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The environmental history and present condition of Saudi Arabia's northern sand seas

by

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THE ENVIRONMENTAL HISTORY AND PRESENT CONDITION OF THE NORTHERN SAND SEAS OF SAUDI ARABIA

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ABSTRACT

Saudi Arabia's northern sand seas are composed dominantly of stable dune systems, even though the modern climate is arid. The stable dunes are large and suport a sparse semidesert vegetation. Active dunes are small and commonly confined to the crests of stable dunes; they comprise less than 5 percent of the dunes in the sand seas. Both the stability of the major dune systems and the small percentage of active dunes in the modern environment indicate a significant decrease in the average velocity and frequency of sand-moving winds since the time of stable-dune deposition. Comparison of modern wind directions with dune trends indicates that southwesterly winds responsible for dune formation in the southern and western An Nafud sand sea and in Nafud Urayq are no longer prevailing winds.

Lake deposits are locally interbedded with deposits of eolian sand and in the lee of stable dunes. Radiocarbon dating of calcareous lake deposits defines at least two episodes of moisture-effective climate and minimal eolian activity: between about 32,000 and 24,000 B.P., just before the onset of the last worldwide glacial stade of the Pleistocene, and during the Holocene between about 8,500 and 5,000 B.P. One lake deposit is more than 38,000 years old and may have been deposited during an earlier pluvial episode about 85,000 to 70,000 B.P. Pollen extracted from these lake deposits indicates that vegetation during late Pleistocene and Holocene pluvial episodes was similar to the present semidesert vegetation; however, the density of shrubs and grasses on the dunes was greater.

The main dune systems overlie the 32,000 to 24,000-year-old lake deposits, whereas the Holocene lakebeds are found in modern interdunal environments, usually at the base of stable dunes. The main dune systems probably formed between 24,000 and 8,500 B.P., during the last episode of worldwide cold temperatures. Increased windiness at this time is also recorded in the world's oceans and in both polar ice caps.

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Eolian sand below the older lake deposits was deposited before 32,000 B.P., and circumstantial evidence indicates that the sand seas may have begun to form as early as late Miocene. In the An Nafud, remnants of a middle Tertiary(?) surface suggest that the original sediment source for the An Nafud may have been the weathered sandstones that underlie this surface.

After lacustrine deposition ceased in middle Holocene time, eolian activity increased slightly. Deflation on windward dune slopes has produced deflation scoops, which look like inverted deltas. The modern active dunes are composed of sand deflated from the stable dunes.

INTRODUCTION

Large sandy deserts, commonly called sand seas or ergs, are one of the most prominent physiographic features of the Arabian Peninsula. Eolian sand covers about 770,000 km^2 or almost one-third of the peninsula's land surface. Nearly 90 percent of this sand is contained in three sand seas: the An Nafud (also called the Great Nafud), located in north-central Saudi Arabia; the Rub al Khali, located in southern and southeastern Arabia; and the Ad Dahna, a 1200-km-long, curvilinear belt of dunes that connects the first two sand seas (see inset map, fig. 1). Together these sand seas form the largest continuous body of eolian sand in the world (Wilson, 1973).

The sand seas are one of the youngest physiographic features of the Arabian landscape. Both Brown (1960) and Holm (1960) suggested that formation of these large sand bodies was related to a dramatic increase in aridity that took place near the end of Tertiary or during Quaternary time. McClure (1978) argued, however, that the Rub al Khali was primarily an alluvial basin throughout most of the Quaternary and that dune formation took place only in late Pleistocene time. The first detailed geologic and environmental information collected from the sand seas in northern Saudi Arabia is presented herein.

Diatomite of probable economic quality was deposited in a freshwater lake in the western An Nafud during a climatic interval characterized by greater effective moisture than exists at present (Whitney, 1982; Garrard and others, in press). In order to understand the changes of climate responsible for lake-forming episodes in the Arabian sand seas, this report concentrates on describing the environmental history of Arabia's northern sand deserts. A knowledge of environmental history of the sand seas is also important because it can be applied to many areas of northern and central Arabia where datable Quaternary deposits are lacking.

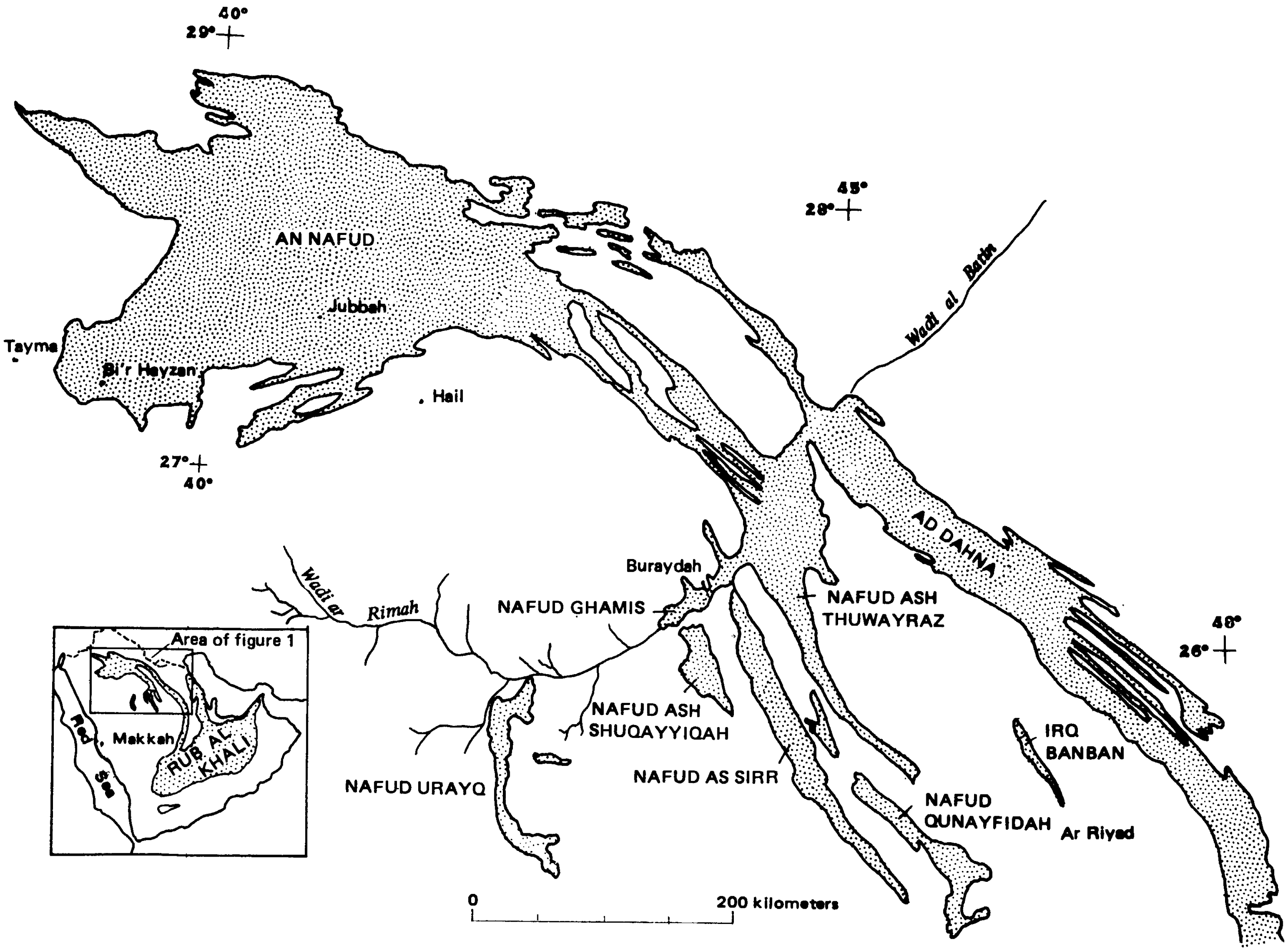


Figure 1.--Map showing distribution of Saudi Arabia's northern sand seas (shaded areas delineate major deposits of eolian sand).

The sand seas on the Arabian Peninsula are normally considered to be composed of active, or moving, dune systems, and, although the An Nafud, Ad Dahna, and Rub al Khali deserts are always included in compilations of the world's active sand seas (for example, Wilson, 1973), there is very little written description of these deserts. Information on the present environment of the northern Arabian sand seas was collected to assess the present geomorphic activity in these dune fields in relation to the modern arid climate and to compare past environments in the sand seas with the modern environment in an attempt to determine how much climatic change has occurred. Wind and rainfall data were supplied by the Saudi Arabian Ministry of Agriculture and Water, Ar Riyad, and were compiled and plotted by Gary Selner and Dennis McMacken (U.S. Geological Survey (USGS) Computer Section). The vegetation in the An Nafud has been described by Erhard Schulz. (unpublished data).

Most of the fieldwork for this study was done in the An Nafud and in Nafud Urayq (fig. 1), and reconnaissance trips into Nafud as Sirr and several different locations in the Ad Dahna have convinced the authors that the sand deserts north of the latitude of Ar Riyad (lat 24°42' N.) have a similar environmental history. Additional lake deposits and sand samples for this study were contributed by James C. Cole (USGS) and John Murdoch (Saudia Special Flights Services).

The work on which this report is based was performed in accordance with an agreement between the USGS and the Saudi Arabian Ministry for Petroleum and Mineral Resources.

PHYSICAL SETTING AND SEDIMENT SOURCES OF THE SAND SEAS

Although large sand seas are found in many topographic basins (Wilson, 1973; Fryberger and Ahlbrandt, 1979), the An Nafud overlies a nearly flat plain that dips gently northwest. This observation was first made more than 100 years ago by the Blunts, who crossed the An Nafud on horseback from Jouf to Hail (Blunt, 1881). Recently, D. J. Faulkender (USGS, written commun., 1982) completed both north-south and east-west topographic surveys across the An Nafud and proved that it does not lie within a topographic basin.

The physical setting of the sand seas is better explained by both the positions and interactions of regional wind regimes and the location of an abundant sediment supply rather than by topography. Broad areas of Paleozoic sandstones are exposed west of the An Nafud (fig. 2) and are the major sources of sand for that sand sea (Holm, 1960; Faulkender, written commun., 1982). These sandstones consist mainly of crossbedded, moderately to well-sorted alluvial and eolian sands and many include thinner units of fluvial gravel and siltstone (Powers and others, 1966). The cement in most of these sandstones is carbonate and, at most outcrops examined, is severely leached. In fact, when the desert-varnish coating of most outcrops is breached with a geologic pick, the sandstone disintegrates to loose sand. Downwind of the exposed Paleozoic sandstones, both grain size and percentage of heavy minerals consistently decrease and sorting increases in the An Nafud sands (Faulkender, written commun., 1982).

Dune trends have been compiled by using Landsat imagery and are shown on figure 2 in the patterns of different dune types. These trends represent the resultant wind direction or directions responsible for formation of the dunes. Winds responsible for the massive dunes in the An Nafud came primarily from the southwest, west, and northwest. Dunes in the western and southern An Nafud formed as a result of winds from one westerly direction, whereas linear dunes in the central and northern An Nafud formed as a result of both northwesterly and southwesterly winds. The linear dunes at the eastern edge of the An Nafud strike more to the south, a trend that reflects the influence of northerly and northeasterly winds. Large fields of star dunes in the eastern An Nafud and in parts of the Ad Dahna signify the importance of multiple wind directions.

The windy season in northern Saudi Arabia extends from late fall to late spring. Strong westerly winds are probably associated with the shift of the subtropical jet stream from its summer position over the Mediterranean and Caspian Seas to its winter position over northern Arabia (Beaumont and others, 1976). However, it should be emphasized that the climatology of Saudi Arabia is poorly known at this time.

The sweep of these strong westerly winds over large areas of poorly consolidated sandstones is the primary reason for the existence of the An Nafud and the northern Ad Dahna sand seas. Although similar conditions of aridity exist over all of Saudi Arabia, except for the high southwestern part, large areas of sand dunes did not accumulate in these regions chiefly because of a lack of an abundant sediment supply. The vast peneplains of central Saudi Arabia are underlain by Precambrian igneous and metamorphic rocks (the Arabian Shield), whereas much of eastern Arabia is underlain by carbonate rocks. Because wind data for many regions of Saudi Arabia are unavailable at the present time, it is difficult to determine if the An Nafud region is significantly windier than other areas. However, our personal observations in many

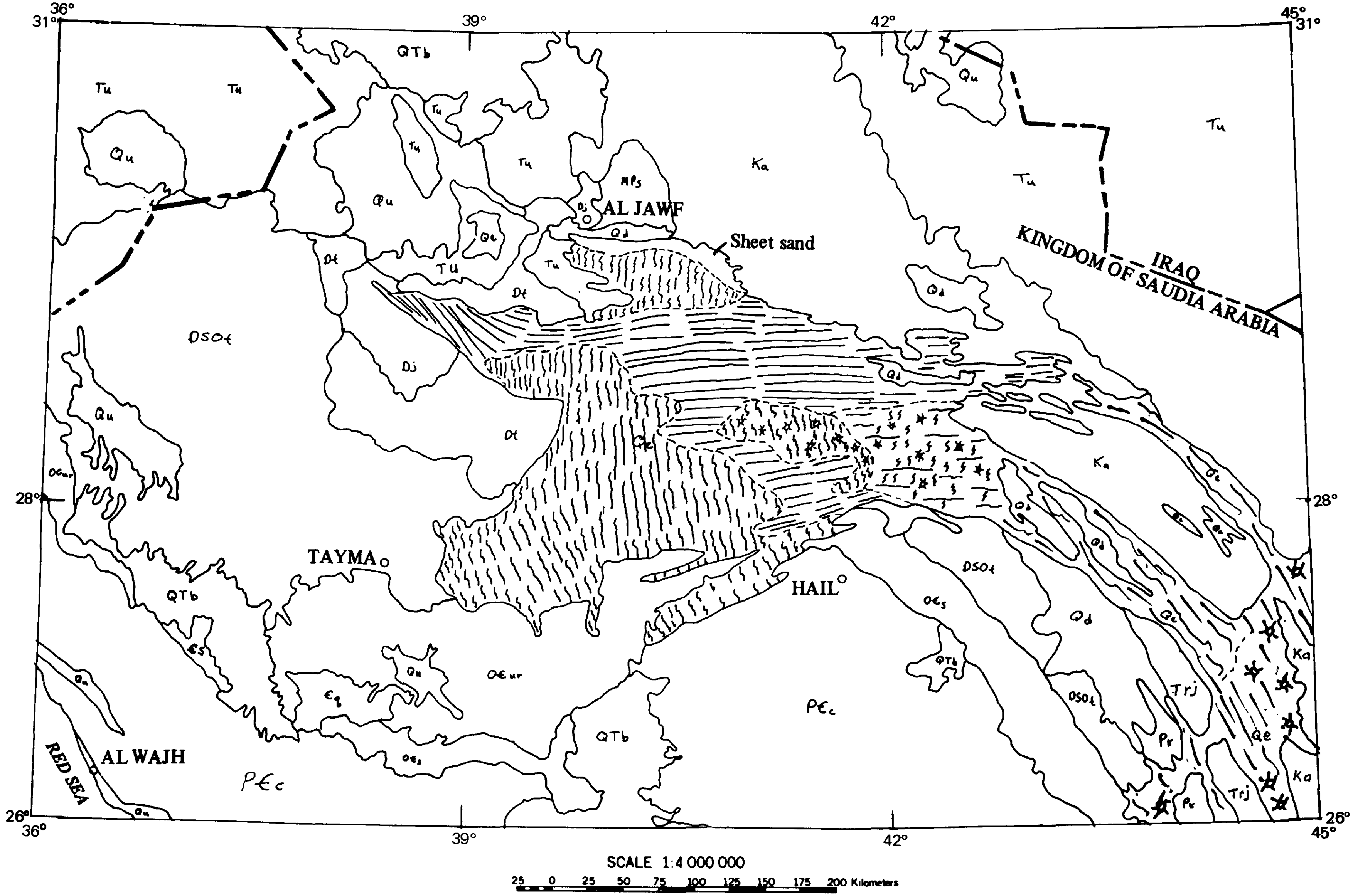


Figure 2.--Map showing generalized geology of the An Nafud region, with emphasis on distribution of Paleozoic sandstones and classification of dunes. Modified from U.S. Geological Survey and Arabian American Oil Company (1963).

EXPLANATION

CENOZOIC

Qs	Eolian sand (also shown as individual dune type)
Qu	Alluvium and related surficial deposits
Qd	Duricrust
QTb	Basalt
Tu	Undifferentiated sandstone, marl, and limestone formations

MESOZOIC

Ka	Aruma Formation
Trj	Jilh Formation
Pk	Khuff Formation
MPs	Sakaka Sandstone

PALEOZOIC

Dj	Jauf Formation
Dt	Tawil Member of the Tabuk Formation
DSOt	Lower Tabuk Formation
O€s	Saq Sandstone
O€ur	Umm Sahm and Ram Sandstones
€q	Quweira Sandstone
€s	Siq Sandstone

P€c	Precambrian complex: Igneous, metavolcanic, and metasedimentary rocks

Dune types

- Sheet sand
- Transverse and barchanoid ridges
- Linear
- Linear and star
- Complex: Includes linear, transverse, star, domal
- Contact
- Dune-form transition zone
- International border

Figure 2--Continued

regions of the Kingdom suggest that areas of large sand accumulations are not now significantly windier than areas of exposed bedrock.

Topography plays an important role in the physical setting of the Ad Dahna and several of the smaller sand seas south of Buraydah (fig. 1). Subparallel belts of sand composed mainly of complex longitudinal dunes emerge from the eastern edge of the An Nafud, near the 43rd meridian. Not only are the winds from different directions in this region, but the topography changes from a nearly flat plain to a gentle ridge-and-valley landscape formed by the scarps and dip slopes of the Phanerozoic sedimentary rocks that overlap the eastern edge of the Arabian Shield (fig. 2). Some of the small, linear sand seas are confined between bedrock scarps; others, such as the Ad Dahna, are subparallel to this arcuate outcrop pattern. The Ad Dahna is less than 30 km wide in some places and appears to connect the An Nafud with the Rub al Khali, over a path of 1,200 km.

There are multiple sources of sediment for the Ad Dahna and smaller, elongated sand seas. The An Nafud supplies sand to the northerly belts of dunes; however, the percentage of An Nafud source sands in these arcuate belts probably decreases to the south. This decrease is compensated for by local sources of sand, including both alluvium and the easily weathered, sandy Paleozoic and Mesozoic formations overlying the eastern edge of the Arabian Shield. Primary alluvial sources are the terrace and flood-plain deposits of Wadi ar Rimah and its tributaries. In fact, part of the Wadi ar Rimah valley east of Buraydah is buried by eolian sand that appears to be derived from the An Nafud. The valley northeast of these dunes is called Wadi al Batin.

Nafud Urayq (fig. 1) is the only sand sea in northern Arabia that lies completely on the Arabian Shield. This north-trending sand sea is roughly confined by several isolated mountain masses (jabals) on the east, by Wadi al Jaris on the west, and by Wadi ar Rimah on the north. Sediments are supplied to this sand sea entirely by alluvial sources that include the two confining ephemeral streams and pediments and fans of the nearby hills.

AGE AND ORIGIN OF THE SAND SEAS

Very little evidence regarding the age and origin of the sand seas can be found within the sand seas themselves. For the most part, the An Nafud is a "choked" sand sea; in other words, over most of the sand sea the dunes are either closely spaced or overlap each other. It is rare to be able to see and study the surface beneath the sands except along the edges and in the eastern part of the An Nafud. The substratum is commonly exposed only in sand desert areas occupied by large star dunes. At most localities visited, the substratum is exposed bedrock, part of one of many peneplained surfaces on the Arabian Peninsula. Near the edges of the Ad Dahna and An Nafud, patches of Quaternary(?) duricrust underlie some dunes (Powers and others, 1966).

Near the southwestern edge of the An Nafud, at approximately lat 27°34' N., long 37°50' E., two exposures suggest the terrain beneath the sand sea was at one time capped by extensive residual deposits. At one of these exposures, a small knoll that rises about 10 m above the general sandstone surface is exposed in the lee of the westernmost barchanoid dune of the southwestern An Nafud. The knoll is capped by a highly resistant deposit of ferricrete (an iron duricrust) that overlies and grades into an iron-rich silcrete (a siliceous duricrust). This sequence is interpreted to be part of a former lateritic weathering profile that developed on a surface underlain by Paleozoic sandstones.

Although this former surface cannot be isotopically dated, the high degree of laterite formation suggests that it correlates with similar lateritic residual deposits preserved at Jabal Umm Himar near At Taif (Madden and others, 1979/1981) and below the volcanic flows in the As Sarat mountains southeast of Khamis Mushayt (Overstreet and others, 1977). In fact, the iron-rich silcretes (dark-red cherts) from the An Nafud and Jabal Umm Himar are visually indistinguishable (D. L. Schmidt, USGS, written commun., 1982). The eroded laterites at Jabal Umm Himar and As Sarat are overlain by middle or late Oligocene basalt flows, a relationship that implies that laterite formation probably began in the Eocene and continued into the early Oligocene. It seems likely that these residual deposits formed during the well-known world-wide Eocene interval of laterite formation. Because thick laterite or saprolite deposits of a later Tertiary age are unknown in Saudi Arabia, the lateritic profile preserved in the An Nafud is probably no younger than late Eocene or early Oligocene. If this middle Tertiary age is correct, then this residual deposit and surface have been subject to erosion for more than 35 million years because the present overlying eolian and lacustrine deposits are late Quaternary in age (Whitney, 1982). In light of this long erosional interval, it is difficult to determine when the first sand seas began to form.

The residual deposit of probable middle Tertiary age also has a significant implication with regard to the origin of the An Nafud's original sediment supply. The sandstone below the ferricrete and silcrete deposits is almost completely leached of interstitial cement. The weathered sandstone has been reduced to a thick accumulation of sand having no grain-to-grain cohesion and thus provides a ready-made supply of sand for the sand sea. After the overlying residual deposits were breached by erosional processes, an enormous amount of sediment became available for wind transportation. We hypothesize that the leached sandstone at the base of the middle Tertiary surface was the initial and primary sediment source for both the An Nafud and northern Ad Dahna sand seas.

The best evidence for the age of the sand seas comes not from the Arabian Peninsula but from the bottom of the world's oceans. Over the past decade, numerous sedimentological and paleoclimatologic studies have been made on deep-sea cores obtained from nearly every ocean and sea on Earth. Studies of these cores are invaluable to understanding world paleoclimate history because many cores record nearly continuous deposition during long time intervals. Some cores obtained as part of the Deep-Sea Drilling Project are as old as late Mesozoic.

Deep-sea core studies are important in understanding the activity of subtropical sand seas because the accumulation rate of eolian-derived sediments in these cores varies with time. This variation in sedimentation rates reflects both the availability of source sediments from arid and semiarid regions and the intensity of atmospheric circulation. Leinen and Heath (1981) described a core (LL44-CPC3) from the north-central Pacific Ocean that records eolian deposition for the last 70 million years. In this core, low accumulation rates are characteristic of much of Tertiary time until 25 million years B.P. and reflect temperate and humid world climates during early and middle Tertiary time. Eolian sedimentation gradually increased between 25 and 7 million years B.P., probably as a result of the northerly drift of this site away from the region of the equatorial winds and into the path of the westerlies. Between 10 and 3 million years B.P., eolian sedimentation rates increased fourfold, probably as a result of climatic changes and increased wind intensities. Eolian sedimentation rates increased dramatically about 3 million years ago, coinciding with the onset of glaciation in the Northern Hemisphere (Shackleton and Opdyke, 1977; Duplessy, 1982). Eolian sedimentation rates in the core were highest during the last million years; these high rates suggest that the last million years of Earth history includes the most intense periods of extreme aridity and vigorous wind activity since Mesozoic times.

The fourfold increase in eolian sedimentation rates recorded in the Pacific Ocean in late Miocene time correlates with evidence of increased aridity in North Africa. The presence of Miocene turbidites off the west coast of Africa suggests strong eolian activity on the continent (Sarnthein and Diester-Haass, 1977), and the influence of coastal upwelling has been detected in late Miocene sediments off Africa (Diester-Haass and Schrader, 1979). This upwelling resulted primarily from strong offshore trade winds. Although upwelling was active in these areas during late Miocene time as well as during Quaternary glacial episodes, it is not active at the present time. This lack of upwelling suggests that aridity in North Africa is probably less extreme, especially in terms of windiness, at present than it was during the earlier episodes of upwelling. Siesser (1978) showed that upwelling in the Bengula Current off southwest Africa did not become intense until about late Miocene time, and he believes that the influx of cold water into the current in late Miocene time may have been responsible for the desiccation of the Namib desert. Thus, nearly all paleoclimatic information derived from studies on marine cores from every ocean strongly implies that late Miocene time may have been more arid and (or) experienced greater wind intensities than the present time. Late Miocene time was also a time of growth of a large marine ice sheet around Antarctica (Drewry, 1978).

Pollen studies in north and central Africa by Maley (1980) show that present-day xerophytic vegetation was already in place during Pliocene time. Maley believed that the desiccation of the Sahara began in late Miocene time and is related to the formation of glaciers in the Northern Hemisphere at that time.

Because the Arabian Peninsula is in the same climate belt as the Sahara, most of the Peninsula also was probably arid during late Miocene time. Unfortunately, deposits of late Miocene age have been found only along the coastal areas of Arabia, and most of the interior of Arabia was subject to erosional processes at that time. An arid climate, as characterized by high evaporation rates and little runoff, is implied for the Arabian Peninsula by the accumulation of thick beds of salt in the Red Sea basin (Gillman, 1968; Stoffers and Ross, 1977). During the same arid interval, the Mediterranean Sea became a desiccated deep basin (Hsu and others, 1973). Miocene paleoenvironmental data are available from Saudi Arabia in the form of palynological and paleontological data on near-shore inland and coastal deposits along the Arabian Gulf. Whybrow and McClure (1981) believe that a savannah grassland existed in Arabia during late Miocene time as the result of a dry, tropical to subtropical climate and that arid conditions did not develope until sometime during Quaternary time. C. T. Madden (USGS written commun., 1982), however, interpreted the same rocks as having been deposited in a hot, arid to semiarid climate. It is also possible that some coastal areas were subtropical and that the interior was arid. This situation does exist at present: the southwestern coast of Arabia receives moisture from the monsoons, whereas the interior, less than 200 km from the coast, is arid. In any case, regional paleoclimate data strongly suggest that the late Miocene climate in the belt of subtropical deserts, including the sand seas of northern Saudi Arabia, was arid and that during late Miocene time eolian sediments were deposited in the ocean basins at higher accumulation rates than at any previous time during Tertiary. These paleoclimate data combined with the fact that at least part of the An Nafud overlies a surface of middle Tertiary age suggest that incipient sand seas may have formed in northern Saudi Arabia as early as late Miocene time.

The growth of the sand seas to their present size probably occurred gradually from late Miocene until late Pleistocene times; such a growth reflects the worldwide climatic trend of decreasing temperature and increasing continental ice volume. The growth was episodic not continuous. Large, stable dunes overlying Quaternary(?) duricrust at the edge of the An Nafud suggest that these dunes on the periphery of the sand seas are younger additions to an older "core" sand sea. Soils preserved under Pliocene basalt flows in western Saudi Arabia provide evidence that the climate was not continuously arid, although Pliocene aridity has been suggested for regions of the Sahara (Maley, 1980). During more humid periods in late Tertiary time, the sand seas were stabilized and inactive. Significant climatic cooling in the Mediterranean commenced between 3.2 and 3.0 million years ago and probably coincided with the increase in permanent Northern Hemisphere ice cover at that time (Keigwin and Thunell, 1979). Eolian accumulation rates in the world's ocean basins greatly increased (Leinen and Heath, 1981; Shackleton and Opdyke, 1977); such an increase undoubtedly reflected the growth and expansion of subtropical deserts, including the sand seas of Arabia. In the next section we shall examine the Quaternary deposits in Arabia's northern sand seas in an attempt to reconstruct the environmental responses in the sand deserts to the last significant climatic changes that affected Arabia.

QUATERNARY EOLIAN AND LACUSTRINE DEPOSITS

Dune systems

The An Nafud is mainly composed of longitudinal, transverse, and star dunes (fig. 2). The predominant dunes in the western and southern An Nafud are large barchanoid ("barchan-like") dunes (fig. 3), which are frequently linked to form long transverse dunes. From the air, these transverse dunes look similar to the serrated edge of a

Figure 3.--Photograph showing typical barchanoid dunes, south-central An Nafud. Note vegetation cover on dunes, including on slip faces. Small active dunes are on the crests of large, stable, and vegetated dunes. A Holocene pan deposit in the lee of the largest dune.

kitchen knife because the crescentic slip faces are separated by the pointed horns of the barchan dunes. Both the transverse and barchanoid dunes formed as a result of a nearly unidirectional wind from the southwest and west-southwest. In the northern, central, and northeastern An Nafud, most dunes are longitudinal; they are, however, a somewhat unusual variant of this type of linear dune. Instead of having a roughly triangular shape in cross section, as do the common seif dunes found in the Rub al Khali and many sand seas of the Sahara, the An Nafud linear dunes are low, broad ridges having a chain of separated, crescent slip faces on the northern side of each ridge. An example of this dune type is shown in Holm (1960, fig. 3). These unique longitudinal dunes probably formed under a bimodal wind regime of southwesterly and northwesterly winds. The crescent slipfaces on the northern side of the dune ridge imply that the southwesterly winds were either dominant over the northwesterly winds for long periods of time or were the last major sand-moving wind to affect the form of these dunes.

In the eastern An Nafud, longitudinal dunes become smaller in size and more widely spaced as the dunes begin to trend to the south. The shape of these south-trending dunes more closely approaches the traditional shape of longitudinal dunes. Large star dunes (also called massif dunes or draa) are concentrated in the southeastern part of the An Nafud. Individual star dunes are as much as 200 m high and have between two and six arms of active sand that project from a stable base. These arms rotate around the base in response to local shifts in wind direction and indicate that this part of the An Nafud is influenced by winds from several directions.

The Ad Dahna is an arcuate belt of parallel longitudinal dunes, locally called "irqs." In the Ad Dahna, ridges and troughs are broad and create a subdued topography that is easy to drive across. Although dunes in the Ad Dahna are similar in size and shape to longitudinal dunes in the central An Nafud, they are more widely spaced and lack local crescent slip faces. The westerly winds that dominate dune formation in the An Nafud have less influence in the Ad Dahna. The linear dunes are deflected more to the south in response to northerly winds, locally called the "shamal", that originate in the Mesopotamian region.

In the smaller sand seas west of the Ad Dahna, dune forms are generally complex as a result of the interaction between winds from multiple directions and the scarp-and-dip slope topography of the regional bedrock patterns. Large (as high as 150 m) cone-shaped dunes are found in Nafud as Sirr (Holm, 1953). These circular dunes do not have slip faces and lack the well-defined arms of a star dune. In Nafud Urayk, the predominance of tranverse and barchanoid dunes indicates a dominance of southerly winds at the time the larger dunes were formed.

Active versus stable dunes

Earlier descriptions of the northern Arabian sand seas were based on studies of aerial photographs or Landsat imagery (Holm, 1960; Breed and others, 1979; Fryberger, 1979; Fryberger and Ahlbrandt, 1979). These studies correctly assessed the wind directions responsible for the major dune systems in the sand seas; however, two important characteristics of the sand seas were not detected. First, the major dune systems of Saudi Arabia's sand seas have stabilized; that is, the large dunes that compose more than 95 percent of the sand seas are not active in the present arid climate. This observation is especially important because the An Nafud has been described, based upon published meteorological data, as possessing a high-energy wind environment that has the highest potential for sand movement of any of the world's sand deserts (Fryberger, 1979; Fryberger and Ahlbrandt, 1979). Second, a superimposed set of active dunes overlies the large, stable dunes. Except in a few locations, this active set of dunes is usually limited in extent to the crests of inactive dunes (fig. 3). The active dunes are too small to be recognized by using Landsat imagery at present state of image resolution, but they can be seen on aerial photographs having scales of 1:60,000 or larger. Landsat imagery therefore should be used with caution when describing the present condition of large sand deserts.

The large, major dunes (including slip faces) of the northern sand seas are partially stabilized by vegetation (fig. 3) and commonly have a surface lag of coarse sand and a few small pebbles. This lag protects the shape of the dune form from deflation by winds of low velocities. In most locations visited by us in the sand seas, we dug small pits to a depth of 50 to 60 cm. Lag deposits varied from about 5 to 35 cm thick, and both the lag and underlying sand reacted strongly to the HCL test for the presence of calcium carbonate. The presence of a significant amount of calcium carbonate in these stable dunes implies that at least one episode of soil-forming processes has occurred in these dunes. Commonly, a loose tangle of dead and living rootlets was found in these pits, and the amount of organic debris seemed to vary with the position of the pit on the dune. Although no visible soil horizons were seen in the pits, a decrease in the relative amount of carbonate with depth was noted in several pits. In most of stable dunes examined, pit walls held their vertical shape, whereas in most of the smaller, active dunes it was impossible to dig a pit deeper than 10 or 15 cm because the walls would immediately collapse. In the active dunes sampled, calcium carbonate was either absent or only present in trace amounts. The active dunes also generally did not have a coarse lag sand, and where the lag was found it was usually less than a centimeter thick. The presence of an armored lag over the principal dunes of the sand seas indicates that eolian winnowing has occurred over some unknown, but significant, length of time.

Active dunes are composed mostly of fine-grained sand, stable dunes of medium-grained sand. Active dune sands are better sorted than stable dune sands. The larger grain size of the stable dune sands implies that the winds responsible for their deposition probably had greater velocities than present-day winds. The formation of coarse lag sands on the stable dunes implies that the winds that have blown since formation of the stable dunes have been capable only of winnowing out finer sizes of sand. Indeed, this winnowing process undoubtedly produces a major source of the sand for the present active dunes. The better sorting of the active sands reflects a small variety of sand sizes in these dunes. The greater variety of sand sizes in stable dunes results from both the presence of larger clasts and in situ weathering in the dunes. Although small percentages of silt and clay were present in stable dune sands, neither were present in active dune sand samples.

The color difference between active and stable dune sands is pronounced. Blunt (1881) described the colors of the An Nafud sand sea as "rhubarb and magnesia". This vivid description refers to the strong reddish cast of stable dune sands when seen in low light, compared with the bright pale-white color reflected by active dune sands in bright sunlight. Aside from the effect of light, the color of dune sand is dependent on many factors, such as the composition of the source sediments, the distance transported, and the length of time the sand has been subjected to soil processes. Although the hues and chromas of dune sands differ from place to place, there is also always a color contrast between active and stable sands at each location. For example, in the central An Nafud, stable dunes sands have a Musell color of yellowish red (5 YR 6/8 to 5 YR 5/8), whereas active sands are reddish yellow to yellow (7.5 YR 8/6 to 10 YR 8/6). The red hue of stable dune sand most likely results from the oxidation of iron-rich minerals in the dunes and the addition of iron-rich clay minerals that infiltrate the sands by precipitation and dustfall. Active sands have partly lost this red hue by grain-to-grain abrasion during eolian transportation.

Active dunes are normally found on the crests of stable longitudinal and transverse dunes. Most are less than 10 m high, whereas the large, stable dunes are commonly more than 100 m high. Patches of active, linear dunes exist at some edges and in the central region of the An Nafud. Active linear dunes in the central An Nafud appear to be moving across the larger, stable dunes. In the southern Ad Dahna (approximately lat 21°15" N., long 47°33" E.), active barchan dunes have been observed moving across stable longitudinal dunes. In the Nafud as Sirr, small tranverse dunes are presently moving across the domal dunes, and the arms of most star dunes in the region are active. The percentage of land area occupied by active dunes in the sand seas ranges from 0 to 20 percent, depending upon local wind conditions; however, the average percentage in the entire region is only 3 to 5 percent.

The significant differences in texture, color, dune size, and distribution between the present-day active dunes and the partly vegetated stable dunes indicate a dramatic difference between the wind regimes responsible for the two dune systems. The older, stable dunes were clearly deposited under a more vigorous wind regime than exists at present. Wind velocities of individual wind storms must have been consistently higher to account for both the larger average grain size in the stable dunes and the vast amount of material moved. In the section on the modern condition of the sand seas, we shall also examine the possibility of shifting wind directions since deposition of the stable dunes.

An absolute determination of the time of stable dune deposition is difficult. The thermoluminescence dating technique has been used with some success on eolian materials; however, the methodology is still experimental (Wintle and Huntley, 1982). Relative age dating of stable dunes can be accomplished by examining both the soil development in the dunes and the stratigraphic relationship between dune sand and datable deposits. At nearly all localities visited, stable dunes have been subjected to a greater degree of *in situ* weathering and soil-forming processes than active dunes. These differences indicate that stable dunes are older and have been subjected to climate changes since dune deposition. In order to initiate weathering and to deposit calcium carbonate in the dunes, the climate must have been less windy and effective moisture must have been available. The presence of active dunes overlying and moving across stable dunes indicates that the climate has once again shifted in the direction of greater aridity. Fortunately, remnants of isotopically datable lake deposits are scattered throughout the sand seas and allow us to bracket those periods of time when eolian activity dominated the sand seas.

Pleistocene and Holocene lake deposits

Dry, remnant lake deposits were found in all of the sand seas visited by the authors in northern Arabia. Stratigraphically, these lake deposits are normally found in two situations. Small pan deposits are commonly found in the lee of large barchanoid dunes (fig. 3) and at the base of some star and domal dunes. These deposits are sediments laid down in ephemeral stands of water in small, natural basins, similar to miniature playas. They are important because they formed after the now-stable dunes were emplaced in their present position. Remnant lake deposits are also exposed below stable dunes and some are sandwiched between units of eolian sand within stable dunes. Typical stratigraphic settings of these lake deposits are shown in figure 4.

Lake deposits exposed near the base of stable dunes or interfingered with eolian dune sand are thin, ranging from 0.3 to 3.0 m thick. The one known exception is near the village of Jubbah in the south-central An Nafud, where a large lake formed in a basin that lies in the wind shadow of a large isolated mountain (locally referred to as a "jabal"). In this lake deposit, at least 12 m of brown clay are overlain by an even greater thickness of calcareous and diatomaceous lacustrine deposits (Garrard and others, in press).

Normally, the thin lake deposits within the dunes are composed of calcium carbonate, which can be dated by using radiocarbon analysis; however, some lake deposits or layers within carbonate lake beds are composed of diatomite (Whitney, 1982). Thin interbeds of gypsiferous sand, salt, and eolian sand are uncommon. Wind erosion since deposition of the lake bed appears to have destroyed so much of the soft lakebed material that reconstruction of the original lake depths and areal extents is almost impossible.

Except where remnant lake deposits are exposed in interdunal areas (for example, see cross section A in fig. 4), they are commonly sandwiched between layers of eolian sand. The overlying dune sand is light red or yellowish red, partly vegetated, and stable. The sand underlying the lake deposits is generally white and may be either unconsolidated or semiconsolidated. The white color of this underlying sand bears a striking resemblance to the basic color of the exposed Paleozoic sandstones that are the primary sediment source for the dunes. It is possible that at some localities this white sand is mostly weathered sandstone; the exposed sand below the remnant Tertiary surface in the western An Nafud is one example. In most instances, however, the underlying white sand is considered to be eolian in origin

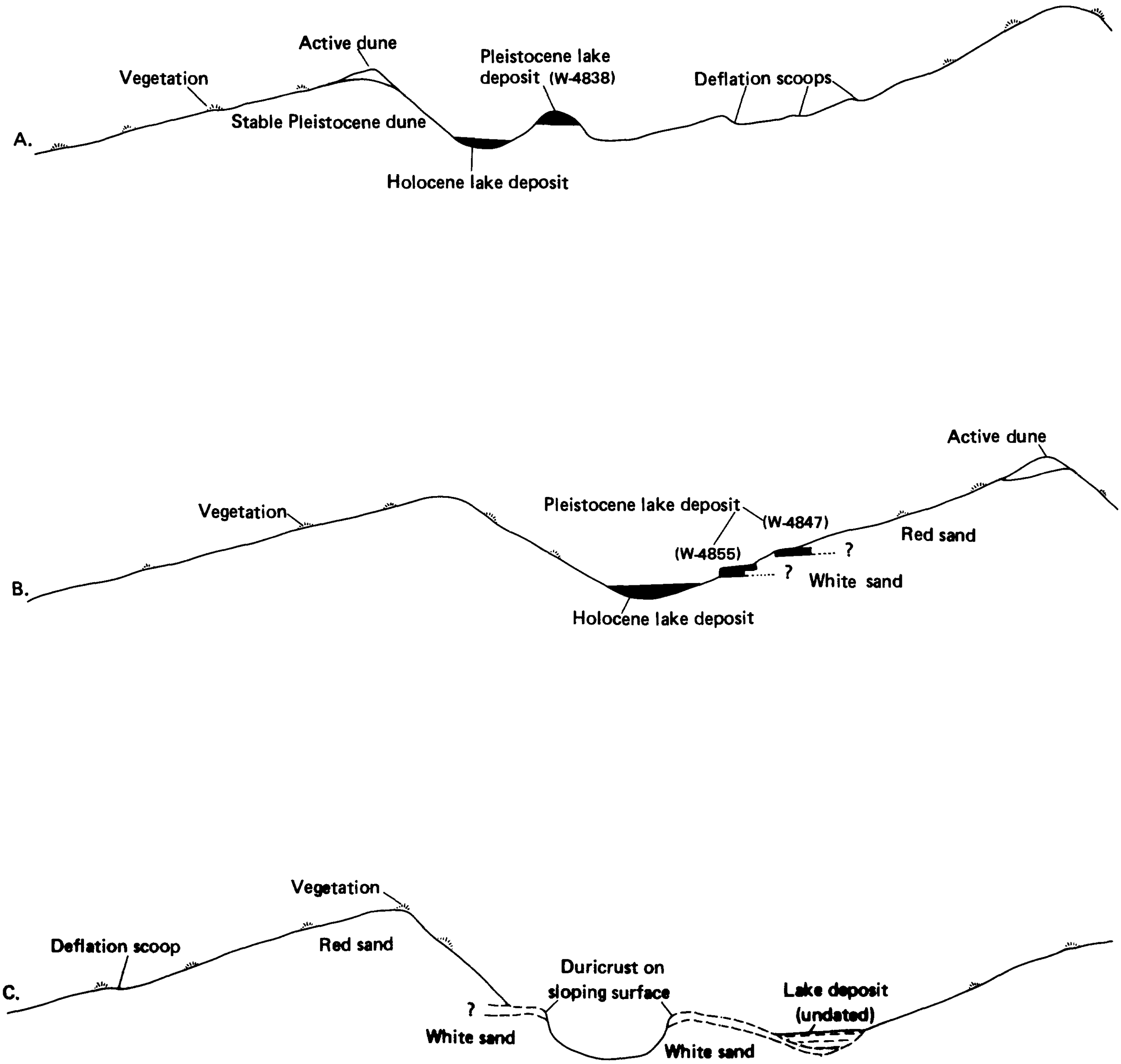


Figure 4,--Schematic cross sections in the An Nafud illustrating the relationship between Quaternary lake deposits and both active and stable sand dunes. Radiocarbon-dated lake deposits are identified by laboratory numbers in parentheses (see table 1).

because white sand is found below lake deposits in localities where the underlying bedrock is not sandstone. Furthermore, at localities where two lake deposits are superimposed (see cross section B, fig. 4), layers of white sand separate the lake deposits. The white color probably results from the addition of calcium carbonate onto and (or) the leaching of oxidized iron from the sand grains during the lake-forming intervals of fluctuating high water table.

A third stratigraphic occurrence of remnant lake deposits is shown in cross section C (fig. 4). In this type of occurrence a lake deposit sometimes overlies a thin duricrust and both of these deposits are overlain by stable dune sand. The duricrust is an indurated carbonate and is more resistant to erosion than the soft lake deposit. At most localities, the duricrust is cracked and sometimes appears to be a lag of limestone fragments. An unusual aspect of the duricrust is that it perfectly contours the underlying eolian sand, including sloping surfaces, to define a former land surface.

The origin of the duricrust is unclear. Calcium carbonate may have accumulated at the former land surface through evaporation of carbonate-rich ground water, or carbonate may have been deposited in the more typical manner of downward migration by infiltrating runoff. If the latter process has occurred, then the upper part of the soil profile must have been removed during a subsequent episode of eolian erosion.

Duricrust in similar stratigraphic settings has also been observed in the Rub al Khali. Radiocarbon analysis of two samples yielded ages of 27,090±320 B.P. and 30,500±920 B.P. (Whitney, unpublished data). These ages indicate that the land surface was stable in the Rub al Khali during the last interstade of the Pleistocene. (An interstade refers to both the time and associated "warm climate" between two glacial advances (known as stades).) The interstade occurred between the last two advances of the Würm (Euorpean, Asian, and African nomenclature) or Wisconsinan (American nomenclature) glacial stage. It is likely that the preserved duricrusts in the northern sand seas also formed during the last interstade of the Würm.

Nine remnant lake deposits were isotopically dated by using radiocarbon techniques (table 1). All but one of these samples was collected in An Nafud and Nafud Urayk and are of Pleistocene age. The lake deposits were collected over a wide area (only the easternmost sandy areas are unrepresented) and are believed to be representative of the pluvial episodes for all the northern sand seas.

Ages of ten Pleistocene remnant lakebed samples range

Table 1.--Radiocarbon ages of lacustrine and interdunal deposits from Saudi Arabia's northern sand seas

[Deposits identified by an asterisk(*) were dated by Garrard and others (in press)]

Sand sea	Location (latitude, longitude)	Laboratory number	Material dated	Age (in radiocarbon years B.P.)
		Holocene lake and pan deposits		
An Nafud	27°36' N., 38°50' E.	B-3461	Organic	5,280±100
N. As Sirr	26°10' N., 44°19' E.	B-2988	$CaCO_3$	5,480± 70
N. Urayq	25°35' N., 42°40' E.	B-3466	$CaCO_3$	5,640± 90
An Nafud	Near Jubbah	Q-3118*	Organic	6,685± 50
N. Urayk	25°37' N., 42°39' E.	B-3523	$CaCO_3$	8,440± 90
		Late Pleistocene lake deposits		
An Nafud	28°50' N., 40°15' E.	W-4835	$CaCO_3$	24,340±300
An Nafud	Near Jubbah	Q-3117*	$CaCO_3$	25,630±430
An Nafud	28°15' N., 41°15' E.	W-4847	$CaCO_3$	25,750±310
N. Urayq	25°20' N., 40°15' E.	W-4987	$CaCO_3$	26,000±400
An Nafud	28°15' N., 39°45' E.	W-4864	$CaCO_3$	27,120±420
An Nafud	28°15' N., 41°15' E.	W-4855	$CaCO_3$	27,570±500
An Nafud	27°50' N., 41°04' E.	W-4838	$CaCO_3$	25,000±600
N. Urayq	25°32' N., 42°36' E.	W-4972	$CaCO_3$	>31,000
An Nafud	28°45' N., 40°45' E.	W-4959	$CaCO_3$	>32,000
An Nafud	29°35' N., 40°13' E.	W-4978	$CaCO_3$	>38,000

from 24,340±300 to greater than 38,000 B.P. The ages of six samples (including one lake deposit dated by Garrard and others, in press) are concentrated between 25,630±430 and 27,570±500 B.P. and define a 2,000-year-long interval of probable maximum pluvial activity in the sand seas of northern Saudi Arabia. The distribution of ages does not permit us to determine if this interval represents one long period of pluvial activity or several shorter episodes interrupted by intervals of drier climate; however, fluctuations did take place. For example, an episode of eolian sand movement is recorded between samples 27,570±500 B.P. (W-4855) and 25,750±310 B.P. (W-4847), as shown in cross section B of figure 4. Also field evidence indicates that a period of duricrust formation predates lakebed deposition in some areas. The juxtaposition of duricrust and lake deposits indicates at least two separate episodes of moisture-effective climate. It is unlikely that a complete record of minor climatic fluctuations is preserved in these sand seas because of the intensive eolian erosion during the extremely arid intervals. The relatively large, sand-free lake basin at Jubbah is probably the best location for future paleoclimate studies because it contains a more continuous record of deposition than that found among the dunes.

The oldest dated lake deposit (sample W-4978) from the An Nafud may have been deposited during an earlier pluvial episode than the 32,000- to 24,000-B.P. episode defined by the ages of the other Pleistocene lake deposits. The apparent age of >38,000 B.P. cannot be considered reliable, however, because the amount of living carbon in this deposit is very small and such a small amount of carbon may easily have infiltrated the porous carbonate lakebeds at a later time, possibly during a subsequent pluvial episode. If this lake deposit was deposited in the preceding Pleistocene pluvial episode, then, on the basis of Pleistocene temperature curves (Shackelton and Updike, 1977), its age is probably between 85,000 and 70,000 B.P. Alluvial and lake deposits of earlier Pleistocene pluvial episodes are also found in other partsof Arabia (Whitney, unpublished data).

The distribution of Pleistocene lake-deposit ages agrees well with that of dated lake deposits and other pluvial deposits from other regions in Saudi Arabia (McClure, 1976, 1978; Al-Sayari and Zötl, 1978; Whitney, unpublished data). Between 32,000 and 24,000 B.P., all regions of Arabia appear to have been under the influence of one, or more likely of several, pluvial episodes. This interval of time was characterized by either an increase in precipitation or a decrease in evaporation or a combination of both. The stability of the dune fields at this time indicates a substantial decrease in windiness; a significant temperature decrease over the region is unlikely, however, because worldwide temperatures during this interstade were higher than those during the preceding glacial-eolian episode (Shackleton and Opdyke, 1977). The stability of the dunes suggests that decreased evaporation is probably related to a significant decrease in eolian activity during the interstade. Preliminary results of pollen studies on the remnant lake deposits indicate that there was not a major change in the vegetation during the time of lakebed deposition. The vegetation was semidesert, as it is today; however the vegetative cover was denser than present. All this paleoclimate evidence indicates that the degree of climatic change in these sand seas was not great (E. Schulz, written commun., 1982); Whitney, unpublished data).

Lake deposits in the lee of stable dunes are commonly different in texture and composition than the remnant lakebeds of Pleistocene age. As shown in cross sections A and B of figure 4, these deposits occupy the present interdunal niche, and, when rare rainstorms pass over the sand seas, these small enclosed basins (known as pans in Africa) collect water that infiltrates from the porous dune sands. Most of the time, however, they are dry. The deposits that form in these pans are not as homogeneous as those of the calcareous, Pleistocene lake deposits; some are primarily gypsiferous sand, and others contain alternating units of carbonate, gypsum, organic material, silt, and sand.

Most of these deposits are not exposed. Fortuitously, local Bedu have dug wells through these deposits in several locations. The deposits range from 0.2 to 2.7 m thick, although datable carbonate layers were only 0.1 to 0.7 m thick. Most pan deposits overlie eolian sand, but at two localities they are directly on bedrock. The thinness of the carbonate layers implies that these pans did not hold standing water for intervals of time equal to the duration of the Pleistocene lakes. Therefore, the precipitation responsible for these Holocene lake and pan deposits is interpreted to have been less than that during the 32,000- to 24,000-B.P. episode.

Deposits from four different pans were submitted for radiocarbon analysis (table 1). Ages ranging from 8,440±90 to 5,280±100 B.P. indicate that small lakes and pans began to form and deposition was most active during the early and middle Holocene. The ages of three samples are within a 400-year period, between about 5,250 and 5,650 B.P., and these samples may represent the culmination of pluvial activity in this region during the Holocene. Pluvial deposits from other parts of Saudi Arabia and different types of sedimentary environments exhibit a similar distribution pattern of Holocene ages (McClure, 1976; Al-Sayari and Zötl, 1978; Whitney, unpublished data).

Isotopic dating of lake deposits not only defines episodes of pluvial climate in the sand seas but also defines, by implication, when eolian activity must have taken place. The presence of eolian sand below the remnant lake deposits indicates that dunes were present in the northern sand seas before 32,000 B.P. The partly vegetated, stable dunes, which account for almost all eolian deposits in the sand seas, were deposited between the last Pleistocene pluvial episode of 32,000 to 24,000 B.P. and the Holocene pluvial episode of 8,500 to 5,000 B.P., and the movement of dunes during the last worldwide glacial advance correlates with increased eolian sedimentation in both the oceans (Parkin and Shackleton 1973) and on the Antarctic ice (Petit and others, 1981).

Movement of these stable dunes during the last 8,500 years has been slight. Although some increase in eolian activity has occurred since the end of the Holocene pluvial episode, it has been confined to deflation of stable dunes. Wind blowouts, also called deflation scoops, are common features on the windward side of transverse and barchanoid dunes in many areas (see cross sections A and C in fig. 4), and sand deflated from these blowouts is the probable source of sediment for the active dunes. The deflation of large, stable dunes during the last 5,000 years implies important differences between the late Pleistocene and Late Holocene wind regimes. The frequency of sand-moving winds during the Holocene has been insufficient to move the dunes emplaced during the last glacial stade of the Würm.

Diatomite

A 2.2-m-thick lake deposit of diatomite has been found at B'ir Hayzan, near the western edge of the An Nafud (Whitney, 1982). Samples from four units of the deposit were analyzed for major chemical components, and the results indicate the deposit contains very little contamination. Compositionally, the deposit compares with commercial deposits from other parts of the world. The deposit is only partly exposed, and further work is needed to detemine its size and extent. Most of the diatomite is buried by dune sand of late Pleistocene age.

After the B'ir Hayzan diatomite study was completed, three more diatomaceous lake deposits were found. All three appear to be much smaller in areal extent than the B'ir Hayzan deposit. Two deposits are completely exposed erosional remnants located in close proximity to each other, and it is possible these two remannts were once part of the same lake. One of the two deposits is located at lat 29°10' N., long 40°21' E.; it covers an area of approximately 120 m2 and is about 3.0 m thick. The other is at lat 29°20' N., long 40°24' E.; it is also 3.0 m thick and covers an area of only 50 m2. The third diatomite lake deposit is located at lat 27°48' N., long 40°10' E. It is only 60 cm thick and is interbedded within a 1.5-m-thick calcareous lake bed. This last deposit visually appears to be contaminated. None of these new diatomite discoveries warrants further investigation for potential economic evaluation. The discovery of diatomite in the large Jubbah lake basin by Garrad and others (in press) may warrant further investigation. Diatomite has now been found at five locations in the An Nafud, and continued exploration may locate a sizeable deposit of industrial grade.

PRESENT CONDITION OF THE SAND SEAS

Precipitation and temperature

Average annual rainfall data for northern Saudi Arabia has been collected by the Saudi Arabian Ministry of Agriculture and Water (fig. 5). The years of record for stations ranges between 3 and 17, and average about 11. Average precipitation in both the An Nafud region and the Paleozoic bedrock region to the west is about 50 mm per year. Average precipitation at the only station actually lying in the sand sea (Jubbah) is 41 mm per year (six years of record). Precipitation on the Arabian Shield, south of the An Nafud, is nearly twice that in the An Nafud and the region to the west. Although the reasons for this precipitation difference are not clear, one reason may be related to the fact that the lower precipitation record is in the region affected by dry, westerly winds. Areas on the northern Arabian Shield may be subject to more moisture sources than the An Nafud region.

Precipitation in the An Nafud region is primarily between late fall and late spring. Rain and occasional hail and snow are brought in by cyclonic depressions originating in the eastern Atlantic Ocean or in the Mediterranean Sea. The cyclonic storms follow narrow paths across Arabia and normally release moisture in heavy rainstorms. These storms are usually of short duration, and their occurrence from year to year in any one place is erratic. If the rains are heavy enough or last long enough, moisture can penetrate the eolian sand to a depth greater than 10 cm. At this depth, the moisture is "sealed" against evaporation loss (Vesey-Fitzgerald, 1957) and is available to support the perennial vegetation in the sand seas. Seepage of water in the dunes tends to make the low, interdunal areas a favored ecological niche for vegetation and hence animal life. After a heavy rain, seepage is especially noticeable because

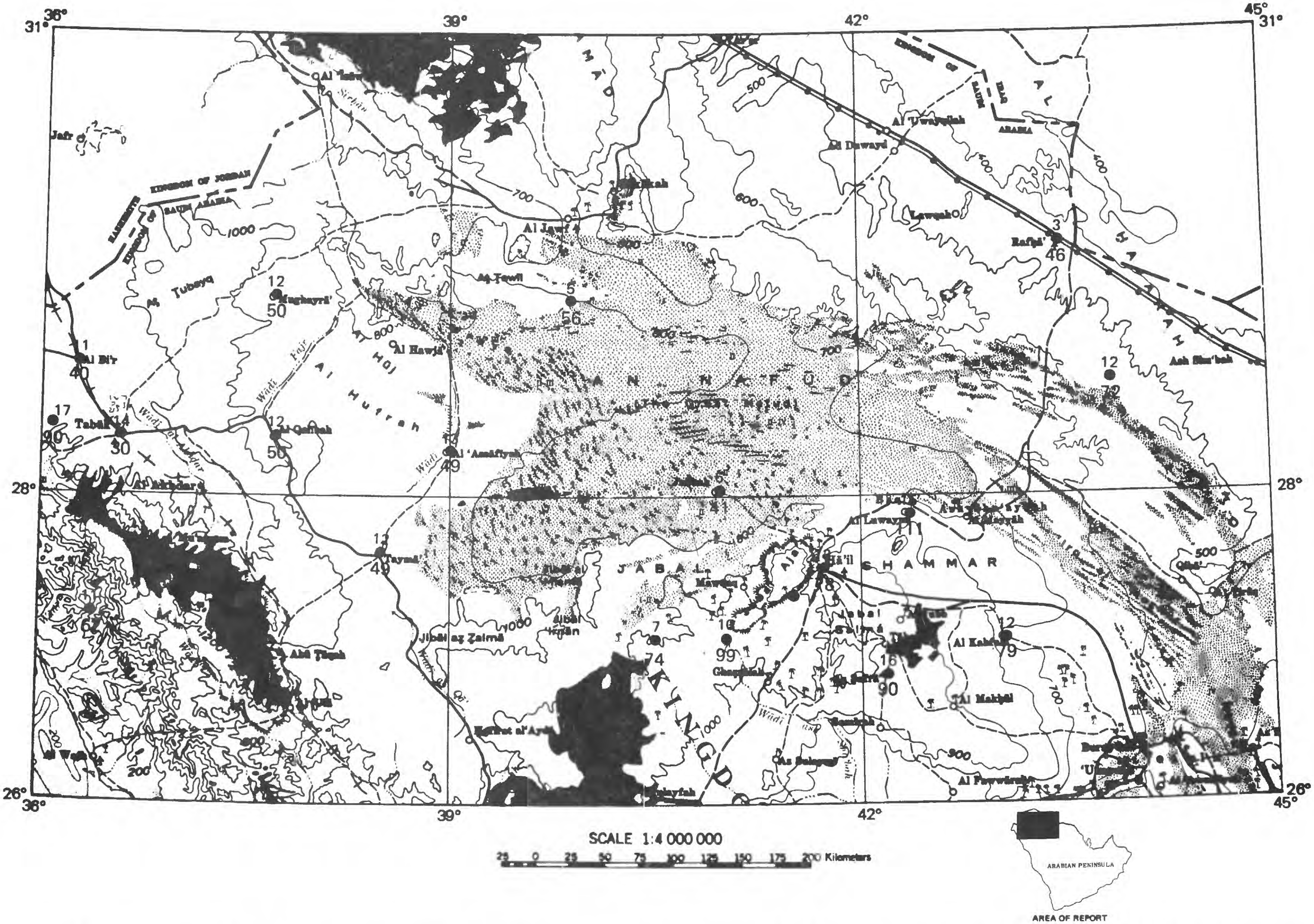


Figure 5.--Map showing average annual rainfall, northern Saudi Arabia. Precipitation in millimeters below station location (solid circle) and number of years of record above station location. Data are from the Hydrology Division, Water Resources Development Department, Saudi Arabian Ministry of Agriculture and Water, Ar Riyad.

individual dunes are ringed with a carpet of annual grasses and herbs.

Mean annual temperatures vary across the northern part of Arabia. In the northwestern area, including the An Nafud and sandstone area to the west, annual temperatures average 18°-20°C, whereas in areas to the south and west annual temperatures average 20°-22°C. The sand seas near Wadi ar Rimah and south of it are still warmer, with annual temperatures averaging 22°-24°C; these temperatures are common over most of the Arabian Shield (Bindagji, 1980).

Average summer temperatures (June-August) increase toward the interior of the Arabian Shield, ranging from about 30°C in the An Nafud to 36°C in the Wadi ar Rimah region. Winter temperatures (December-February) are also cooler in the north, ranging from 8° to 12°C, and warmer on the Arabian Shield in the south, ranging from 12° to 16°C (Bindagji, 1980). The cooler temperatures in the An Nafud region are partly responsible for the effectiveness of the low winter rainfall in supporting vegetation. Unfortunately, potential evaporation data are not yet available for Saudi Arabia.

Vegetation

In 1848, Wallin described the An Nafud as a rich pasture land that was unusable most of the year only because of the lack of wells in the interior of the sand sea. However, as stated earlier, the sand seas of northern Arabia have more recently been described as active sand seas (Wilson, 1973; Breed and others, 1979; Fryberger and Ahlbrandt, 1979). Probably the main reason for this misconception is that there have been few detailed descriptions of the present environment in these sand deserts.

The stable dunes of the sand seas support a variety of shrubs, grasses, and herbs. This carpet of vegetation is found on all slopes of the stable dunes, including the slipfaces. In fact, it was the presence of this vegetation that originally convinced us that the major dune systems in the sand seas were stable. The most common dune grasses are *Panicumm turgidum*, *Stipagrostis obtusa*, and *Astenatherum forsskalii*. The common perennial plants are *Calligonum comosum*, *Artemesia monosperma*, *Artemesia abyssinica*, *Monsonia nivea*, *Ephedra alata*, *Cornulaca monacantha*, *Haloxylon salicornicum*, and *Scrophularia deserti* (Vesey-Fitzgerald, 1957; E. Schulz, written commun., 1982). A more complete species list of plants found growing on eolian sands is given in table 2. This plant assemblage is more appropriately described as a semidesert vegetation association than as a true desert association. A more exhaustive list of plants

Table 2.--Common plant species in Saudi Arabia's northern sand seas

[Compiled from Vesey-Fitzgerald (1957), Migahid (1978), and Schulz (written commun., 1982)]

Anthemis deserti	*Linaria ascalonica*
Aristida obtusa	*Maresia pygmaea*
Aristida pumila	*Matthiola arabica*
Artemesia abyssinica	*Matthiola longpetala*
Artemesia monosperma	*Medicago aschersoniana*
Asthenatherum forsskalei	*Moltkiopsis ciliata*
Astragalus asterias	*Monsonia nivea*
Calligonum comosum	*Neurada procumbens*
Cassia italica	*Panicum turgidum*
Cornulaca monacantha	*Paronychia desertorum*
Cutandia memphitica	*Pennisetum divisum*
Cyperus conglomeratus	*Plantago albicans*
Ephedra alata	*Plantago cylindrica*
Eremobium aegyptiacum	*Plantago deserti*
Erodium laciniatum	*Polycarpea repens*
Fagonia glutinosa	*Rumex pictus*
Gypsophila capillaris	*Scrophularia deserti*
Haloxylon salicornicum	*Scrophularia hyperifolia*
Helianthemum salicifolium	*Senecio desfontainei*
Heliotropium digynum	*Stipa capensis*
Hippocrepis bicontorta	*Stipagrostis obtusa*
Ifloga spicata	*Stipagrostis scoparia*
Koelpinia linearis	*Ziziphus spina-christi*
Limeum indicum	

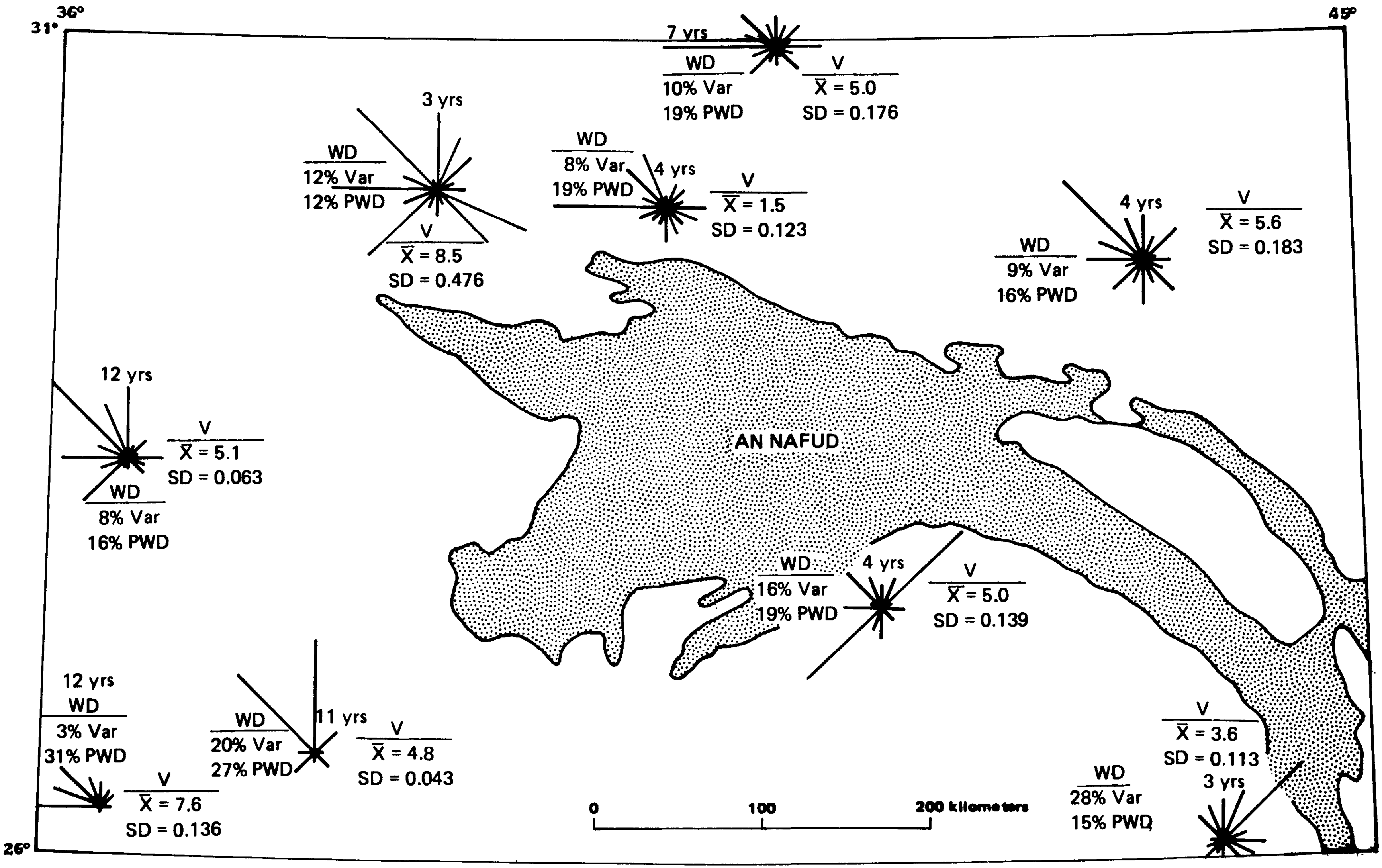
found in eolian sand environments may be compiled from Flora of Saudi Arabia (Migahid, 1978); however, in Flora of Saudi Arabia plants are listed by plant classification, not by associations.

In December 1982, the senior author made a traverse from Hail to the central An Nafud with Dr. E. Schulz, a botanist from the Geographisches Institut, University of Würzburg (FRG). Schulz noted that, although Ephedra is commonly associated with Calligonum and Artemesia in the southern part of the sand sea, it is absent in the central region and appears to be replaced by Haloxylon. If this relationship holds for a major part of the sand sea, it implies that the central region of the sand sea is drier than the southern edge. This shift to drier vegetation in the An Nafud correlates with an increase in the number of mobile (active) dunes.

Modern and paleo-wind systems

Frequencies of wind directions were compiled and plotted (fig. 6) from data supplied by the Water Resources Development Department of the Ministry of Agriculture and Water. Total average wind velocities (in knots per hour) were calculated for all wind directions and serve as a measure of relative "windiness" for the purpose of station-to-station comparison. All average velocities are less than the minimum wind velocity necessary to transport sand. This present wind condition is reflected in the very low percentage of active dunes in the sand seas. A more useful measure of present wind effectiveness would be a compilation of wind storm data because such storms are the effective sand-moving eolian events. These data are not available at the present time. The generally low values of standard durations of daily wind speed indicate that the range of wind speeds between minimum and maximum was narrow. The fact that the standard deviation of daily wind speed at one station at the northwestern edge of the An Nafud was 0.476, an order of magnitude greater than the others, possibly indicates much higher wind velocities. At this station the highest average wind velocity was also recorded; however, this station has only three years of record, and these have been unusually windy years.

Prevailing winds blew from 12 to 31 percent of the time (fig. 6), and, without specific data on individual wind storms, we can only assume that sand-moving storms are from the prevailing wind directions. If wind storms capable of transporting sand are not from prevailing wind directions, then the number of sand-moving events must be quite small in number.



EXPLANATION

4 yrs	Number of years of observed data	SD	Standard deviation of mean wind velocity	Var	Variable wind; percent of total observations
$\overline{X} = \frac{V}{5.0}$	Mean wind velocity, in knots per hour	WD	Wind direction values	PWD	Prevailing wind direction; percent of total observations

Figure 6.--Map showing frequency of wind direction for meteorological stations, northern Saudi Arabia. The length of each arm represents the proportion of total wind-direction observations recorded at the station for 16 points of the compass. Data are from the Hydrology Division, Water Resources Development Department, Saudi Arabian Ministry of Agriculture and Water, Ar Riyad.

The prevailing winds on the western or upwind side of the An Nafud sand sea are from the northwest. Strong secondary winds come from the north and west, and southwesterly winds are infrequent. Dune trends in the western An Nafud indicate that the primary sand-moving winds came from the west-southwest and the southwest (fig. 2). In the central region of the An Nafud, longitudinal dunes having an east-west orientation indicate that winds blew strongly from both the northwest and southwest, whereas the unusual crescentic slipfaces on these dunes indicate the southwesterly winds were the least effective winds in this region. This contrast between dune trends and modern wind data strongly suggests a significant change in wind regimes between the time of late Pleistocene deposition of now-stable dunes and the present time.

In the Nafud Urayq, the contrast between modern and paleo-wind environments is even greater. The large, stable tranverse dunes in this sand sea formed as a result of nearly unidirectional winds from the southwest, whereas the modern prevailing wind at nearby Buraydah airport (a wind station in the southeastern corner of fig. 6) is from the northeast. Recent meteorological records indicate that winds blowing from the south and southwest are of minor frequency in this region. This change in wind direction is also reflected in the orientation of the dunes: active dunes have slipfaces oriented in the opposite direction from those of the underlying, partly vegetated Pleistocene dunes.

The two most significant changes in the wind regime over northern Arabia since late Pleistocene time have been a decrease in overall eolian activity and a shift in the prevailing wind directions over at least the southern part of this region. Stable dunes of late Pleistocene age are the predominant dunes composing Arabia's northern sand seas, whereas active dunes occupy less than 5 percent of the land area. The modern wind environment is clearly not capable of moving or significantly altering the shape of the larger, older dunes. In fact, the primary eolian activity in the sand seas since middle Holocene time has been minor deflation on the windward slopes of the stable dunes. This decrease in eolian activity is also indicated by textural and sorting differences between the active and stable dunes. Active dunes are primarily composed of fine sand, whereas stable dunes are commonly composed of medium-grained sand. The sorting of active dune sands is greater than that of stable dune sands, a relationship that indicates a smaller variety of sand sizes in active dunes and implies less variation in the velocities of modern sand-moving winds. This decrease in eolian activity from late Pleistocene time to the present appears to be a worldwide climatic event because decreases in the rate of eolian deposition are also recorded in marine sediments of the eastern Atlantic (Sarnthein and others, 1981) and decreases in upwelling have taken place along coastal areas (Diester-Haass and Schrader, 1979).

Comparison of stable-dune trends with modern wind conditions indicates that in late Pleistocene time one of the prevailing wind directions was from the southwest. Transverse and barchanoid dunes in the western An Nafud and Nafud Urayq indicate that sand-moving winds were primarily unidirectional and came from the west-southwest, southwest, or south-southwest. Yet, in the modern wind environment, these are no longer the prevailing wind directions.

ENVIRONMENTAL HISTORY OF THE SAND SEAS

From the physical evidence in the sand seas, it is difficult to determine when the sand seas of northern Arabia began to form. Locally, residual deposits are exposed between dunes in the sand seas; however, these weathering products are not easily dated. In the western An Nafud, remnants of a former surface are underlain by ferricrete and silcrete. This residual deposit may have formed during a shieldwide, middle Teritary weathering period, and erosion of this surface during middle to late Tertiary time must have exposed the underlying, weathered Paleozoic sandstones to eolian erosion during times of arid, windy climate. These poorly consolidated, weathered sandstones may have been the primary source of sand for the original An Nafud.

Paleoenvironmental information for the latter half of the Tertiary is almost nonexistent in Saudi Arabia, except for the coastal areas. Miocene botanical and faunal remains from along the Arabian Gulf have been interpreted in the context of both a dry, tropical climate (Whybrown and McClure, 1981), and a hot, arid to semiarid climate (C. T. Madden, USGS, written commun., 1983). Late Miocene deposition of a thick accumulation of evaporites in the Red Sea basin also suggests that climatic conditions on the Arabian Peninsula were arid at that time. Evidence of a worldwide trend of aridity in late Miocene time is the desiccation of the Mediterranean Sea, botanical changes in North Africa, and increased deposition of eolian sediments in the world's oceans. We hypothesize that the first sand seas may have developed during late Miocene time on the the present erosional surface, or peneplains, of northern Saudi Arabia.

These sand seas were undoubtedly much smaller than the present sand seas and were probably stabilized during episodes of humid climates in late Tertiary and early to middle Quaternary times. During the last 3 million years, a dramatic increase in eolian deposition is recorded in marine cores. This increase in eolian activity resulted from decreasing world temperatures, which were also responsible for increased continental ice volumes in the poleward regions (Shackleton and Opdyke, 1977). The greater volume of ice in the arctic and temperate zones apparently caused a contraction of the climatic wind systems because cold polar air was brought closer to the equatorial regions. This contraction of wind belts most likely resulted in an increase in wind activity (Parkin and Shackleton, 1973).

The environmental history of the sand seas is chiefly a history of alternating climate changes that resulted in alternating episodes of vigorous eolian activity and dune-system stability. Evidence of moisture-effective climates in Arabia during the late Tertiary time is recorded by well-developed soils overlain by dated basalt flows (Al-Sayari and Zötl, 1978; Whitney, unpublished data). During late Quaternary time, alternating climates are recorded in the sand sea by a stratigraphic succession of eolian sands and lake deposits.

Dated lacustrine deposits from the sand seas fall primarily into two periods of pluvial activity. A late Pleistocene episode of lake deposition took place between about 32,000 and 24,000 B.P.; the largest number of dated lakebeds were deposited between 27,800 and 25,500 B.P. This latter interval is interpreted as being a time of maximum lacustrine activity in northern Arabia. In general, this late Pleistocene episode correlates with a time of worldwide, warm climates associated with the retreat of glaciers on other continents. Higher worldwide temperatures were probably the main cause of increased evaporation over equatorial and subtropical oceans, which itself resulted in increased precipitation over dry, subtropical regions.

A second lake-forming episode occurred in early to middle Holocene time between about 8,500 and 5,000 B.P. This Holocene lacustrine episode appears to have had a period of maximum activity between about 6,500 and 5,200 B.P. On the basis of composition and thickness of Holocene lacustrine deposits, the Holocene pluvial climate appears to have been less moisture effective than the climate during the late Pleistocene lake-forming interval. Both of these pluvial episodes correlate well with pluvial activity in other parts of Arabia (Al-Sayari and Zötl, 1978; Whitney, unpublished data) and in the subtropical regions of Australia (Bowler, 1978) and North Africa (Haynes and others, 1979; Williams and Faure, 1980).

Evidence in the sand seas for earlier Quaternary pluvial episodes is circumstantial. One lake deposit from the An Nafud yielded an age of greater than 38,000 B.P., and it is possible that this lakebed was deposited during a pluvial episode that predates the 32,000- to 24,000-B.P. episode. Lake deposits have also been found in the Rub al Khali that appear to be associated with earlier Quaternary pluvial episodes (Whitney, unpublished data). If these lakebeds were deposited during the next-earliest period of warm climate associated with worldwide continental glacier retreat, then deposition occurred about 85,000 to 70,000 years ago. Significantly, eolian sand underlies these old lake deposits of questionable age and indicates that sand dunes were probably present in the sand seas more than 80,000 years ago.

Preliminary results from a study of fossil pollen from both Holocene and Pleistocene lakebeds suggest that the vegetation association in the sand seas during the time of lakebed deposition was not significantly different from the modern vegetation association. The basic elements of the pluvial species association are almost the same as those at present; however, the density of open, semidesert vegetation (mainly shrubs and grasses) on the dunes was greater. Because the change in vegetation was not great, we conclude that the climate during lacustrine phases was not much wetter that the present climate. In fact, the most significant climatic change was probably the near cessation of violent eolian activity. An increase in moisture accompanied the decrease in eolian activity and temporarily created locally high water tables that filled natural basins with water. The precipitation increase, based on the modern rate of 50 mm to 100 mm per year, was probably three- to five-fold to about 250 mm to 300 mm annual precipitation, most likely that of a dry savanna (Schulz and Whitney, unpublished data).

Episodes of increased eolian erosion and sand deposition occurred between episodes of lacustrine deposition. Eolian sand is found stratigraphically above and below lake beds that have radiocarbon ages between 32,000 and 24,000 B.P. Eolian sand below one lake deposit of a questionably much older age may define an even earlier episode of sand-dune deposition. Small Holocene-dated lake and pan deposits in the present interdune environments indicate that the main dune systems occupying the sand seas of northern Arabia formed between 24,000 and 8,000 B.P. This time interval correlates approximately with the last glacial stade of the Pleistocene and with increased marine eolian deposition (Parkin and Shackleton, 1973). Increased eolian activity during the last glacial maximum has also been recorded from other subtropical deserts (Sarnthein, 1978), including the Simpson desert in Australia (Bowler, 1978) and the Egyptian Sahara (Haynes, 1982).

The late Pleistocene wind environment responsible for the last major episode of dune formation is difficult to reconstruct. The large dune size (commonly greater than 50 m high) and the medium-sized sand indicate that late Pleistocene winds were significantly stronger than those of the present climate. Presently active dunes in the sand seas are generally small, are composed of fine-grained sand, and occupy less than 5 percent of the land area. The number of sand-moving winds per year during late Pleistocene is also inferred to have been much greater than in the present climate because of the enormous volume of sand deposited. Comparison of modern prevailing winds in the sand seas with Pleistocene dune trends indicates that the modern wind environment lacks the dominant southwesterly and westerly winds that were responsible for dune formation in the southern An Nafud and in Nafud Urayq. Both the significant decrease in wind activity and the shift in prevailing winds in northern Saudi Arabia are assumed to be related to the worldwide temperature increase at the beginning of Holocene time (about 10,000 B.P.).

Since early Holocene time, the major dune systems in the sand seas have been stable (Whitney, 1981). After lacustrine deposition ceased about 5,000 years ago, eolian activity in the sand seas increased slightly, as evidenced by eolian erosion on the windward slopes of dunes. Small deflation scoops or blowouts formed on transverse and barchanoid dunes and perhaps supplied some of the sands that now compose the small active dunes in the sand seas. Active deflation in the sand seas appears to have decreased recently because most of the deflation scoops observed in the field or on aerial photographs contain vegetation.

The present sand seas are arid and average between 50 mm and 100 mm per year precipitation; however, this amount of moisture is adequate to support the open, semidesert vegetation found partly covering the stable dunes. The main dune systems of the sand seas are not responsive to the present wind environment. Present winds are neither as substantial nor as frequent as the winds responsible for the formation of the now-stable dunes. Active dunes are primarily limited to the crests of stable dunes and, in some areas, are actually moving across older dunes. The small percentage of active dunes composing the present sand seas (less than 5 percent) reflects this relatively low level of eolian activity.

DATA STORAGE

No data files and no Mineral Occurrence Documentation System numbers have been established as a result of this work.

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