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GEOLOGICAL IMPORTANCE OF LUMINESCENCE DATES IN OMAN AND THE EMIRATES: AN OVERVIEW

KENNETH W. GLENNIE[1], STEVEN G. FRYBERGER[2], CAROLINE HERN[3], NICHOLAS LANCASTER[4], JAMES T. TELLER[5], VACHASPATI P. PANDEY[6, a] and ASHOK K. SINGHVI[6]

[1]*Department of Geology, School of Geosciences,King's College, University of Aberdeen, Aberdeen AB24 3UE,*
[2]*Petroleum Development Oman, POB 81, PC 113 Muscat, Oman*
[3]*Shell Technology, Shell Development Oman LLC, P.O. Box 74, P.C. 116, Mina Al-Fahal, Muscat, Sultanate of Oman*
[4]*Desert Research Institute, Reno, Nevada, USA*
[5]*Department of Geological Sciences, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2*
[6]*Physical Research Laboratory, Navarangpura, Ahmedabad 380 009, India*
[a]*Present Address: Geology Division, Mangdechhu HE Project, NHPC Ltd, Trongsa, Bhutan- 33001*

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Abstract: In the Wahiba Sands of eastern Oman, luminescence dating of sands enables us to relate wind activity to climatic variations and the monsoon cycle. These changes resulted from Polar glacial/interglacial cyclicity and changes in global sea levels and wind strengths. Luminescence dates show that development of the Sands began over 230 ka ago when the sand-driving winds were the locally arid, northward-blowing SW Monsoon.

During late Quaternary low sea levels, the Tigris-Euphrates river system flowed across the floor of the Persian/Arabian Gulf to the Gulf of Oman SE of the Strait of Hormuz. OSL-dated sands containing calcareous bioclastic fragments deflated from the exposed Gulf floor during glacial low-water periods indicate that during the last glacial cycle, and at least one earlier cycle (~120-200 ka and possibly as far back as 291 ka), the floor of the Arabian Gulf was exposed. This is deduced from the presence of aeolian dune sands containing bioclastic detritus on the coastal plain of the Emirates and south into Al Liwa (Abu Dhabi), which were built by northern "Shamal" winds. Those calcareous sands now locally overlie sabkhas formed during interglacial high sea levels. Within the present interglacial, marine flooding of the Gulf occurred between about 12 and 6 ka.

Keywords: Oman, Wahiba Sands, Emirates, Al Liwa, dune sands, Persian Gulf.

1. INTRODUCTION

Over the last 15 years, a series of mostly aeolian sand samples from SE Arabia has been collected by different workers and dated using a variety of luminescence techniques. These dates have enabled inferences on the evolution of sand seas in the area in relation to glacial-interglacial climatic cycles. We synthesise these studies to develop the regional picture of sand sea development.

Corresponding author: K. W. Glennie
e-mail: glennie_ken@hotmail.com

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2. EARLY STUDIES AND BACKGROUND

Early desert studies in Oman and The Emirates began with Carter (1849), who first coined the term 'miliolite' after the high content of miliolid foraminifera in coastal sands. An aeolian origin for the miliolite of NW India was suggested by both Evans (1900) and Chapman (1900), to be followed in the Persian Gulf by Pilgrim (1908). High carbonate content coastal foraminifera often made it difficult to recognize their aeolian origin (e.g. Holm, 1960).

Desert conditions on the Sinai Peninsula of NW Arabia were described by Johannes Walther in 1898, and that was followed in 1900 by the book "Das Gesetz der Wüstenbildung". Both these publications were in German and did not receive the readership they deserved; an English version of its 1924 (4th edition), "The Law of Desert Formation – Present and Past", edited by Gischler and Glennie, was eventually published in 1997. These early authors made important contributions by showing that ancient desert sediments did exist and could be studied even if the workers had no idea of how old those sedimentary sequences were. Those interpretations contradicted other opinions in the first half of the 20th century.

This lack of understanding has been rectified by, among others, Evans *et al.* (1964a, b) and more recently by Kirkham (1998), and Evans and Kirkham (2002). Their work on near coastal sediments of the Emirates did not use luminescence dating, although some ^{14}C dates have been used by other authors. An early study by Glennie (1970) had only archaeological dating in Libya to constrain the timing of desert events, but his interpretations did use a 1965 photograph of the NE Wahiba Sands of Oman taken from space to help interpret the age relationships. A major study of the Wahiba sands was undertaken by the Royal Geographical Society from 1985 to 1987 (Dutton, 1988), which included a terrain classification by Jones *et al.* (1988a) and an early interpretation of the sands by Gardner (1988) who used ^{14}C dating of associated near-coastal shells.

The luminescence dating of desert sediments was first demonstrated by Singhvi *et al.* (1982) in the context of The Thar Desert, India. Its application to Arabia began when Juyal *et al.* (1998) provided reconnaissance dating of the region with luminescence dates of various surfaces. These were followed by Juyal *et al.* (1998), Glennie (1998), Teller *et al.* (2000), Glennie and Singhvi (2002), and Glennie *et al.* (2002) (see **Figs. 1-2**). Since then, others have undertaken dune-sand dating within Oman (e.g. Preusser *et al.*, 2002, 2005; Radies *et al.*, 2004) and The Emirates (Hadley *et al.* 1998; Goudie *et al.*, 2000; Stokes and Bray, 2005) and have added to the present understanding of the event chronology of aeolian transport and deposition. OSL studies of the Wahiba Sands in Oman by Preusser *et al.* (2002; 2005) and

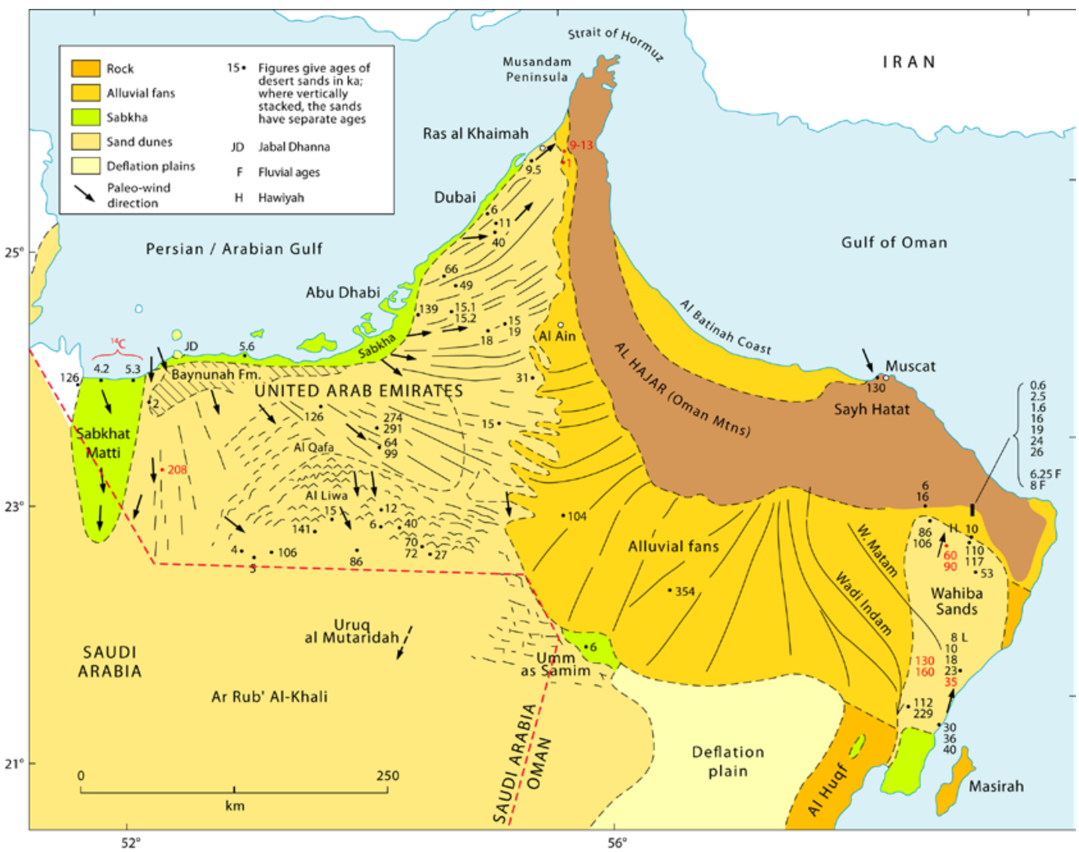

Fig. 1. *Simple outline of the main desert features of the Wahiba Sands of Oman and the greater United Arab Emirates. Ages are all luminescene dates and are ×1000 yrs BP, with those in black from sands collected by (or for) the writers for OSL dating at National Physical Research Laboratory, Ahmedabad, and in red collected and dated by other workers. Dune trends are shown schematically as linear (almost straight lines) or transverse (wiggles) and a selection of deduced wind directions as arrows. Sabkhas, mainly coastal, are shown schematically in green – those of Al Liwa are too small to show at the map scale but can be seen on Landsat image* ***Fig. 11****.*

Radies *et al*. (2004) give ages locally from a more continuous sequence of both core and outcrop samples than our own.

Such chronometric studies are also of value in interpreting ages in terms of environments of deposition of desert sediments, as exemplified by a variety of papers in Goudie *et al*. (1999), Hern (2000), and Hern *et al*. (2003), and in the global analyses by Lancaster (2008) and Singhvi and Porat (2008). Important conceptual and sedimentological desert studies in North America in McKee (1979), Fryberger *et al*. (1988) and Kocurek (1988), before OSL dating was used, have also been key to the interpretation of desert sequences and their evolution through time.

Polar glaciations played an important role in creating past tropical deserts. Shackleton (1987) and others have expanded our understanding of Quaternary Glacial-Interglacial cycles. Shackleton (1987) studied glacially-induced changes in the stable oxygen isotope values of benthonic and planktonic fossil foraminifera extracted from sediment cores from the Pacific Ocean and from the uplifted terraces in New Guinea, and found that these indicated that there had been sea level changes of some 120 m over the past 140 ka. Earlier, from a South Atlantic core, Shackleton and Opdyke (1973) showed a similar but less detailed cyclicity extending back for over 700 ka. Boulton (1993) plotted the oxygen isotope changes over the past 575 ka in which when inverted, the first 140 ka part virtually matches Shackleton's (1987) changes in sea level (see **Fig. 2**). These dramatic sea level changes not only illustrate the timing and duration of late Quaternary climate change, but also provide insight into changes in fluvial, dune, and sabkha development at this time over Oman and The Emirates, as well as elsewhere in the world, (see e.g. Alsharhan *et al.*, 1998).

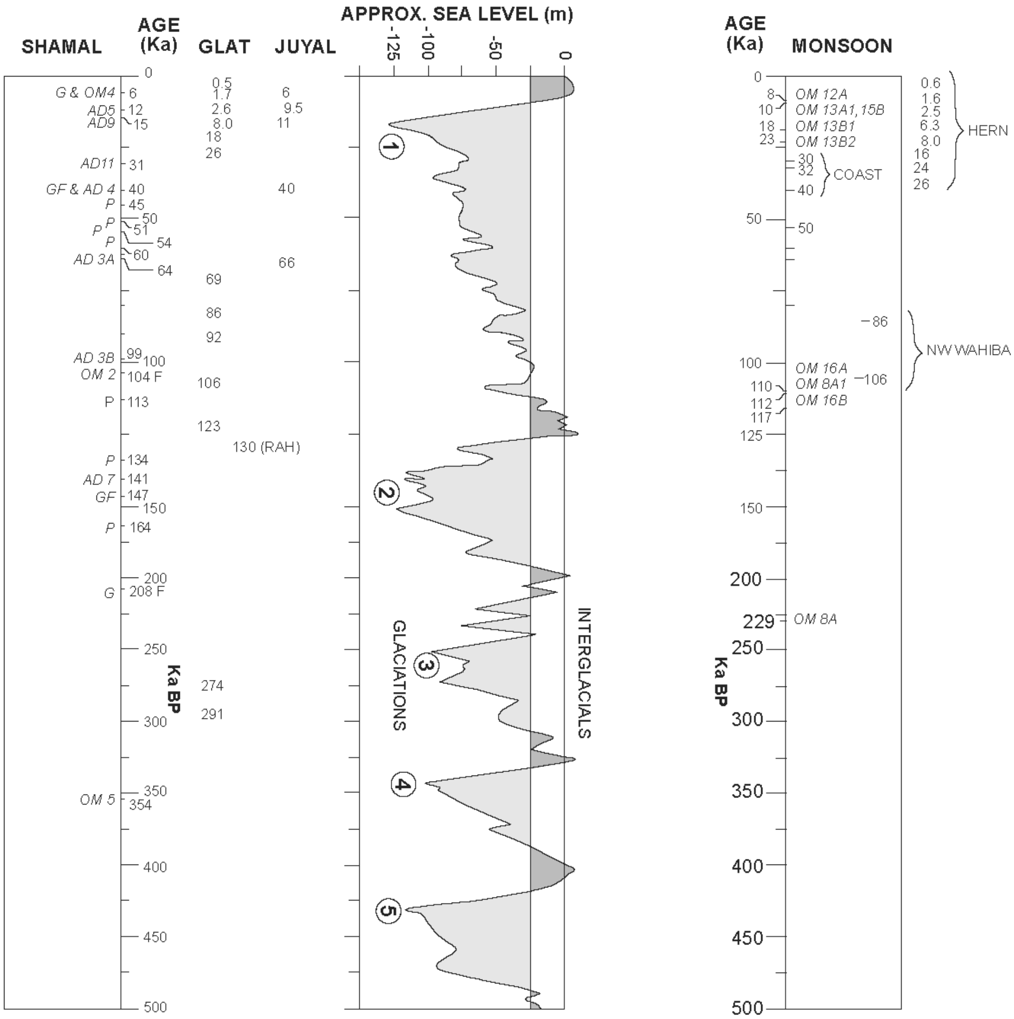

Fig. 2. *Simplified outline of changes in global sea level over the past 500 ka (modified from Boulton, 1993). Note the change in time scale at 150 ka. Distribution of OSL dated sands (×1000 ka) of SW Monsoon origin is in right-hand column and those of Shamal origin to the left of the sea-level curve. Boundary between glacial and interglacial conditions is shown arbitrarily at 25 m below present sea level. Samples marked G and P in the Shamal column were collected separately by Goodall and Pugh and dated in UK.*

The winds across the globe are currently driven by differences between the cold Polar Regions of high atmospheric pressure and the Equatorial zone of low-atmospheric pressure. In sub-tropical desert areas, this is characterised by the modern path of the Shamal (north) wind system, which in today's winters, crosses much of Arabia in a clockwise semi-circle (Glennie, 2005). During glacial times, however, the Shamal would have been 'squeezed' into a much flatter circuit, as suggested by the trace of the west-to-east linear dunes over the northeastern Emirates, that then gently curve to the NE on approaching the Oman Mountains (**Fig. 1**). At that time the more southerly part of the Shamal system may have extended far south into the Arabian Sea (e.g. Glennie *et al.*, 2002). Another, essentially summer wind system, the SW Monsoon, has been responsible for transporting most of the dune sands of NE Oman from south to north.

Samples OSL dated at Physical Research Laboratory (PRL) in Ahmedabad, were collected at different times from both Oman and the Emirates (**Figs. 1** and **3**) by Juyal, Singhvi, Glennie, Teller, Lancaster, and Hern. In this paper we use these dates along with luminescence ages published by others and discuss their geological implications. Because of clear differences in the direction of sand transport in these two regions, induced by the winter Shamal and summer SW Monsoon, their interpretations are discussed separately.

3. WAHIBA SANDS (NOW KNOWN AS AL SHARQIYAH SANDS)

These dune sands have been divided into five areas based on morphology and age (**Fig. 3**).

1) In the southwestern region, the Al Jabin sands form the roots of dunes that now occur as a series of eroded mesas of variable height, and comprise sub-horizontal aeolian sands that range in age from 229-112 ka (**Fig. 4**) in the far southwest and 160-130 ka farther north.
2) To the north, these dune sands are replaced by small N-S trending dominantly linear dunes at least as far as the south-eastern extension of Wadi Matam; they are probably represented north of this wadi along the western margin (dashed line) of the dunes of area 3.
3) In area 3, northeast of Wadi Matam, the large asymmetric linear dunes of the High Wahiba are up to about 80 m high, with crestal spacings of 1 to 1.5 km and major west-facing slip faces that imply a degree of sand transport from the E or SE (**Fig. 5**). Sands in borings date between 60 and 90 ka (Radies *et al.*, 2004). The dunes of area 3 are truncated in the north by Wadi Batha (**Fig. 3**), which flows eastward to the sea. Thin interbedded aeolian sands occur in 'borrow pits' in Wadi Batha; one such is dated to 6.25 ka. During dry periods, small barchans to linear dunes cross the wadi to the north, where the larger of two major dunes was sampled by Hern; the ages for these range from about 1 to 26 ka. At the northern end of Hawiyah town, aeolian sand streaks within fluvial gravels date to 10 ka while to its south, 117 ka dune sands at the bottom of a water-well overlie wadi gravels. Borings for water showed that other dune sands overlay a south-flowing palaeo-Wadi Batha (Jones *et al.*, 1988b). It is presumed that this palaeo-wadi was forced to find another route to the sea by the monsoon-driven northward growth of dune sands over a time span extending back some 120 ka. Carbonate cemented sands at the NW margin of the Wahiba Sands indicate dune and interdune deposition between 86 and 106 ka. Some interdune lacustrine deposits contain freshwater gastropods.
4) Along the south-eastern flank of the Wahiba Sands, a set of carbonate-rich aeolian sands in the south range upward from 40 ka at sea level at Ras Ruways to about 30 ka at the top of nearby cliffs (**Fig. 6**), and young to 12 ka in the north. Similar undated sands have been dredged from beneath the sea between

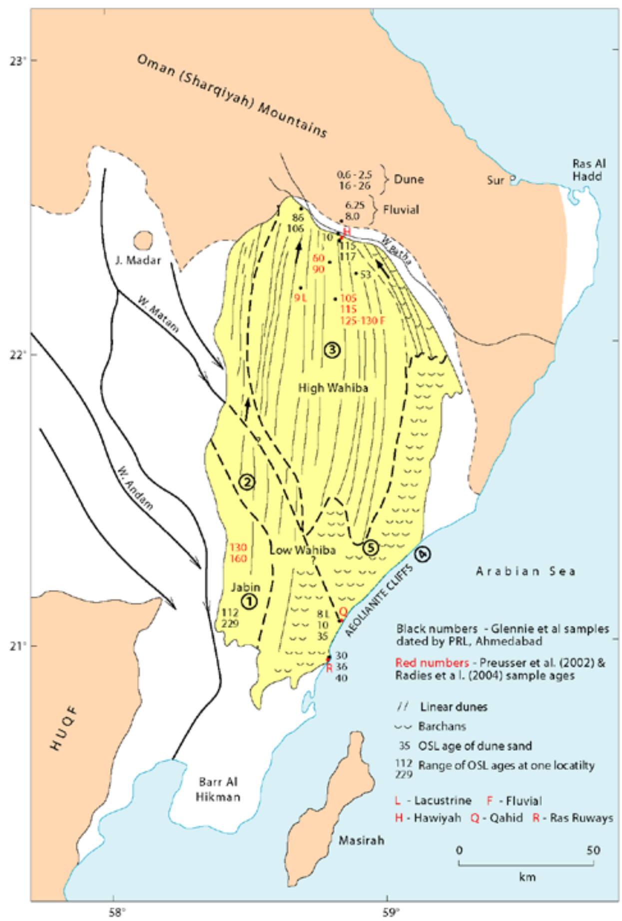

Fig. 3. *Outline of the five major divisions of the Wahiba Sands showing dunes of linear and transverse origin schematically. Black numbers indicate ages of sands (×1000 ka) dated at NPL and those in red at other dating centres. Area 5 "Barchans" are mainly tranverse (barchanoidal) dunes.*

Fig. 4. *Cliff of aeolianite near the SW margin of the Wahiba Sands; dated to 229 ka near the base and 112 at the top. Note the darker soil horizon, possibly formed during the humid phase of interglacial ~200 ka BP, and the man for scale. Wind blew from right (S) to left (N).*

Fig. 5. *RAF photo of northern Wahiba Sands and adjacent Wadi Batha taken in 1957. Asymetrical megadunes trend about N-S and small 'feather' dunes diverge towards the crests of their flanking mega dunes and have small slipfaces nearest the megadunes on either side. Small oasis of Al Jahis is to the left. Al Mintirib in the south and Al Ghabbi to its NNW have small intervening barchanoid to linear dunes nearby.*

Barr al Hikman and Masirah. At Qahid (**Fig. 7**), lacustrine and sabkha sediments (possibly near the seaward end of Wadi Matam), OSL dated to 8 ka (Radies *et al*. (2004), overlie aeolian sands that range downslope from 10 to 35 ka.

5) Following the last post-glacial rise in sea level, the former sand cover of the Barr al Hikman (**Fig. 3**) was deflated down close to the water table and transported NNE as transverse dunes ("Barchans" on **Fig. 3**) in the southern and eastern Wahiba, thereby forming a fifth division of the Wahiba Sands.

Fig. 6. *Wahiba coastal dunes north of Ras Ruways, dated from about 38 to 32 ka. Note the contrasting foresetted dune sands at the top underlain by almost horizontal sands.*

Fig. 7. *Al Qahid mesa of lacustrine sediments dated to 8 ka (blackened by desert varnish) underlain by dune sands that range from 10 ka down to 35 ka out of picture. The lacustrine sediments were possibly deposited at the downstream terminus of Wadi Matam. Note the contrast in relief between the uncemented modern transverse dunes of unit 5 advancing from left (south) to right towards the mesa, and the cemented dunes beneath the mesa.*

The Al Qahid lacustrine and sabkha sediments were radiocarbon dated to 9-6 ka BP which was a warmer phase of higher rainfall (the 'Climatic Optimum') (Petit-Maire, 1994) when plants, animals and mankind thrived after the earlier arid period of the last Glacial maximum.

The sands of the Sharqiyah (Wahiba) dune system in all 5 areas (**Fig. 3**) were transported from south to north by winds of the SW Monsoon. These sands were probably derived from three sources. Much of the older sand in the southwest (Jabin, **Fig. 4**; area 1 of **Fig. 3**), which contains no carbonate, would have been deflated from the wadis draining the Huqf area SW of the Barr al Hikman (**Fig. 3**) and its adjacent exposed sea floor between late Glacial 3 and early Glacial 1 stages. In contrast, the carbonate content of dune sand in the other four areas, and especially in area 4, implies nearby exposures of shallow-marine sands at times of glacially induced lower sea level. So far as the Jabin area is concerned, however, there is another source, namely the wadis flowing south from the eastern (Al Hajar or Sharqiyah) Mountains (**Fig. 3**). This is supported by the content of reworked ophiolite and other lithic grains redistributed over the rest of the Sands by the SW Monsoon (e.g. Allison, 1988). These observations reaffirm that the SW Monsoon was sensitive to glacial cyclicity, with onshore penetration controlled by the position of the intertropical convergence zone; this was an hypothesis also proposed by Preusser *et al*. (2002) and Radies *et al*. (2004).

Another age of interest in Oman is the 6 ka of aeolian sands (adhesion ripples) deposited beneath a thin layer of halite over the western half of the Umm as Samim (the 'Mother of Poisons') near the Oman-Saudi border (**Fig. 1**). Today, the central Umm as Samim is covered with polygonal salt, with the salt extending down for up to about 5 m where it is underlain by Cenozoic sands. At the time of deposition of the adhesion-ripples, the locality was probably marginal to a lake, which in part would have been a product of the mid-Holocene 'Climatic Optimum'. Since then the Umm as Samim has become an evaporation pan because of the present conditions of hyper-aridity, and this is exemplified by its infill of thick salt (Heathcote and King, 1998). Much of the salt in the Umm as Samim is probably derived from evaporation of artesian water contained in an underlying Eocene limestone aquifer that flows up through late Cenozoic evaporites (Glennie, 2005).

Two events that appear somewhat out of context are highlighted along the northern and northeastern coasts of Oman. The coastal dune sands at Ras al Hamrah, just west of Muscat, are rich in marine microfossils and are dated to 130 ka (**Fig. 1**), which can be linked to an offshore source area in the Gulf when sea level was about 60 m below present sea level (see **Fig. 2**). These sands dip toward the NW but more widespread bedding relationships indicate aeolian transport gently upslope to the SE for at least 2.5 km (**Fig. 1**; see also Glennie, 2005). The direction of transport, interpreted from the cross-bedding, implies that the sands were driven by the clockwise Shamal wind system (Glennie and Gökdag, 1998) which is more typical of the Emirates. OSL dating was an essential component of this interpretation.

And to the west, along the northeastern flank of the Al Hajar Mountains (formerly Oman Mountains), wadis occasionally carry the products of erosion down slope towards the Batinah Coast (**Fig. 1**). Winter winds of the NE Monsoon, however, no doubt assisted by convection of late afternoon hot air, deflate these sands and transport them back toward the mountains as mostly small linear dunes. Between the above two areas, Al-Belushi (1998) describes similar alternations of transport directions.

4. THE EMIRATES

Researchers have used OSL and other types of dating such as ^{14}C and U series ages of sands from The Emirates to interpret the history of dune formation. The oldest ages take dune activity back to at least 160 ka and probably >250 ka using a U-Th age for a moderately cemented mixed carbonate and siliciclastic palaeodune within the Ghayathi Formation in the western Emirates (Hadley *et al*., 1998). In turn, the Ghayathi Formation palaeodunes overlie fluvial sands of the Late Miocene Baynunah Formation (8-5 Ma; Friend, 1999; **Fig. 1**), dated from its vertebrate fossils (Whybrew and Hill, 1999). In the Baynunah area, these fluvial sands flowed to the east, possibly reaching the sea across Oman via the Umm as Samim; this route would have followed a structural low formed by gentle curvature of the Arabian Crust that had resulted from the opening of the Red Sea/Gulf of Aden when the Hejaz Asir, Oman and Zagros Mountains were uplifted (**Fig. 8**). In turn, these fluvial sands overlie aeolian sands of the Shuwaihat Formation at Jabal Barakah (about 30 km SW of Jebel Dhanna, **Fig. 1**), which are riddled with rhizoliths (fossil plant roots) and overlie sabkha deposits (Glennie and Evamy, 1968). Such sands are found in a variety of localities as far west as Sila (S in

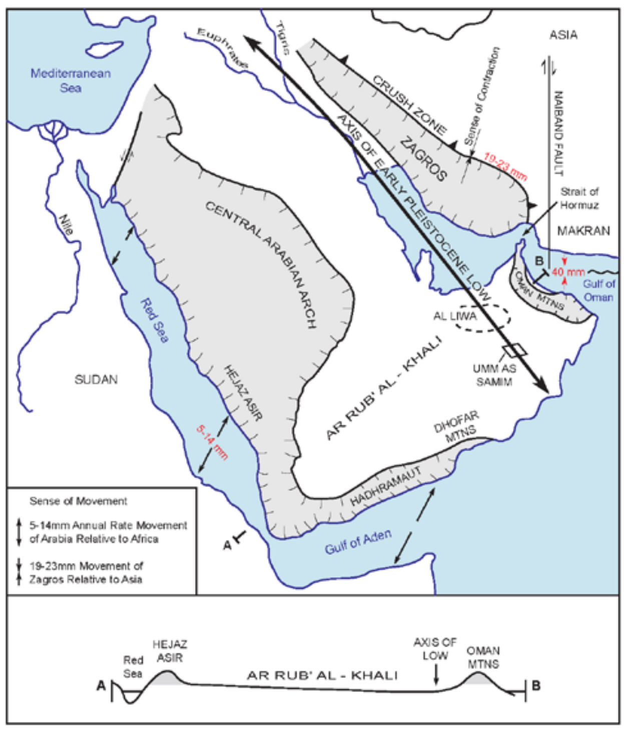

Fig. 8. *Gentle synclinal warping of the Arabian Plate caused by Miocene opening of Red Sea and Gulf of Aden and ensuing uplift of the Hejaz Asir, Zagros and Oman Mountains. Figures in red indicate rates of relative tensional or compressive movement in mm/a. Note that the northern tip of the Musandam Peninsula is subsiding into the Strait of Hormuz at 6 mm/a (Vita-Finzi, 1979).*

Fig. 9), just west of the Sabkhat Matti coastline, and especially on Shuwaihat Island about midway between Jabal Dhanna and Jabal Barakah to its south (see **Fig. 9**). Bristow (1999) dates this formation at about 15 Ma (Mid Miocene). This age stresses a time gap of some 9 Ma between it and the overlying fluvial Baynunah Formation, during which a considerable change in climate must have taken place. It is obviously the later fluvial conditions that allowed plant roots to penetrate the older dune sands at Jabal Barakah.

These ages, of course, are estimates and far too old to be dated by the OSL technique; they do infer, however, that the geological history of the area is full of time gaps with no sedimentary record of intervening climatic or depositional conditions.

Following the effective opening of the Red Sea and Gulf of Aden during the late Miocene, Arabia has been moving to the NE, eventually colliding with southern Asia. Since that collision, the Arabian Plate has become a gently warped syncline whose axis trends NW-SE across eastern Arabia including the lowlands of Iraq (see Glennie, 2005 for more details; **Fig. 8**). Arabia is still closing with southern Asia at a rate of about 20 mm/year, so the degree of warping is probably increasing with time. If so, then the Arabian Gulf should have been shallower in the past than it is now, so that lowering of sea level during former glaciations 2 and 3 (see **Fig. 2**) or even older would have kept the area free from marine flooding for an even longer periods than was the case during the last glaciation. This possibility is emphasised by the depth of the Strait of Hormuz, whose southern margin, the northern tip of the Musandam Peninsula, is currently subsiding at about 6 mm/a (Vita-Finzi, 1979). This implies that the last post-glacial reflooding of the Gulf probably occurred at an even higher global sea level than would be the case today.

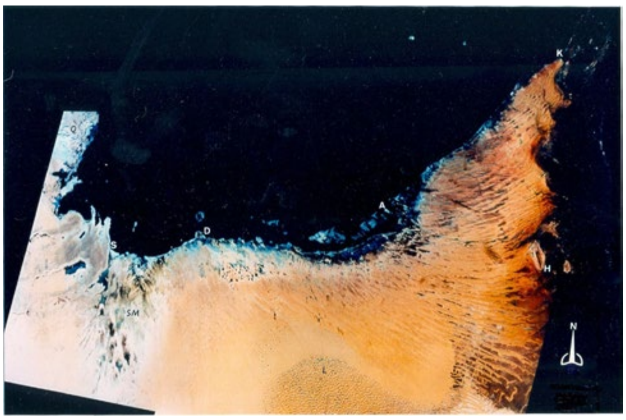

Fig. 9. *Landsat image of the Emirates. From the east coast of Qatar to Ras al Khaimah is about 500 km. The area is dominated by linear dunes whose trends vary from SW to NE near Ras al Khaimah (K) to N-S east of Sabkhat Matti (SM). In Al Liwa (L) the slip-faces of giant barchanoidal dunes face mostly to the SSE. Note coastal sabkhas and shallow-marine near-coastal rocks. Sabkhat Matti extends south of Sila (S) for some 130 km. A=Abu Dhabi Island; D=Jabal Dhanna; H=Jabal Hafit; Q=Qatar. Most of the coastal sabkhas and near-coastal shallow-marine rocks look dark and are difficult to see. Ophiolites of Oman Mountains (RH edge) are almost impossible to discern.*

Interpretation of the aeolian sands within the Emirates is more complex than for the Wahiba Sands. Sea level curves (**Fig. 2**) imply that during the past 500 ka or more, there were periods when the present Persian (Arabian) Gulf was the site of the SE-flowing Tigris-Euphrates river system, whose waters were derived from the rainy highlands of Anatolia north of the Arabian sub-tropical desert belt. At peak glacial times this river was flanked by sand dunes (Sarnthein, 1972) and reached the open ocean only SE of the Strait of Hormuz.

Late in the last glacial, the exposed fluvial sands were deflated by a strong Shamal that, in the northern Emirates, blew northeastward towards the northern Oman Mountains and built gently curved linear dunes subparallel to the modern coastline (**Figs. 1** and **9**). We know from Kirkham (1998) that the linear quartz dunes of the northern Emirates are enriched westward in limestone grains derived from late Quaternary calcareous marine organisms exposed during that glacially-induced low sea level. These well cemented grains have a higher resistance to erosion than poorly cemented quartz sands; they now form the protective northwestern edge of a series of peninsulas (e.g. Al Dabb'iya), islands, and submarine banks along the Abu Dhabi coast, as well as isolated mesas of dune sand dated, for example, to 66 ka and capped by gypcrete (**Fig. 10**).

The interbedded dunes and sabkhas of the Liwa Depression in the southern Emirates (**Figs. 1** and **11**) can be traced from the coast, west of Abu Dhabi Island to across Al Qafa, where abraded microfossils in dunes indicate both nearby marine and adjacent lacustrine origins. Because of abrasion to dust-size particles during aeolian transport, the carbonate content of the dunes decreases

Fig. 10. *NE dipping dune sand dated to 66 ka stands out in relief because of its protective layer of gypsum. The foreground is part of an extensive modern sabkha near Abjan, close to the Abu Dhabi-Dubai border.*

from about 70% near the coast to less than 30% in the middle of Al Liwa (Pugh, 1997) where dunes locally reach a height of up to 150 m.

The Al Liwa dunes are slowly migrating to the SSE across interdune swamps and sabkhas; most of these are too small to show on **Fig. 1** but occur beneath the blue-coloured interdune areas on the false-coloured Landsat image (**Fig. 11**). At ground level, however, a thin cover of sand may hide the sulphate-enriched ground water just beneath the surface. Local outcrops can consist of cemented dune sands interbedded with one or more gypsiferous horizons precipitated as part of earlier interdune sabkhas. Modern inter-dune temporary lakes have been created when digging for gypcrete for use as road foundations. Because today's climate is hyper arid (see Glennie, 2005) one of these temporary lakes formed a crust of halite within two years, while gypsum crystals were probably already forming below the surface crust. During the Quaternary, the water table beneath Al Liwa would have fluctuated in general concert with sea level in the Arabian Gulf, with some time lag caused by the distance between the two areas. This was coupled with periods of higher local rainfall such as occurred during the Climatic Optimum 6-9 ka BP, which would have given rise to local interdune lakes. In general, these rainfall events would have been relatively rare, but if continued over hundreds to thousands of years this would have made a difference in groundwater levels. Water levels in interdune areas and sabkhas probably varied from location to location, and sediment accumulation in low areas would also have been controlled by the topography of migrating dunes.

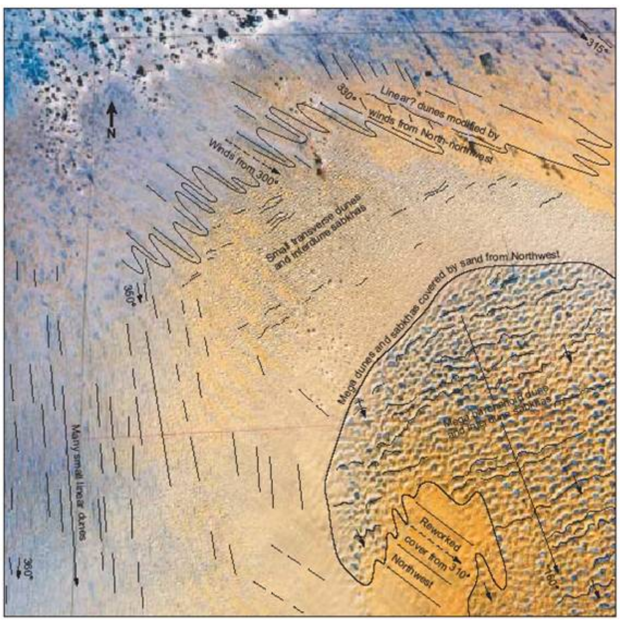

Fig. 11. *Landsat image of Al Liwa, whose giant barchanoid dunes are separated by interdune areas (blue) where the water table is at or close to the surface; these dunes are apparently moving slowly to the SSE. The smaller Al Qafa dunes in the north indicate former winds that blew from the WNW before being reworked by winds from NNW (trend of northern part of road - black line) from Al Liwa to the coast.*

During the maximum glacial aridity, when the sea level was low, the water table under Al Liwa is presumed to have been mostly well below the surface, where it was not subject to evaporation and the growth of beds of halite and gypsum crystals. The timing of these drier events is given by the OSL ages of the sands between gypsum horizons that formed during the wetter periods. In one case, a foresetted dune sand had an OSL age of 12 ka; these sands became riddled with rhizoliths during later swampy conditions (9-6 ka) and that was followed by gypsum cementation during the past 5 ka of high aridity (**Fig. 12**). In other isolated outcrops, gypsum-rich horizons formed during wetter phases between deposition of separate dune sands dated at 291 and 274 ka, 99 and 64 ka, 72 and 70 ka over greater Al Liwa, while gaps in sand accumulation have also been noted between the coast and Al Ain at 15-19 ka (**Fig. 1**). OSL ages of sand between the Abu Dhabi coast and Al Liwa range from 4.5 ka (mid-Holocene) to >250 ka (glacial 3; **Fig. 2**). It is not clear whether these different ages have a regional significance for sand sea evolution or represent local depositional gaps in the migration of dunes over interdune swamps and sabkhas. A series of excellent photographs in Pugh (1997) illustrate the range of depositional and erosional environments across Al Liwa.

In the context of the above, it is worth noting that today's water table in Sabkhat Matti (**Fig. 1**) in the western border area between the Emirates and Saudi Arabia rises steadily south from the coast, feeding partly dune-covered sabkhas (Glennie, 2005). Near its limit some 130 km from the coast, the water table is about 75 m above present sea level (see Plate 35 in United Arab Emirates University Al Ain, 1993); for a general discussion of Sabkhat Matti see Goodall (1995).

Fig. 12. *Foreset beds of dune sand dated to 12 ka are riddled with plant roots formed when the depositional area became an interdune swamp during the 'Climatic Optimum (~ 9-6 ka). The sequence was then cemented by gypsum crystals that presumably formed when the swamp altered to a sabkha during the last 5 ka of increased aridity.*

5. IMPLICATIONS OF LUMINESCENCE DATING IN OMAN AND THE UNITED ARAB EMIRATES

Apart from giving the general age of dune and associated fluvial and marine sediments in this part of the Middle East, what else do OSL dates tell us about the geological and climatic history of the area in terms of local or regional erosion and deposition?

Dating of the Al Sharqiyah (Wahiba) dune system of northeastern Oman has shown that its construction resulted from SW Monsoon winds during several distinct stages that straddle parts of at least three, mostly interglacial, time spans. The availability of carbonate grains of marine origin, which are present in some dunes, occurred when global sea level was lower than at present; this was especially the case with construction of the coastal dunes of area 4. The SW Monsoon winds provided the driving force. And with that wind system being still active, the Late Glacial rise in sea level resulted in the former cover of dune sand over the Barr Al Hikman being deflated down to the modern water table and redeposition of sand to the north (area 5).

In the Emirates, we now have luminescence ages for desert sediments that apparently extend back locally to the time span 291 to 274 ka (**Fig. 1**). Global climate reconstructions show that there were dozens of glacial episodes during the Quaternary, and **Fig. 2** shows 5 of them during the past 500 ka, each of which built up over time spans of around 50-100 ka and each consisting of many shorter-term fluctuations. During the growth and decline of polar ice caps, sea levels fluctuated by up to 120 m or more. Many glaciations exhibited a rapid collapse; the last one peaked at about 21.5 ka and the sea reached its present level by about 4 ka (Moorey, 1982). As already noted above, this had a profound effect on the desert coastlines. During glacial low sea levels, near-coastal deposits of carbonate-rich sediment were exposed and blown ashore to form the well known 'miliolite' so-named over a century ago. During such low sea levels, the floor of the Arabian Gulf was a dry land across which the joint Tigris-Euphrates River traversed, reaching the marine Gulf of Oman southeast of the Strait of Hormuz. Rapid post-glacial rises in sea level resulted in rapid flooding of the Persian Gulf. It is perhaps worth emphasising that the last marine flooding of the Arabian Gulf probably began only 12-10 ka BP, with the ocean reaching the ancient city of Ur about 240 km inland from the northwestern end of the present coast of the Gulf about 6 ka (see Teller *et al.*, 2000); at that time, sea level was 2-3 m higher than at present (Hill, 2000) (**Fig. 13**).

Between 12 and 6 ka, the sea advanced across the flat floor of the Persian Gulf, a distance of about 1200 km from the Strait of Hormuz to Ur. Although this was an average of about 200 m/a, at times this rate probably exceeded a kilometre per year, because the rate of glacial meltwater returning to the oceans varied considerably (see Teller *et al.*, 2000). The biblical character Noah and his family may have been caught up in this "flood" (Teller *et al.*, 2000). Part of this period of re-flooding of the Gulf coincided with a time of generally higher rainfall than at present across the Arabian and North African deserts (9-6 ka; Climatic Optimum of Petit-Maire, 1994). This may well have been the reason why Noah believed the flood to have resulted from rain for 40 days and 40 nights. Sea level eventually reached up to about 3 m above present, flooding Ur with saline water, not fresh water, then retreating to its modern level between about 4 and 2 ka. Arabia's climate has again been mostly arid for about the past 5000 years with slightly more moist conditions between 2100-1400 and 1100-700 years ago (Edgell, 2006).

During glacial times of lower sea level, the floor of the Persian Gulf was subjected to deflation under the influence of the Shamal winds. During the last glacial maximum, the Shamal is thought to have been 'squeezed' into a more easterly trajectory (**Fig. 13**) that caused deflation of exposed parts of the Gulf, creating west-east linear dunes (**Fig. 1**). At other times, the Shamal followed today's more typical semi-circular route over southern Arabia, transporting sand across the Rub' al Khali. On a more local scale, sand was also redistributed from the Gulf floor or current coastal areas of Abu Dhabi southward across Al Liwa (**Fig. 1**). And rather surprisingly, some 130 ka BP, and well east of its recognised area of influence, an ancient Shamal seems to have transported sands from an exposed sea bed upslope onto adjacent land just west of Oman's capital Muscat.

6. CONCLUSIONS

The range of OSL ages derived from the dating of dune sands from SE Arabia has been used to interpret the contrasting depositional areas of Oman, mainly the Wahiba (Sharqiyah) Sands, and those of the United Arab Emirates.

The Wahiba (Sharqiyah) Sands were deposited under the influence of an almost unidirectional north-blowing SW Monsoon. With only minor changes in direction, the wind's influence varied with varying exposure of unconsolidated sand onshore and of glacially exposed shallow marine sands offshore. During low sea levels associated with glacial periods, including the last glacial maximum, monsoon winds transported sands to the north (area 1, **Fig. 3**); in support of this conclusion, there are OSL ages on dunes bearing marine carbonates at 229 ka and 112-160 ka in the southwest (area 1) and from about 105 to 120 ka farther north (area 3) (**Fig. 3**). Younger dates of 53-90 ka in area 3 may reflect deflation of sands during the progressive lowering of sea level during this period prior to the last glacial maximum (see **Fig. 2**). However, after several thousand years of exposure, deflation of marine bioclastic sediments along the coast may have become more difficult because of cementation or stabilization by vegetation (Teller *et al.*, 2000). In summary,

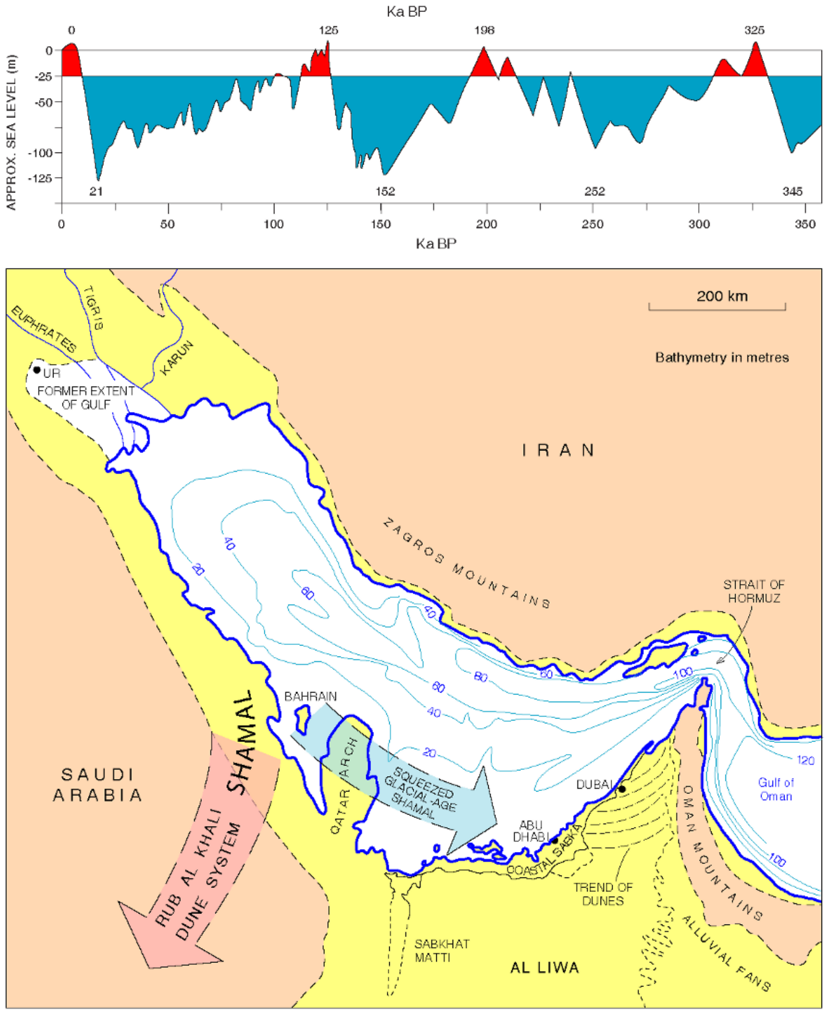

Fig. 13. *Upper: Global sea-level curve for past 350 ka caused by changes from glacial to interglacial conditions, which are suggested here at an arbitrary sea level 25 m below present. Lower: Bathymetry of the Arabian Gulf in metres and schematic paths of the present interglacial Shamal wind (pink) to S and SSW, which transported sands from coastal areas south to Al Liwa and the Rub al Khali; and the 'squeezed' glacial-age Shamal (blue) whose stronger winds built the gently curved system of linear dunes inland of Abu Dhabi and Dubai from sediments of the then exposed Gulf. The last flooding of the Gulf probably began around 12 or 10 ka, reaching the old city of Ur about 6 ka in southern Iraq almost 1200 km from its start SE of the Strait of Hormuz. Bathymetry simplified from Kassler (1973).*

low sea level during glacial periods exposed shallow-marine sands, which were deflated by northward-blowing winds and then deposited as the Wahiba Sands. During each post-glacial rise in sea level, the supply of sand from the south was cut off. When the supply of marine sands was cut off by the Holocene rise in sea level, the former dune cover of Barr al Hikman was deflated down to the water table, and its sands were transported northward over much of the southern and eastern Wahiba (area 5), covering older cemented dune sands along their route. The dating of these sands implies that dune deposition was sensitive to glacial cyclicity, with onshore penetration controlled by the position of the intertropical convergence zone, as proposed by Preusser *et al*. (2002) and Radies *et al*. (2004); see also Figs. 1 and 4 in Glennie *et al*. (2002).

Within the Emirates, the supply of dune sand was more complex, being controlled by both the presence or absence of a source for sediments on the floor of the Persian (Arabian) Gulf and changes in the Shamal winds. During glaciations and associated low sea levels, the Gulf was the site of the Tigris-Euphrates river system. The OSL ages of sands in the Emirates, deposited during the last glacial period range widely from 11 to 99 ka (**Fig. 1**); there are a few older ages that must relate to a previous glacial period. Late in the last glaciation, sands were deflated from what is now the southern Gulf area of the Emirates by a 'squeezed' Shamal that blew to the east towards the northern Al Hajar Mountains, rather than south across the Emirates (**Fig. 13**). This resulted in construction of SW to NE trending linear dunes in the north-eastern Emirates; up-wind western parts of the dunes have now been cemented by carbonate grains deflated from exposed older marine sediments. During the last three interglacials the Gulf was flooded by marine waters. Prior to and following full flooding of the Gulf such as now, the clockwise-rotating Shamal transported loose sands over the Abu Dhabi Emirate in a general southward direction, building transverse (barchanoid) dunes over Al Liwa. Farther west, mainly linear dunes extended to the southwest over the main Rub' al Khali basin towards the highlands of Yemen.

The date of the first interglacial marine flooding of the Arabian Gulf is not known, and tectonics of the region dictated when that region first was available to flooding by the sea. OSL ages of dunes in the Emirates extend back as far as 274 ka, during a period of low sea level associated with glaciation 3 (**Fig. 2**), but it is likely that there were previous episodes when marine sediments on the Gulf floor were exposed to deflation and subsequent dune construction; we simply do not have dates to confirm this, partly because of limitations on maximum ages that are imposed by the luminescence dating technique. Dune construction events are reflected in the Al Liwa area by the development of interdune swamps. Wetter interdune conditions probably were caused by a combination of increased rainfall and an associated higher water table. OSL dating suggests that the opposite occurred during glaciations, with lower sea levels inducing greater aridity and lower water tables; these drier conditions are associated with gypsum cementation at the capillary fringe of the water table in interdune areas in Al Liwa. The arid conditions of the past 5 ka, although not associated with a glacial climate, have also resulted in the growth of gypsum in the sands. This series of climatic changes from dry to wet to dry is exemplified locally where foreset dune sands deposited at 12 ka in an interdune area contain plant roots from an overlying swamp during a succeeding wetter period (9-6 ka) that were then cemented by gypsum.

Similar changes from deflation to swamp deposition, followed by arid-type gypsum cementation, have occurred at other localities but at different times in the past. Locally exposed sequences of older aeolian sand deposited at, for example, 40 and 141 ka in the Al Liwa area, are also separated by horizons where the sands were cemented by gypsum (or even by lacustrine limestone farther north over Al Qafa) at or just below the surface. However, OSL dating of the Al Liwa sand sequences shows that water table levels at any given point in time between about 4 and 141 ka may have been different in different places, depending on the local distribution of dunes and sabkhas. Sabkhas formed between dry aeolian sand horizons dated 35 ka apart but separated vertically by only 2 m. Other sands separated by gypsum were deposited only 2000 years apart. The OSL ages indicate times of active sand deposition that were influenced by the Shamal irrespective of whether conditions were "glacial" or "interglacial" from as far back as 291 ka (early Glacial 3) and certainly by 141 ka (maximum of Glacial 2) to 86 ka (early Glacial 1) right to the present. However, the presence of these gypsum horizons may only be related to local and short-term changes in the level of groundwater at a location, which may not be related to glacial cycles.

With a general lack of any other means of dating wind-blown sand, the OSL technique has been invaluable for our understanding of the many ways in which the desert of southeastern Arabia developed. Although some of our gaps in the time span of dune deposition are due to incomplete sampling, a beginning has been made in unravelling the timing of these processes and their relationship to global climates. More studies in the future should help us understand the complexity of desert processes and hence refine some of the interpretations presented here.

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