

Chapter 26

Palaeoclimatic Interpretations From Desert Dunes and Sediments

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Introduction

During the late Quaternary, the world's major deserts experienced dramatic changes in the nature and frequency of aeolian processes (Fig. 26.1). Sand seas (ergs) cover 5% of the global land surface and reveal evidence of repeated phases of dune formation (Thomas et al. 2005). This paper presents a review of dune-building episodes during late Quaternary time and their palaeoclimatic significance. The emphasis of the paper is on African and North American sand seas. Although beyond the scope of this paper, a more detailed synthesis and chronologies of global sand seas is presented by Tchakerian (1999), Goudie (2002), Munyikwa (2005) and Lancaster (2007).

In the Sahara-Sahel drylands of North Africa, peak dune deposition is believed to have occurred between 20 and 12 ka (Sarnthein 1978), during the Last Glacial Maximum (LGS). On the other hand, aeolian activity was drastically reduced between 11 and 5 ka, as the region experienced a period of humid conditions characterised by increased vegetation cover, high lake stands, incised fluvial channels, and a rise in neolithic cultures (Williams 1982). Owing to the geologic and climatic setting of the North African sand seas, the major dune constructional episodes are believed to have been nearly synchronous between regions, although significant variations in the timing of the dune-building episodes did occur (Tchakerian 1999, Lancaster 2007). Since 5 ka, aridity has slowly returned to the Sahara-Sahel, as the subtropical high

pressure cells assumed their current position, with today's hyper-arid central Saharan core region well established by 2 ka. Re-activation of some of the stabilized Sahelian dormant/relict dune systems has been the direct result of increased population pressure in the region, owing to the fact that stabilized dunes provide a richer plant cover for grazing and firewood gathering, and are easier to cultivate.

In the North American arid zone (with the exception of some mid-Holocene aeolian depositional periods in the Nebraska Sand Hills in the Great Plains), major dune-building episodes in the Mojave Desert and the Great Basin, appear to be highly episodic and discontinuous in time and space, and controlled primarily by sediment production, availability and transport capacity systems (e.g. Kocurek 1998), rather than by hemispheric or regional changes in atmospheric pressure fields, such as in the Sahara-Sahel region. Although highly episodic, the period between 25 and 7 ka witnessed multiple pulses of aeolian deposition as recognized from the dune fields and sand ramps of the Mojave Desert (Lancaster and Tchakerian 2003).

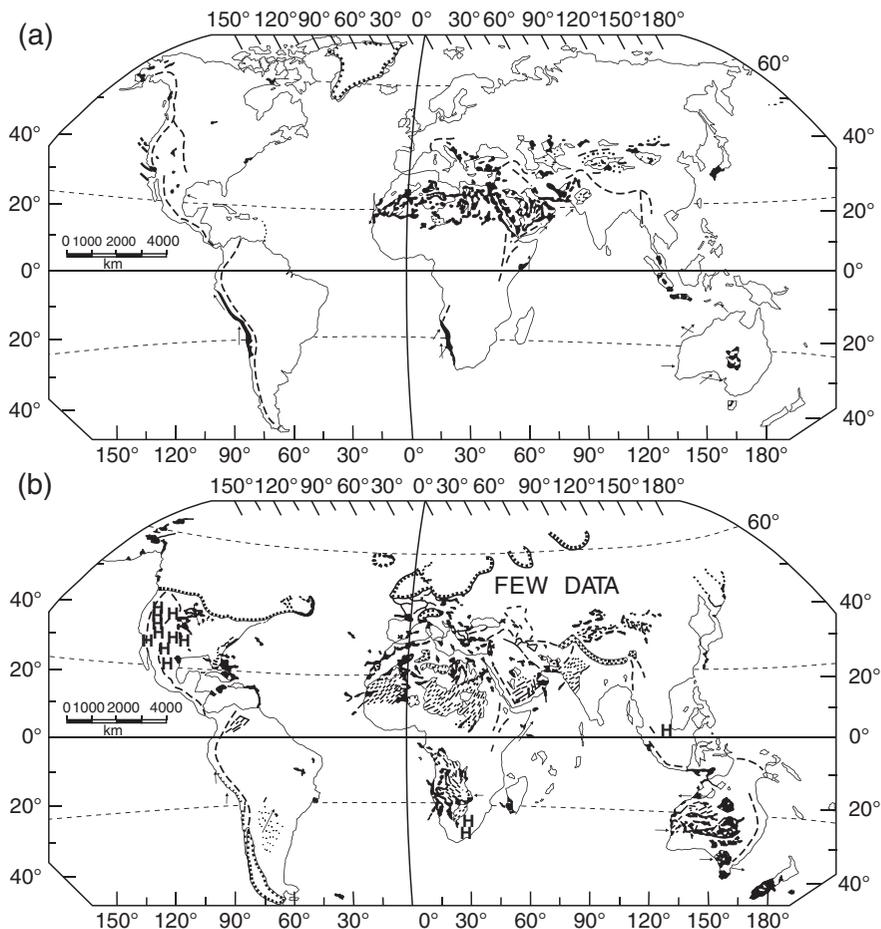
Quaternary Aeolian Activity From Continental Deserts

Africa

In the ergs of the African continent, the last Wisconsin cool substage most likely coincided with an arid episode as initially suggested by Grove and Warren (1968). This tropical aridity is believed to have been the result of high-latitude glaciations

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Fig. 26.1 Global distribution of sand seas for (a) the present and (b) the Last Glacial Maximum (LGM), 18 ka (after Sarnthein 1978). H denotes humid conditions



(Williams 1975, Sarnthein 1978). In North Africa, the evidence for late Wisconsin aridity comes in the form of extensive belts of fixed, fossil, degraded dunes, which now extend from the Sahara south to latitude 10–12° N in the Sahel over a latitudinal distance of about 5000 km (Grove and Warren 1968, Sarnthein 1978, Rognon 1987, Thomas 1989). The majority of the Sahara-Sahel dune systems are believed to have been formed between 20 and 12 ka, a time interval characterised by drier and windier than present climatic conditions, with the driest period occurring between 14 and 12 ka (Rognon and Williams 1977, Bowler 1978, Williams and Faure 1980, Ali-men 1982, Goudie 1983, Grove 1985, Thomas 1987, 1989).

Based on detailed geomorphic and stratigraphic relations, together with luminescence ages from the different aeolian units, Kocurek et al. (1991) found evidence for the formation of large linear dunes between

20 and 13 ka in the Akchar Erg in Mauritania. The dunes were subsequently stabilized by vegetation and paleosols between 11 and 4.5 ka. In the western Sahara of Mauritania, OSL (Optical Stimulated Luminescence) dating, combined with sedimentological studies, revealed three main generations of linear dunes formed during periods 25–15 ka (centered around the LGM), 13–10 ka (spanning the Younger Dryas cooling episode), and after 5 ka (Lancaster et al. 2002). The above sequence of widespread aeolian activity beginning at or near the LGM and continuing until about 12 ka, followed by humid conditions and dune stabilization from 11 to 5 ka, and a return to more arid and widespread aeolian activity since 5 ka, seems to have occurred in large parts of the central and southern Sahara-Sahel drylands (Swezey 2001). Figure 26.2 is a chronological synthesis of the main dune-building phases and/or activity from the continental deserts of Africa, Asia and Australia.

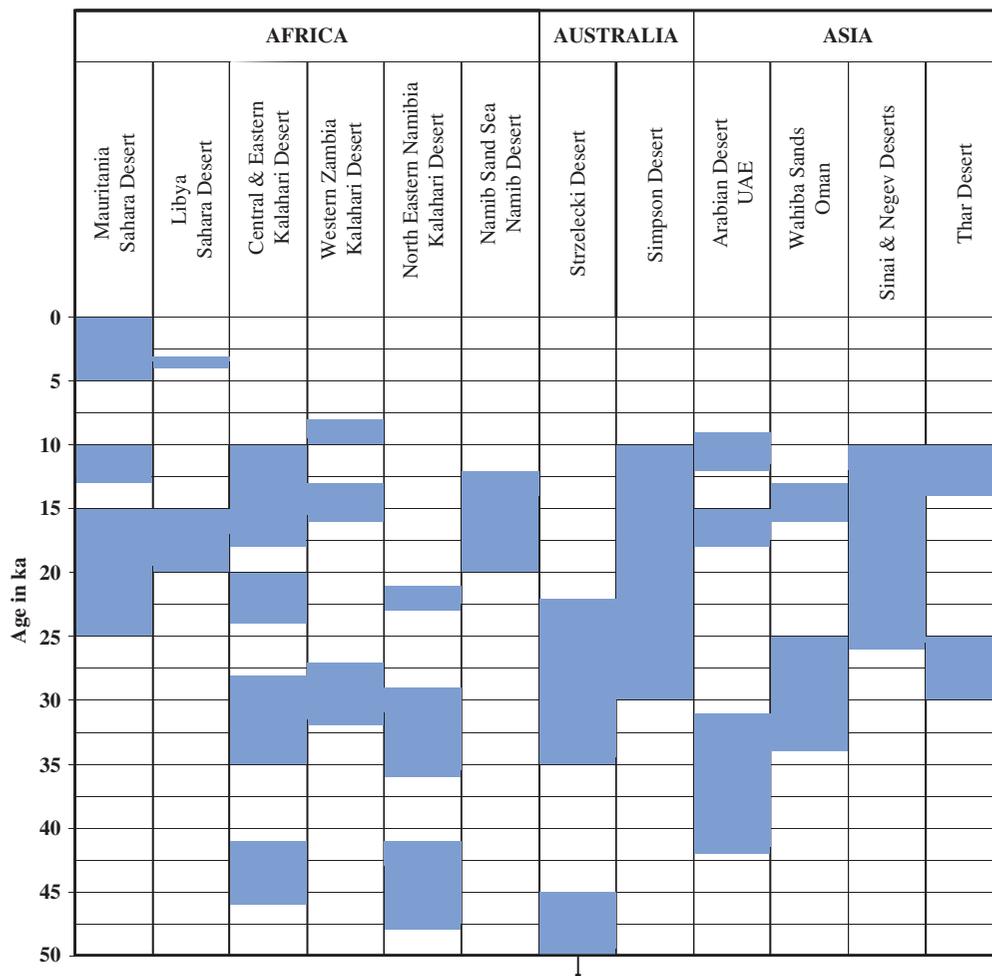


Fig. 26.2 A chronological synthesis of late Quaternary major dune-building and/or aeolian activity from the tropical and subtropical continental deserts of Africa, Asia and Australia. Most dates are from luminescence methods. Some radiocarbon and

other proxy data also included. More references are found in the text as well as in Tchakerian (1999), Munyikwa (2005) and Lancaster (2007). A much longer luminescence chronology is also provided by Lancaster (2007)

In the Selima sand sea of Libya in the eastern Sahara Desert, Stokes et al. (1998), based on sedimentary and OSL dating studies, propose two major episodes of dune construction of 20–15 and 4–3 ka, similar in chronology to the Mauritanian ergs, with the exception of the missing 13–10 ka Younger Dryas event. On the other hand, in some of the northern Saharan ergs, aeolian activity was diminished owing to the incursions of moisture from the quasi-permanent low pressure cells associated with the colder conditions in Europe as well as the presence of glaciers in the higher latitudes (Nicholson and Flohn 1980, Rognon 1987). Based on atmospheric general circulation models, Nicholson

and Flohn (1980) proposed that the northern sections of the Sahara located in the Maghreb countries of North Africa, experienced relatively wet conditions between 20 and 14 ka. The Grand Erg Occidental and Erg Chech were inactive during the LGM and resumed their dune-building activities only some time after 10 ka (Nicholson and Flohn 1980, Rognon 1987). Thus the majority of the northern Saharan ergs are believed to have been inactive during most of the late Pleistocene, while in the central and southern Sahara and the Sahel, aridity was more widespread with major dune-building episodes between 20 and 12 ka.

Additional evidence for glacial age aridity comes from ocean cores, in which significant concentrations of aeolian quartz grains have been found reflecting the enhanced trade-wind transport of dusts from arid regions (Sarnthein and Koopman 1980). Pokras and Mix (1985) presented evidence for high concentrations of aeolian biosiliceous particles in deep sea cores from the tropical Atlantic and attribute its presence to the deflation of diatomaceous deposits from dry lake beds beginning at about 20 ka. Quartz-rich layers in marine sediments from the eastern Atlantic are believed to have been deposited during the LGM, as a result of increased aeolian activity and dust deflation from the western Sahara Desert (Pokras and Mix 1985). The proponents of cool-stage aridity in the tropics have also utilized information from meteoric groundwater. In the Sahara, Sonntag et al. (1980) indicated that very little discharge occurred from 20 to 14 ka, and suggest a period of substantially reduced hydrological activity during the last cold stage of the Wisconsin.

In the Mega-Kalahari sand sea of central southern Africa, Stokes et al. (1997) and Thomas et al. (1997), using detailed luminescence dating methods, have identified multiple dune-building episodes during the late Pleistocene (Fig. 26.2). The Mega-Kalahari erg consists primarily of three major linear dune complexes, interspersed with interdune corridors and pans (dry lakes): northern, eastern and southern. In the southern Mega-Kalahari, two late-Pleistocene dune-building episodes have been identified by optically stimulated luminescence (OSL) dating, the first between 30 and 23 ka, and the second between 16 and 10 ka (Stokes et al. 1997). A comprehensive study, based on OSL chronology on quartz grains of the central and eastern Mega-Kalahari erg, revealed five late Pleistocene major arid intervals with linear dune construction: 115–95, 46–41, 35–28, 24–20 and 18–10 (Stokes et al. 1997, 1998, Thomas et al. 2000). On the other hand, some of the dune-building activity in parts of the Mega-Kalahari in western Zambia indicate dune building phases from 32 to 27, 16 to 13, and 10 to 8 ka (O'Connor and Thomas, 1999). Linear dunes in the north-eastern Namibian portion of the Mega-Kalahari also exhibit three stages of dune construction: 48–41, 36–29, and 23–21 ka, with limited aeolian activity since 21 ka, and hence no dune phases at the LGM (Thomas and Shaw 2002). The arid intervals lasted between 5 and 20 ka, separated by humid phases lasting between 20 and 40 ka. Linear dune emplacements are believed to be linked to changes in southeast Atlantic

sea surface temperatures (SST), which causes changes in the NE-SW summer rainfall gradient, with periods of low SST's corresponding to periods of enhanced aridity and hence dune construction (Thomas and Shaw 2002, Munyikwa 2005). Episodic aeolian activity throughout the Mega-Kalahari has continued from 9 ka to the present, especially around 5 ka and also between 2 and 1 ka (Thomas et al. 1997, O'Connor and Thomas, 1999). Holocene aeolian activity has been confined largely to the reworking of Pleistocene linear dune sands and the formation of lunettes (clay dunes) on the lee side of the numerous pans that dot the region (Goudie 2002). Remobilization of the stabilized dunes in the Kalahari Desert (and the Sahel) under various land degradation scenarios owing to global warming, can have detrimental effect on the pastoral and agricultural activities in the region (Thomas et al. 2005).

The Namib erg, a sand sea that covers about 35,000 km², is dominated by a core of inland linear dune complexes associated with bi-directional wind regimes, mostly SSW-SW and NE-E (Goudie 2002). According to Lancaster (1989), the linear dune complexes constitute about 75% of all the aeolian sands in the erg, followed by a belt of highly mobile coastal crescentic (mostly barchans) dunes (14%) and star dunes (9%). Owing to the paucity of luminescence dates from the Namib erg, palaeoenvironmental reconstruction is primarily through proxy records. Uranium series dating from speleothems in presently flooded caves and cenotes (solution hollows in carbonates), indicate dry conditions from 15 to 11 ka and between 9 and 7 ka (Brook et al. 1999). Palaeohydrologic evidence suggests periods of increased river discharge and groundwater flow, as well as the presence of shallow lakes and ponds in interdune corridors centered on 8–12, 20–24 and 26–32 ka (Lancaster 2002), thus implying arid conditions potentially favorable to dune construction between 20 and 12 ka. Using GPR (ground-penetrating radar for identifying changes in dune sedimentary structures) and OSL dating on linear dunes in the northern Namib erg, Bristow et al. (2007) recently report two phases of major dune-building: the first between 5.7 and 5.2 ka and the second between 2.4 and 1 ka, thus lending support to the return of more widespread and episodic aeolian activity after 5 ka.

The available data from the African deserts suggest that late glacial aridity and aeolian depositional phases were not synchronous between the two desert regions, north (Sahara-Sahel) and south (Kalahari, Namib) of

the equator. In parts of the Kalahari Desert, wetter conditions are believed to have prevailed up until c. 10 ka with no major dune development during the LGM (Thomas and Shaw 2002).

Australia

Dunes cover over 40% of the Australian continent, with linear dunes as the most widespread aeolian landform type (Goudie 2002). The majority of the linear dunes are found in the Simpson and Strzelecki deserts. Luminescence, radiocarbon and stratigraphic data from the Simpson desert indicate multiple dune-building phases between 33 and 9 ka (Nanson et al. 1995, Twidale et al. 2001). According to Wasson (1984), peak dune formation in the Simpson Desert occurred between 20 and 16 ka, with significant reduction in aeolian activity and dune formation after 13 ka. In the Strzelecki Desert, dune-building episodes are concentrated between 65 and 45 ka and again between 35 and 22 ka (Lomax et al. 2003). Based on thermoluminescence and radiocarbon dating, Gardner et al. (1987) proposed that the linear dunes in the southwestern Australian deserts were formed between 30 and 10 ka. The combined chronologies from the Australian arid zone indicate that major dune constructional episodes occurred between 35 and 10 ka (Fig. 26.2).

Wyrwoll and Milton (1976) first proposed that aridity during glacial stages was widespread, especially in northwestern Australia, owing largely to increased anticyclonic activity. Additional evidence for increased aeolian activity during this arid episode of the last glacial maximum comes from the submerged discordant dunes in Fitzroy Sound, dunes formed when sea level was lower (Jennings 1975). Renewed aeolian activity is evidenced by the reworking of stabilized linear dune sediments in parts of the Australian interior between 3 and 1 ka, when lake levels and temperatures fell from their high levels during the early Holocene (Wasson 1984).

Asia

Geomorphic, chrono-stratigraphic and luminescence data from the fossil dunes in the Thar Desert of India indicate that the major dune-building episodes took

place between 30 and 25 ka and 14 to 10 ka (no dune construction during the LGM), with some reactivation of stabilized dunes in the Holocene (Singhvi and Kar 2004). Data from the dune complexes in the UAE suggest periods of dune construction as indicated by OSL ages of 42–31, 18–15 and 12–9 ka (Glennie and Singhvi 2002). In the Wahiba sand sea of Oman, the periods from 34 to 25, and 16 to 13 ka represent major times of sand accumulation and dune formation, including some of the spectacular, 50–100 m high, south-north oriented complex linear dune systems (Preusser et al. 2005). The above dune complexes in the Wahiba sand sea are in turn underlain by older dune deposits and aeolianites (carbonate cemented aeolian sands). There is evidence from Lake Lisan sediments in the Dead Sea and from the northern Sinai Desert for hyperaridity and increased rates of aeolian sedimentation from 26 to 15 ka (Gerson 1982). Based on radiocarbon dates from playa sediments, two dune-building episodes from 21 to 16 ka and 12 to 10 ka are recognized in the north-western Negev Desert of Israel (Magaritz and Enzel 1990). In the Al-Jafr basin of southern Jordan, there are indications of dune deposition after 26 ka (Huckreide and Weissmann 1968). Playa sediments from the Iranian Plateau also show evidence for increased concentrations of aeolian sands between 22 and 12 ka (Wright 1966). Once again (with the exception of the Thar Desert dunes), intensified periods of aeolian activity and dune-building seem to correspond with the LGM, with glacial episodes in the high-latitudes and arid (with major aeolian depositional phases) episodes in the low-latitude deserts of Africa, Australia and Asia (Fig. 26.2).

North America

Great Plains

The majority of the evidence for late Quaternary aeolian activity comes from stabilized (dormant and relict) sand dunes and sand sheets in the Central Plains of the USA (Fig. 26.3). In the Sandhills of Nebraska (the largest stabilized sand sea in the western hemisphere), recent studies based on detailed radiocarbon and OSL dating, indicate that the dunes formed in two major depositional phases during the Holocene: the first from

4.5 ka. It is apparent that the central High Plains experienced major aeolian depositional episodes between 9 and 3 ka, particularly between 7 and 5 ka (Fig. 26.3).

Since 3 ka, there is supporting evidence for discontinuous and episodic accumulation or re-activation of sand dunes from the Great Plains, in essentially modern climatic conditions. These dune reactivations are most likely occurring in response to periods of extended droughts (more intense than the Dust Bowl events of the 1930s), such as 20 to 30 year quasi-periodic cycles that extend back thousands of years (Muhs et al. 1996). The late Holocene dune constructional episodes most likely took advantage “pirating” of the Pleistocene sand dunes and sand sheets deposited during the LGM or earlier. The current vegetation stabilized dunes and sand sheets in the Great Plains (such as the Nebraska Sandhills) can be reactivated if the plant cover is significantly reduced because of extended drought or anthropogenic activities. According to Muhs and Maat (1993), wind speeds in the Great Plains typically exceed the threshold wind velocity 30–60% of the time. The sand dunes and sand sheets are thus “poised” for renewed aeolian activity if and when the present vegetation cover is removed or significantly disturbed.

South-Western Deserts

Compared with other continental deserts of the world, aeolian deposits form only a minor component of the total surficial deposits in the North American arid zone (Tchakerian 1997). With the exception of the Great Plains, the Mojave Desert in California and Nevada, and the Gran Desierto del Altar in Sonora, Mexico, are the only areas with significant aeolian depositional landforms.

The few detailed studies from the Great Basin also indicate dune-building episodes during early to mid-Holocene times (Fig. 26.3), similar to those in the Great Plains (Tchakerian 1999). In Catlow Valley, south-east Oregon, two dune episodes overlie lake deposits between 7.5 and 4 ka (Mehring and Wigand 1986). In the dissected badlands at Corn Creek Flat, 30 km north-west of Las Vegas, Nevada, Quade (1986) found evidence of increased aeolian sedimentation between 8 and 5 ka accompanied by a drop in the water table of at least 25 m. Renewed aeolian activity in the form of coppice dunes of up to 4 m high is believed to have started within the last

1000 years (Quade 1986). Additionally, renewed late Holocene activity commencing around 3 ka is also documented in the Tucson Mountains in southern Arizona based on ^{14}C dates from archaeological remains embedded in sand dunes (Brakenridge and Schuster 1986).

The aeolian sediments in the Mojave Desert consist primarily of small dune fields, sand sheets and sand ramps (amalgamated deposits consisting primarily of aeolian sands, as well as colluvial and alluvial deposits on the slopes of desert mountains). Because sand ramps contain multiple aeolian depositional units separated by paleosols formed in periods of geomorphic stability, they offer a unique opportunity for detailed geomorphic, stratigraphic and luminescence dating, thus their use in palaeoenvironmental reconstruction. Whitney et al. (1985) were one of the first to conclude from limited studies of sand ramps at four localities in the northern Amargosa Desert in Nevada, that the aeolian sediments were deposited during dry and windy Pleistocene climatic episodes as long ago as 750 ka. They noted the presence of up to 10 buried soils with Bishop Tuff, K/Ar dated at 740 ka, near the base of two of the four sand ramps.

Sand ramps are found astride topographically well-defined sand-transport corridors that follow the region's geologic and tectonic setting (Zimbleman et al. 1995), and have been the focus of detailed geomorphic research (Lancaster and Tchakerian 1996). Most sand ramps are relict features and are not accumulating today, with boulder-to-gravel size talus mantles and incised stream channels that expose the underlying sequence of sedimentary units (Lancaster and Tchakerian 1996). Chronological dating based on optical stimulated luminescence (OSL) and infrared stimulated luminescence (IRSL) dating of aeolian deposits in sand ramps indicate a clustering of depositional phases between 30 to 20 ka and 15 to 7 ka (Fig. 26.3). An 18 m thick sand ramp at Dale Lake in the southeastern Mojave Desert, has been the subject of many studies (Tchakerian 1991, Rendell et al. 1994, Lancaster and Tchakerian 1996, 2003, Clarke and Rendell 1998), and based on detailed analysis of geomorphic, granulometric, soil-stratigraphic, sedimentological and luminescence dating, a long period of aeolian accumulation, with intervening periods of stability and soil formation, has been proposed. A total of 6 sedimentary units are recognized and two main periods of dune emplacement suggested: the first between >35 and 25 ka and the second between

15 and 10 ka. In the central Mojave Desert, the stratigraphy and sediments of the Soldier Mountain sand ramp (about 30 m thick) have been exposed by a combination of mining activity and gully incision, enabling the use of detailed luminescence dating. OSL and IRSL ages indicate that the Soldier Mountain sand ramp accumulated between 20–25 ka and 7–8 ka (Lancaster and Tchakerian 2003). One of the largest and best studied dunefields in the Mojave Desert is the Kelso Dunes, located about 50 km downwind from its initial source, the Mojave River Wash (via Afton Canyon) and Pleistocene Lake Manix. The Kelso dune complex features many juxtaposed areas of dunes of distinctly different morphologies, type, size, spacing, alignment and age (Lancaster and Tchakerian 2003). The distinct mosaic of the dune complex suggests the independent development of the aeolian units, each representing a depositional episode either from new sediment sources or from the reworking of existing dunes. Luminescence ages for dune sediments at the Kelso Dunes indicate numerous aeolian constructional episodes, especially between 18 and 15 ka, and from 11 to 4 ka, with extensive reworking and reactivation of dunes during the last 1500 years (Lancaster and Tchakerian 2003).

Investigations of the late Quaternary history of Lake Manix in the Mojave Desert indicate that the lake spilled and rapidly cut Afton Canyon sometime between 18 and 16 ka (Meek 1999), hence the paucity of luminescence ages greater than 20 ka in the Kelso Dunes. It is highly probable that the exposed lake sediments were ultimately mobilized by the regional winds and ended up in the Kelso Dunes, thus the clustering of ages within the 18–15 ka range.

Additional evidence for Quaternary aeolian activity in the Mojave Desert comes from alluvial stratigraphy, and stages of soil development on dated lava flows of the Cima volcanic field. Studies by Wells et al. (1987) on the late Quaternary geomorphic history of the Silver Lake in the eastern Mojave Desert have documented two aeolian depositional episodes based on stratigraphic relationships between alluvial fan deposits and ^{14}C dated high shoreline stands. These two episodes are believed to have occurred sometime between 10.5 and 8 ka. Indirect evidence for late Pleistocene aeolian activity is also recognized from buried soils within accretionary loess mantles on K/Ar dated basalt flows from the Cima volcanic field in the eastern Mojave Desert (McFadden et al. 1986). The youngest

basalt flow, dated at 16 ka, is overlain by several aeolian units (McFadden et al. 1986).

In the Sonoran Desert of Mexico, the dune systems in the Gran Desierto del Altar have been the focus of several studies (Lancaster 1995). The dune complex, its sediments largely derived from the Colorado River and its delta, has a spatially heterogeneous pattern consisting of multiple generations of linear, crescentic, and star dunes, with extensive sand sheets surrounding the various dunes. Recent geomorphic, sedimentologic, stratigraphic and luminescence dating by Beveridge et al. (2006), indicates a continuous pattern of dune construction as well as reworking of older sands from 27 ka to the present, with peak dune-building periods between 25 and 12 ka (mostly the linear dunes), around 7 ka (the eastern crescentic dunes) and during the last 3 ka (the western crescentic dunes and the star dunes).

The foregoing discussion reveals a sharp contrast in the timing of major dune-building episodes between North America, where these episodes exhibit a nearly continuous but episodic sedimentation pattern beginning around 35 ka, with an early to mid-Holocene peak, and the deserts of Africa, Asia, and Australia (with the exception of sections of the Thar Desert and some of the southern African ergs of the Mega-Kalahari and nearby areas), where dune deposition seems to have peaked between 18 and 12 ka (around the LGM), with a distinct humid period between 11 and 5 ka. In the next section the relationship between general atmospheric conditions and dune-building episodes will be discussed.

Late Quaternary Palaeoclimates and Aeolian Episodes

Africa, Asia, and Australia

For the majority of the tropical and subtropical deserts of Africa, Asia, and Australia, the currently accepted paradigm equates the extension of the ergs to the development of high-latitude glaciations during the late Quaternary, with most of the major dune systems being formed on or just after the onset of the LGM at ~20 ka (Williams 1975, Sarnthein 1978). With some exceptions from the Mega-Kalahari dunes and the Thar

Desert, the above paradigm seems to still support the hemispheric nature of aeolian activity with peak dune-building episodes concentrated between 18 and 12 ka (Munyikwa 2005). The general atmospheric characteristics associated with such a scenario are given by Nicholson and Flohn (1980) and include the migration of the climatic belts towards the Equator and southwards, the increase in meridional (pole to Equator) atmospheric temperature gradients, the lessening of thermal contrasts between the two hemispheres, and an increase in wind speeds of the trades and mid-latitude westerlies. During the LGM, the equatorial trough (including the ITCZ) and the subtropical high pressure belts were displaced equatorwards and are believed to have been instrumental in the development of the extensive belts of dunes in Africa. The intrusion of the ITCZ south of the Equator may explain why some of the southern African ergs in the Mega-Kalahari were inactive or were contracting, and thus out of phase with their northern counterparts in the Sahara-Sahel.

The reduction in temperature and precipitation patterns in conjunction with changes in wind regime also affected the overall vegetation. According to Talbot (1984), in addition to an increase in the wind regime, precipitation had to have been 25–50% less than present values for the establishment of dunes in the Sahel between 20 and 13 ka. A prolonged period of aridity and reduced moisture most likely led to a reduction of vegetation cover and density on dunes (especially on linear dunes).

According to Thomas and Shaw (1991), the use of vegetated fossil dunes as indicators of former arid conditions should be used with caution. Linear dunes are believed to be preferred sites for vegetation establishment (especially along the windward slopes) because of their migratory or extending forms (Thomas and Shaw 1991). On the other hand, transverse dunes (such as barchans) are too migratory to allow any form of vegetation foothold, while complex dunes exhibit vertical accretion and are usually found within ergs in hyperarid climates, and not conducive for vegetation establishment. Additionally, vegetated linear dunes are preferred sites for plant anchorage and growth owing to the unique moisture-retaining capabilities of their sands, especially within interdune corridors and lower windward slopes. For example, aeolian transport has been documented from vegetated linear dunes with up to 35% plant cover (Ash and Wasson 1983), especially at the dune crests, where wind speeds tend to be accel-

erated and sediment transported at a much higher rate (Mulligan 1987). Throughout much of the Australian desert dunefields (where vegetation densities are below 10%), low wind velocities are thought to be responsible for the immobility of the sand bodies rather than the anchoring role of vegetation (Ash and Wasson 1983, Bowler and Wasson 1984, Wasson 1984). Thus enhanced aeolian activity and dune-building phases at the glacial maximum are thought to have resulted from strengthening of the anticyclonic winds, steeper meridional temperature gradients, and increased continentality owing to lower sea levels, as well as from lowered temperatures and precipitation, and to a lesser degree, a decrease in vegetation cover and density.

For the late Pleistocene, the picture that emerges is one of increased aeolian sedimentation in the southern Sahara and southwards (Sahel), with humid and stable conditions in the northern Sahara and the Maghreb (Rognon 1987). In the southern African ergs, aeolian activity around the LGM seems to have been limited to the central Mega-Kalahari, with relatively humid conditions prevalent in some parts of the Mega-Kalahari and adjacent deserts (Thomas 1989). For example, there was no dune construction in parts of the northwestern Mega-Kalahari in Zambia and Namibia during the LGM (Thomas and Shaw 2002).

The understanding of larger spatial and/or temporal scales of dune construction, driven primarily by hemispheric scale atmospheric processes, need to be balanced by the complex interplay that occurs at small spatial scales (such as one basin) and/or temporal scales (such as decadal) which ultimately control the rates of sediment supply, storage, entrainment, and transport capacity, as well as basin geomorphology and the nature and cover of vegetation.

During the late Pleistocene and the early Holocene (after the cessation or diminution of major aeolian activities around the LGM), and because of pronounced thermal differences between oceans and lands (owing to significant variations in solar insolation), a strong monsoonal flow developed from 12 to 6 ka with the majority of the Saharan lakes exhibiting high water stands (Street-Perrott et al. 1985, Zubakov and Borzenkova 1990). Lake Megachad reached its highest level sometime between 9 and 6 ka (Maley 1977, Nicholson and Flohn 1980, Servant and Servant-Vildary 1980). In the Malian Sahara, two lacustrine phases are believed to have occurred, the first between 9.5 and 6.4 ka, and the second between

5.4 and 4 ka, with the period in between characterized by a dry episode (Petit-Maire and Riser 1983). Also, pollen samples from Holocene lacustrine sediments in north-west Sudan indicate a period of wetter conditions and high lakes between 9.5 and 4.5 ka (Ritchie and Haynes 1987). The lacustrine sediments are overlain by aeolian sands and are believed to represent the beginning of the arid conditions which still dominate the region (Ritchie and Haynes 1987). The early to middle Holocene moist periods are thought to have been instrumental for the development of the famous Neolithic cultures and rock art of the Sahara, and arguably the rise of Egyptian civilization in the Nile Valley (Williams 1982, Zubakov and Borzenkova 1990, Kuper and Kröpelin 2006). During the same period, lake levels were generally lower in the south-western basins of the United States (Smith and Street-Perrott 1983, Benson et al. 1990). Current arid conditions in the Sahara are thought to have begun sometime after 4 ka (Rognon 1987).

North America

An earlier paradigm proposed that dune deposition in the basins of the southwestern deserts of the United States was at its peak during early to middle Holocene time, a period of aridity and drought from about 8 to 5 ka (Smith 1967). This period was characterized by higher temperatures, drying of basin lakes, reduction in effective moisture, and a concomitant increase in aeolian activity (Van Devender et al. 1987, Wells et al. 1987, Spaulding 1991). Antevs (1955) first proposed such a climatic interval, which he labelled the *Alithermal* (it is currently referred to as the *Holocene Climatic Optimum*).

Currently, it is generally understood that the various aeolian sediments presently found within the basin and range type deserts of the south-western United States have accumulated primarily in response to the lowering of lake basins and a consequent increase in the availability of fine sediment, as well as to changes in hillslope, fluvial and alluvial geomorphic systems (Lancaster and Tchakerian 2003). Lake-level fluctuations can provide extensive sandy sediments for subsequent deflation. Sediments are also supplied or replenished by ephemeral desert streams. Additional sources for aeolian dune construction include fan-deltaic and

beach deposits formed in and around lakes, and from alluvial fans and wadis and/or arroyos. These environmental changes are attributed to significant climatic oscillations (Wells et al. 1987). Additionally, there is increasing evidence that winds were stronger in intensity and more persistent during the glacial maximum (Kutzbach 1987). As sediment transport varies with the cube of the shear velocity, any increase in the speed and persistence of the wind (especially over longer time-spans) can lead to an increase in sediment transport and thus dune deposition. This increased aeolian component, combined with falling lake levels, contributed to the formation of the sand dunes and sheets in the deserts of the American South-west (Wells et al. 1987, Lancaster and Tchakerian 2003).

In the Mojave Desert, between ~35 and 9 ka, a series of full and intermittent lakes occupied the drainage basin of the Mojave River, the largest fluvial system in the Mojave Desert (Fig. 26.4). The Mojave River originates in the San Bernardino Mountains of southern California and currently ends in Silver Lake. Three basins and their lakes have received Mojave River flows: Lake Mojave (including present day Soda and Silver lakes), Cronese Basin, and Manix Basin (including Afton, Troy, Coyote and Harper sub-basins). Sediments from the above fluctuating and dessicating lake basins (and their adjoining alluvial and fluvial sub-basins) are believed to be the primary source for the sand dunes and sand ramps of the Mojave Desert (Tchakerian and Lancaster 2002). The relations between dune-building episodes and lake levels can be seen in Fig. 26.5. Aeolian depositional events seem to take place during both high and intermittent lake levels, as well as during periods of lake dessication. Dune construction appears to be mostly episodic, discontinuous or in discrete pulses controlled largely by the availability and mobility of sediment. A time-lagged, temporally and spatially disjointed, Sediment State System (Fig. 26.6) has been proposed by Kocurek (1998) and Kocurek and Lancaster (1999) that explains the rather complex, but inter-related processes associated with lacustrine, hillslope, fluvial, and aeolian sediment production, storage, transport and deposition. These processes ultimately control the rates, fluxes and the timing of the aeolian depositional episodes for the Mojave Desert (and in similar tectonically controlled geographic drylands). High sediment production occurs during sub-humid and/or semi-arid climatic periods,

Fig. 26.4 The Mojave River system and its associated Pleistocene lakes and the Kelso Dunes. See text for further discussion

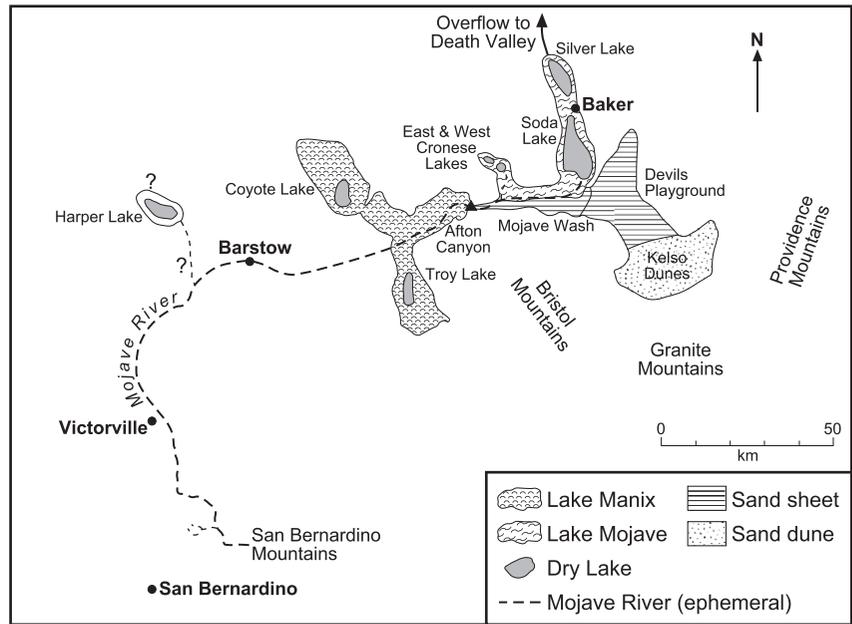
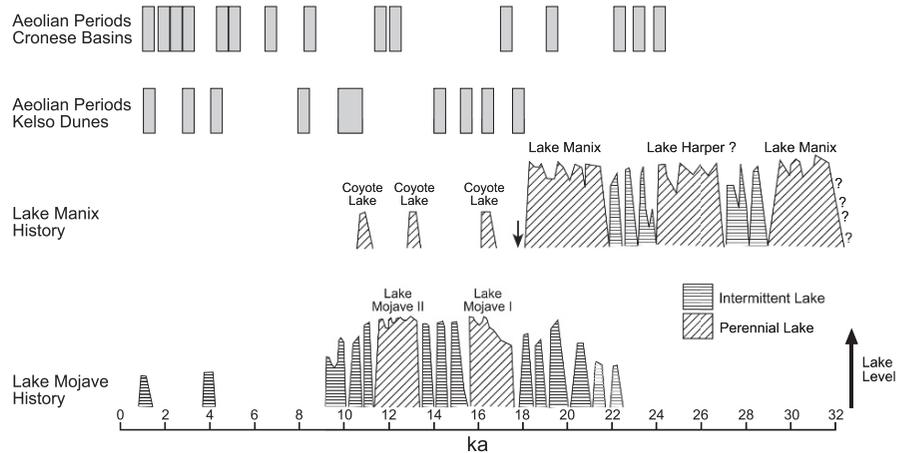


Fig. 26.5 Comparison of the history of dune-building episodes and palaeolake fluctuations from the Mojave Desert. Aeolian constructional periods based on luminescence ages. Arrow indicates the draining of Lake Manix. See text for further discussion and references



while at the same time, aeolian sediment mobility and availability remain low because of higher precipitation and vegetation cover. This climatic interval is characterized by abundant sediment supply and storage in various geomorphic environments, particularly around lake basins and adjoining lower piedmont slopes. During more humid and/or wetter periods (e.g. high to intermediate lake-levels), increased vegetation cover inhibits or dramatically reduces sediment entrainment, deflation, and transport, leading to the stabilization of most aeolian sands, and the formation of palaeosols (e.g. on the sand ramps). During more arid periods, sediment supply from fluvial and lacustrine sources

is drastically curtailed, vegetation cover is sparse, and the stored sediment in lake basins and adjoining geomorphic environments (fan-deltas, distal fluvial deposits) is mobilized or re-activated.

On the other hand, during the more arid and perhaps windier Climatic Optimum (Altitheimal), between 7 and 5 ka, dune construction in the Mojave Desert was more localized and not as widespread, since most sediments had already been mobilized and new sediment supply was at negligible levels. Arid and hyper-arid sub-cycles tend not to be conducive for the deposition of new aeolian deposits, particularly if not enough time has elapsed to generate, store, and

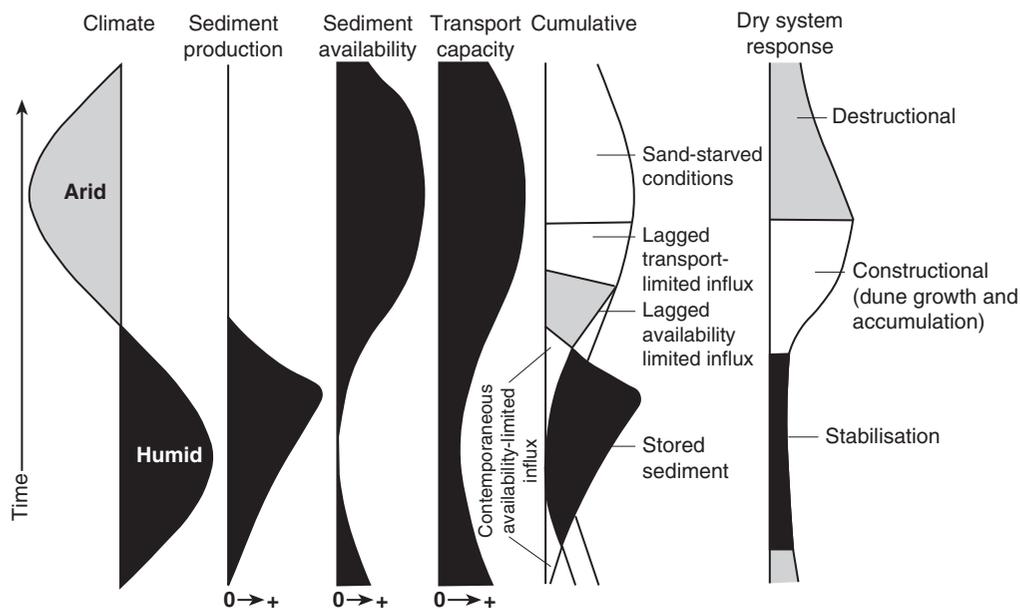


Fig. 26.6 The Sediment State System. A process-response model based on sediment production, sediment availability (supply) and transport capacity of wind as first proposed by Ko-

curek 1998) for Saharan sand seas and modified subsequently by Kocurek and Lancaster (1999) for the Kelso Dunes in the Mojave Desert, California, USA

mobilize fine sediments for deflation and subsequent deposition. In contrast, the Pleistocene to Holocene climatic transition (12–10 ka) was characterized by fluctuating environmental conditions and witnessed warmer temperatures, greater effective moisture (the latter both from winter precipitation and summer monsoonal rains), and brief high lake stands, owing primarily to the northward displacement of the jet stream and its associated atmospheric phenomena, and sporadic aeolian activity (Spaulding and Graumlich 1986, Kutzbach 1987, COHMAP Members 1988, Tchakerian and Lancaster 2002). Intermittant aeolian activity and brief lake level fluctuations have been established for the past 800 years among the basins of the Mojave River. Between 1850 and 1994, fourteen extreme floods on the Mojave River produced documented high lake stands, albeit lasting for only a few months in Silver Lake and the Cronese Basin (Wells et al. 2003). These lacustrine sediments (after desiccation), along with fluvial sands and silts from the Mojave River floodwaters, were eventually entrained all along the Mojave River Wash/Devil's Playground Sands/Kelso Dunes sand transport corridor (Clarke and Rendell 1998). These events of the last 150 years provide additional support to the Sediment State model

of Kocurek and Lancaster (1999) in that most aeolian deposition is highly episodic and discontinuous, and primarily driven by sediment supply, availability, storage, and the transport capacity of wind.

During the LGM, atmospheric conditions were dramatically different in the deserts of the American South-west. At the same time that the tropical and subtropical deserts were experiencing significant dune-building episodes and low-lake stands, aeolian activity in the basins of the south-western deserts of the United States was highly episodic, with fluctuating climatic conditions and desert basin lakes at high levels (Benson et al. 1990, Tchakerian and Lancaster 2002). According to general circulation models (COHMAP Members. 1988), in the south-western deserts, temperatures were 2°C to 3°C lower than at present, while precipitation and potential evapotranspiration were higher. The changes reflected increased winter rains (associated with the southward shift of the storm track and jet), reduced evaporation (associated with lower temperatures), and stronger and more persistent winds, the latter associated with the steep gradient in atmospheric pressure between glaciers in the mountains, such as the Sierra Nevada, and warmer land areas farther south, such as the Mojave Desert. Regional studies

indicate that the majority of closed-basin lakes in the south-western deserts of the United States were high to intermittant from about 25 to 11 ka (Wells et al. 2003).

In contrast to the American South-west and the Great Plains, late Quaternary aeolian activity in most other deserts (some of the southern African ergs excluded) appears to have peaked between 20 and 12 ka (Fig. 26.1). The contemporaneity of earlier Holocene aeolian activity in different parts of western North America is probably the result of the re-establishment of arid conditions, previously displaced by a cooler moisture atmospheric circulation system around the margins of continental ice sheets farther north. In Eurasia, the continental deserts were farther removed from the effects of smaller ice sheets and deglaciation episodes to the north and responded instead to fluctuations in subtropical anticyclones and SST's. When these anticyclones weakened and SST's increased (warmed), for example between 8 and 5 ka, intrusive westerly and/or tropical airflows introduced moisture to such areas as the Sahara Desert (COHMAP Members 1988).

Discussion

The concept of synchronous hemispheric tropical aridity (northern glaciations = tropical aridity) and dune episodes (Williams 1975, Sarnthein 1978), needs to be refined to accommodate the complex temporal and spatial nature of dune construction. At larger spatial and/or temporal scales, dune formation in the Sahara-Sahel region and in the southern African ergs is influenced by the intensity and persistence of trade wind circulation, as well as changes in Atlantic sea surface temperatures (SST's), with periods of low SST's corresponding to periods of enhanced aridity. Changes in the strength of the African monsoon has also been invoked to explain some of the disparities between dune construction in the Thar Desert of India with those in Africa (Lancaster 2007). In contrast to the Sahara-Sahel, major dune-building episodes in the southwestern deserts of North America is influenced by the nature of the polar jet and its accompanied atmospheric phenomena (e.g. increased wind and storm frequencies) and their role in the presence or absence of pluvial lakes and major flood events on desert streams. Continental or regional scale changes in atmospheric phenomena and pressure

fields are not alone sufficient for ultimately triggering dune deposition in desert basins, although major climatic transitions can produce significant changes in geomorphic processes.

At small spatial and/or temporal scales, dune-building episodes need not be correlated with aridity owing to the fact that aeolian deposition is most likely controlled by rates of sediment supply and storage, local and regional topographic and geomorphic controls, the frequency, magnitude, persistence and direction of the prevailing winds (which strongly influence sediment entrainment and transport capacity), and vegetation (as proposed by the Sediment State model). The complex loops within and among the above variables seem to ultimately control whether dune construction will take place. For example, a decrease in the vegetation cover over dunes and stabilized sand sheets, can lead to increased sediment mobility. High wind speeds combined with lower vegetation densities (and reduced roughness) and ample sediment supply (from dry or intermittant lake beds and surrounding piedmont areas) were most likely responsible for the accumulation of sand dunes, sand sheets and sand ramps in the basins of the American Southwest.

Because of the complex nature of aeolian depositional processes, a global systems approach need not necessarily be the correct paradigm through which to investigate the relationships between major dune-building episodes and global aridity associated with climatic changes in the deserts of the world. A more regional and systematic analysis of the aeolian deposits found in the basins of the major deserts should be accomplished before any generalizations can be made as to the global synchronicity of major atmospheric and climatic events and their likely effects on dune-building episodes.

With further refinements and fine tuning in luminescence dating methods (and other dating tools), coupled with new theoretical concepts (such as the Sediment State model), and field techniques (such as GPR), the temporal and spatial patterns of global dune deposition and the various geomorphic, climatic and ecological factors that control the complex nature of sediment supply, availability and mobility, will be better elucidated in the near future. Reactivation of the world's stabilized and vegetated dunes by 21st century global warming would represent one of the most daunting environmental challenges for society (Thomas et al. 2005).

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