of other aggraded surfaces. These calcretes show advance stage features like hardpan that were later brecciated with concentration of lag on the surface[38,42,75]. These calcretes show features suggestive of repeated dissolution and reprecipitation that are manifest in the pisoliths and lamellar growth (Figure 3). The latter features develop slowly and hence attest to their inferred antiquity. ESR dating has shown that calcrete-forming episodes have occurred all through from ~ 600 ka to 1550 kyrs. The presence of these calcretes as surficial features, though in a degraded form, suggests that the Thar possessed mainly a semi-arid climate and that it never experienced any pronounced period of wetter climate, as in that case the calcretes would not have survived. As regards climate at the transition from Neogene to Quaternary, some information exists. Lukose[76] reported alternating variegated clay and sandstone in Jaisalmer area, which he named as Shumar Formation. Achyuthan[70] described ferricrete crust from the same stratigraphic layer. Such a lateritic crust has also been recorded at Jayal[43] and Bikaner and Jaisalmer area[25,77], and was interpreted as a change from a humid tropical climate in the Neogene to a dry climate later at the onset of the Quaternary period.

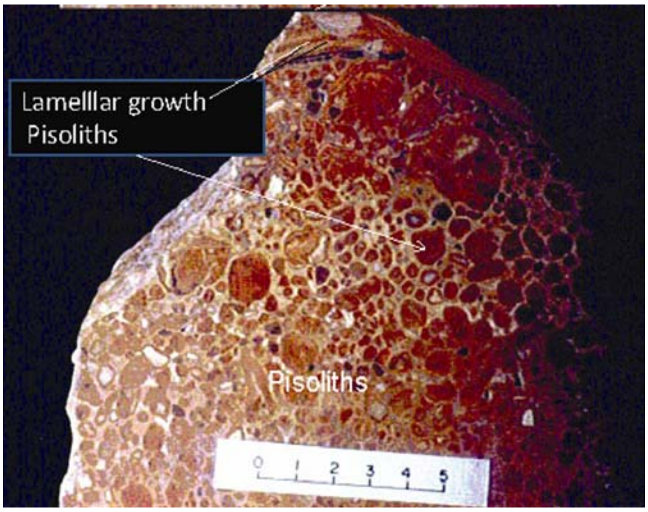

Figure 3. Polished slab section of an early Quaternary calcrete. Reconstituted features, pisoliths and laminar growth are indicators of its evolved nature. Scale is in centimetres.

Conclusion

Morphologically well-evolved calcretes hosted in alluvio-colluvial deposits and in regolith of basal rocks occur in widely separated geographic areas in the Thar. Their ages lie in a range of 1650–600 ka. These are succeeded by a stack of sheetwash aggradations, each episode with its own well-formed calcrete. These are not as well evolved and date to mostly 350–650 ka. Thus, the style of clastic sediment aggradation, large mobility and accumulation of carbonate as calcretes suggest that during much of the Quaternary period, the Thar Desert experienced a predominantly semi-arid climate. Aeolian aggradations were episodic with extended periods of stability and calcrete formation in between. These were phase lagged with respect to glacial epoch, which in the Thar was a period of relative quiescence as far as sediment aggradation was concerned. Calcretes in the aeolian context are simple in morphology and are also only weakly to moderately developed. The oldest aeolian sand record so far extends to 200 ka, showing thereby that this period was more arid then the preceding more than a million years. However, there is ample scope of further refinement of palaeoclimate information, particularly of the transition period.

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