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Evolution of the Rub' al Khali Desert

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ABSTRACT. The Rub' al Khali is the world's largest contiguous sand dune desert (640,000 km² area). It originated only during the Late Quaternary. Earliest low-rounded dunes within this desert are of Middle Pleistocene age; approximately 700,000 years old. No evidence exists of any desert sand dunes in the area during the early part of the Quaternary Period.

Several Late Quaternary pluvial phases of most notably from –17,000 to –36,000 years, occurred with high lake levels in the southwestern Rub' al Khali and periodic streams flowing to a much diminished Arabian Gulf. There were also much vegetation and wildlife. Stone Age man prospered, with his distinctive arrowheads found around old lake bed margins in the Rub' al Khali. A moderately arid interval (–10,000 to –17,000 years) with lakes low or absent was followed by an Early Holocene pluvial phase (–6,000 to –10,000 years). Lakes were again present in the southwest, with abundant surrounding Neolithic flints, and streams flowed intermittently.

The last phase of the Holocene (–6,000 years to present-day) has been mostly hyperarid with slightly moister intervals. High-crested, longitudinal dunes ('uruq) of the Rub' al Khali formed during this phase. These dunes typify vast areas of the Empty Quarter, being widely spaced and up to 230 m high. They are draa dunes, plus some oblique seif dunes, barchans and zibars. Formation of these huge longitudinal dunes is due to vortex-type wind flow alternating from the northeast and southwest.

During the last 6,000 years, very limited surface wadi flow occurred within the Rub' al Khali and cities like Qaryat al Fau flourished under a slightly milder climate from –1,400 to –2,100 years when limited irrigation was possible in peripheral areas.

Longitudinal, transverse and solitary dune types found in the Rub' al Khali are described with examples and a brief explanation of the dynamics of their formation.

Introduction

Although the Rub' al Khali has long been known as the world's largest contiguous sand desert with an area of about 640,000 km² (Ministry of Agriculture and Water 1984), many questions remain unanswered. Some of these are; how long has it been in existence?, and why are almost all the sands siliceous in an area surrounded by mainly carbonate rocks ?

Clearly, the Rub' al Khali was present throughout the entire period that historical records have been kept, *i.e.*, at least the last 5,000 years. Yet, there is every indication that, in the Early Holocene, there were many lakes and considerable grassy vegetation, where Neolithic man flourished in what is now the hyperarid Rub' al Khali and where Hippopotamus teeth have been found (Field 1956 & 1960b, Clark 1989).

Thus, the Rub' al Khali as we know it now, with high-crested longitudinal dunes, seems to have originated about 6,000 years ago. However, there were alternations of moist and dry climate during the Pleistocene (Butz r 1961) and eolian processes were probably active during times following glacial maxima of the Pleistocene. The first low dunes and sand sheets may have formed in the Middle Pleistocene as early as 700,000 years ago, and certainly before the wet phase from 325,000 to 560,000 years, or more, before present (Rauert *et al.* 1988). At this early stage, there was no Rub' al Khali Desert, only a precursor of more arid conditions to come in the Late Pleistocene and, especially, in the Holocene.

Development of the Rub' al Khali

To trace the evolution of the Rub' al Khali, one must go back to the formation of the tectonic depression of the Rub' al Khali Embayment during the Neogene, when the Arabo-Nubian Shield was also uplifted and rifted along the Red Sea, at the beginning of the separation of the Arabian and African Plates at rates of up to 2 cm per year (Fig. 1).

tion, as well as hominoid and other mammalian remains, including crocodile teeth (Andrews *et al.* 1978, Hamilton *et al.* 1978, Whybrow *et al.* 1987). At the end of the Pliocene and in the Early Quaternary, very large alluvial fans were formed (Fig. 2) to comprise conglomeratic and sand deposits where major periodic

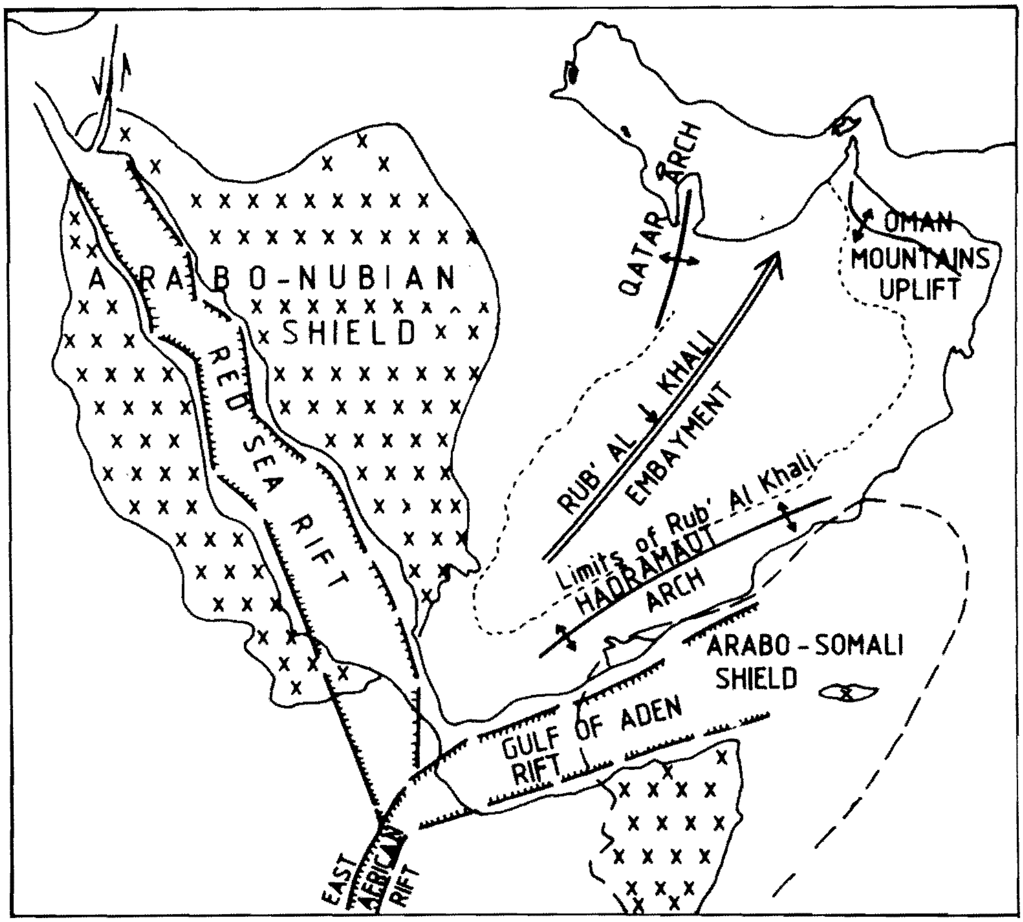

FIG. 1. Formation of the Rub' al Khali Embayment by uplift and rifting of the Arabo-Nubian and Arabo-Somali shields.

During the Miocene and Pliocene epochs drainage from the uplifted Arabian Shield broke through the Mesozoic escarpments of the Interior Homocline to deposit vast amounts of quartzose clastic sediments, which now form the Miocene Hadrukh and Mio-Pliocene Hofuf Formations (Powers *et al.* 1966), as well as undifferentiated Upper Tertiary sands and marls (Tsm). These sandy Neogene formations are important because they later became one of several sources (McClure 1978) for the huge volumes of sand in the sand dunes of the Rub' al Khali.

It seems to be evident from the volumes of Neogene sediment deposited that a pluvial and humid climate prevailed during the Miocene and Pliocene (Whybrow and McClure 1981), as indicated by warm, shallow-water, marine fossils from the Miocene Dam Formation

streams, or wadis, debouched into the Rub' al Khali, as at Wadi ad Dawasir, Wadi Najran, Wadi al Maqran, Wadi al Judwal, Wadi Jawb and Wadi as Sabha (Holm 1960).

The onset of semi-arid conditions led to the formation of low dunes about 560,000 to 700,000 years ago before the isotopically dated Middle Pleistocene cold-wet period. This was followed by a pluvial phase, when lakes were formed in broad interdune depressions in the Rub' al Khali, as well as rejuvenated drainage channels during a Mid Pleistocene interval of higher rainfall from 320,000 to 560,000 years ago. Oxygen isotopes also give a useful indication of warm (arid) and cold (relatively wet) intervals back as far as to 700,000 years ago (Martinson *et al.* 1987, Die Geowissenschaften 1988-89).

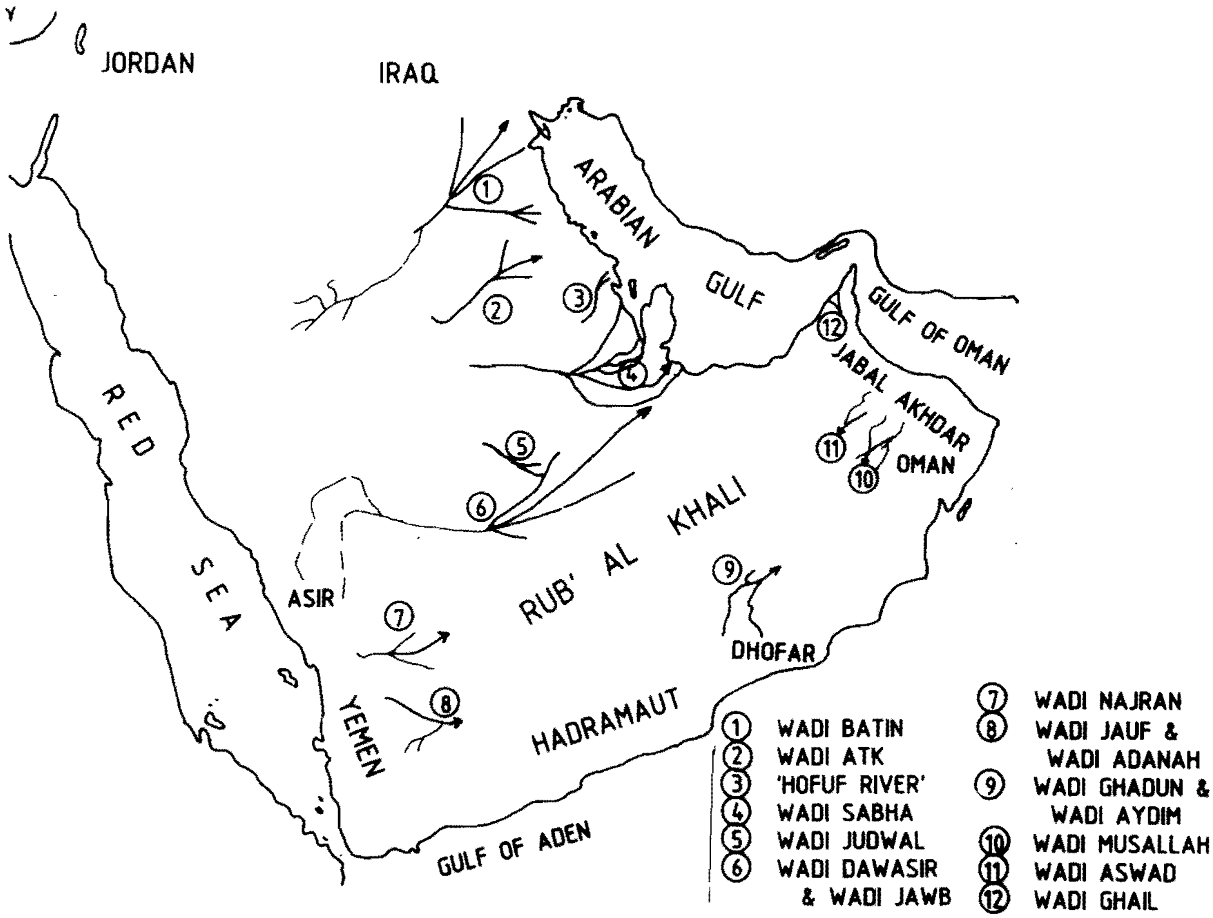

FIG. 2. Pleistocene alluvial fans bordering the Rub' al Khali and in northeastern Saudi Arabia.

A mild arid interval followed between 270,000 to 320,000 years ago, but does not seem to have reactivated early low dunes and has a moister phase between approximately 70,000 and 270,000 years BP. These dates are interpreted from U/Th isotope datings (Rauert *et al.* 1988) of sinter formation in As Summan Plateau caves, adjacent to Ad Dahna sands, which are an arm of the Rub' al Khali.

In the Late Pleistocene, a major pluvial phase occurred from 17,000 to 36,000 years BP (McClure 1976 & 1984) coinciding with the last glacial maximum, which caused a northward shift of the southwest summer monsoon belt. During this pluvial phase, lakes were again formed in many parts of the Rub' al Khali, especially in the southwest Rub' al Khali and the whole Hofuf area was an inland lake, as also at Al Aflaj (Ministry of Agriculture and Water 1984). Quaternary drainage systems of the Rub' al Khali, such as wadis Sabkha, Jawb, Judwal, Maqran, Dawasir, and Najran were almost certainly reactivated (Holm 1960), although not as perennial streams.

A significant arid interval, from 10,000 to 17,000 years ago (McClure 1984), took place toward the end of the Pleistocene and numerous dunes were reactivated and enlarged.

At the beginning of Holocene time, an Arabian Neolithic Wet Phase (Ministry of Agriculture and Water 1984) took place between 6,000 and 10,000 years BP (Fig. 3), as also noted by Brice (1978). Once again, the Rub' al Khali area contained many lakes surrounded by vegetation where Neolithic man also lived, so that his flint implements, especially arrowheads, are found in abundance around these now dried lakes (Field 1960a, Clark 1989).

A hyperarid phase followed this Neolithic Wet Phase and extended from approximately 3,000 to 6,000 years BP,with a minor break indicated by Neolithic camps between 5,000 and 5,500 years ago, noted by Zeuner (1954) who states that somewhat damper conditions than those of the present day are thus indicated. It is generally conceded that the formation of the high-crested dunes, which typify the Rub' al

GEOLOGICAL EPOCH	CHRONOLOGY IN YEARS BP	CLIMATIC PHASE	EVENTS IN RUB' AL KHALI
	0 - 700	HYPERARID	CONTINUED MOVEMENT OF HIGH CRESTED DUNES.
	700 - 1,300	SLIGHTLY MOIST	HOFUF RIVER NOTED BY YAQUT AND OTHER GEOGRAPHERS.
	1,300 - 1,400	ARID	DUNE MOVEMENT.
	1,400 - 2,100	SLIGHTLY MOIST	SABEAN KINGDOM FLOURISHED AND ALSO KINGDOM OF KINDA AT QARYAT AL FAU (AL-ANSARY, 1982).
	2,100 - 5,000	HYPERARID	DUNE MOVEMENT
HOLOCENE	5,000 - 5,500	SLIGHTLY MOIST	NEOLITHIC CAMP SITE IN SW RUB' AL KHALI 5120 YEARS BP (FIELD, 1956).
	5,500 - 6,000	HYPERARID	HIGH CRESTED DUNES; 'IRQS AND INTERDUNE CORRIDORS.
	6,000 - 10,000	WET (PLUVIAL)	"NEOLITHIC WET PHASE" LAKES IN SW RUB' AL KHALI (C14 DATING OF ORGANIC REMAINS AND SINTER).
	10,000 - 17,000	HYPERARID	DUNE TOPOGRAPHY AND LONGITUDINAL DUNES EXTENDED.
	17,000 - 36,000	WET (PLUVIAL)	LAKES IN THE SW RUB' AL KHALI; ARABIAN GULF DRY, DUE TO LOWERED SEA LEVEL OF THE LAST GREAT ICE AGE (C14 DATING OF ORGANIC REMAINS AND SINTER).
LATE PLEISTOCENE	36,000 - 70,000	ARID	MAIN MOVEMENT OF SAND FROM OLD WADIS IN THE SHRUNKEN ARABIAN GULF.
	70,000 - 270,000	MOIST	EARLY PHASE OF WURM GLACIAL & RISS-WURM INTERGLACIAL (U/Th ISOTOPE DATING).
	270,000 - 325,000	ARID	SUMMAN PLATEAU CAVES DRY.
	325,000 - 560,000	WET	ACTIVE KARSTIFICATION & CAVE FORMATION IN SUMMAN PLATEAU (U/Th ISOTOPE DATING).
MIDDLE PLEISTOCENE	560,000 - 700,000	ARID	BEGINNING OF LOW DUNES (O_2 ISOTOPE EVIDENCE OF WARMER CLIMATE).
EARLY PLEISTOCENE	700,000 - 1,610,000 + (possibly to -2,500,000)	WET HUMID (PLUVIAL)	EARLY QUATERNARY DRAINAGE SYSTEMS IN THE RUB' AL KHALI. LARGE ALLUVIAL FANS FORMED (O_2 ISOTOPE EVIDENCE OF COOLER CLIMATE).

FIG. 3. A provisional chronology of Quaternary climate and events in the Rub' al Khali. [Time scale adapted partly from Nikiforova (1978), Nilsson (1983), Martinson *et al.* (1987), and *Global Stratigraphic Chart, Int. Union Geol. Sciences* (1989)].

Khali today, dates from this very arid interval, which some geologists would extend up to the present day.

Within the last 3,000 years, there are indirect, or historical evidences to indicate several moister intervals. Between about 1,400 and 3,000 years BP, a relatively moist phase took place, as indicated by speleothems, in caves of the adjacent Summan Plateau (Rauert *et al.* 1988) and also by the Kingdom of Kinda at Qaryat al Fau, which flourished in a now arid area from 1,400 to 2,100 years ago (Al-Ansary 1982). The most recent moist phase from 700 to 1,300 years ago was recorded by historians, such as Yaqut (1955) and Al-Hamdani (Forrer 1942), who both wrote about the flow of a great canalized river from Hofuf to the Arabian Gulf, also noted by the Greek geographers as the Aftan River (Golding 1984). This was not observed at all by Abdul Fida, writing some 600 years ago when the miost phase had evidently ended.

The last hyperarid phase, which has prevailed in the Rub' al Khali and Jafurah to this day, began about 700 years ago, following the Hofuf and Al Aflaj lake phase, and has remained relatively constant with much sand movement and only the very occasional rainier year (Fig. 3). The climate of the Rub' al Khali has not been constantly hyperarid over the last 6,000 years, as maintained by McClure (1984), and evidence of intervening less arid intervals comes from sinter isotope datings in As Summan Plateau caves (Rauert *et al.* 1988), as well as from archaeological evidence of irrigation along wadis in the western Rub' al Khali (Clapp and Hedges 1987) and of old towns at Gerrha, Thaj and Yabrin.

Dunes in the Rub' al Khali

During the last 6,000 years many differnt types of dunes have formed in the Rub' al Khali. The type of dune formed depends upon the amount of sand supply, the grain size and composition of sand, the surface roughness, the velocity, direction, duration and variability of wind, humidity, and the nature of the subsurface and vegetation. Sand dune accumulation generally takes place by interruption of sand-laden wind masses, due to the presence of obstacles or variation in the ground relief (Aufrère 1929, Bagnold 1941), although the complete understanding of dune initiation mechanisms has not yet been achieved (Warren and Knot 1983).

The greater part of the Rub' al Khali sand desert is covered by linear dunes, or 'uruq (Bagnold 1951, Wilson 1972 & 1973). Various types of linear dunes can be recognized, including draa dunes, seif dunes, sigmoidal dunes, fishhook dunes, feather dunes and divergent dunes. A large area of the southern and southwestern Rub' al Khali, between the towns of As Sulayyil and Najran and the Ramlat Mitan in northwestern interior Dhofar, is covered by gigantic linear dunes of the draa type, spaced from 2 to 6 km apart and with an average trend of N 60°E. These draa dunes are up to 260 km long and commonly 150 km long (Fig. 4). They are formed by air rising from cooler inter-

FIG. 4. Draa dunes of the southwest Rub' al Khali shown on a satellite image taken in 1985 by H.H. Prince Sultan bin Salman bin Abdulaziz Al-Saud.

dune areas to the hotter dunes, while winds blowing subparallel to the dunes convert the uprising air into double helical vortices (Fig. 5) blowing along interdunes (Hanna 1969, Cooke and Warren 1973, Goudie and Wilkinson 1977, and Warren 1984). Smaller linear dunes are known as seif dunes (McKee and Tibbitts 1964, Tsoar 1983) and comprise a large part of the southwestern and central Rub' al Khali. Where draa dunes are found, smaller seif dunes often join them obliquely (Collinson and Thompson 1982).

plexes,as with the chevron-like belts of sigmoidal dunes seen in the northeast Rub' al Khali. Another type of linear dune is the feather dune consisting of a number of dune ridges joining downwind to form a single ridge, as can be seen some 280 km east-northeast of As Sulayyil (Fig. 6). Linear dune complexes of another type consist of aligned belts of pyramidal dunes (Fig. 7), as seen in the eastern Rub' al Khali, Ramlat al Mitan area, where individual pyramidal dunes occur in linear arrangements with sand sheets

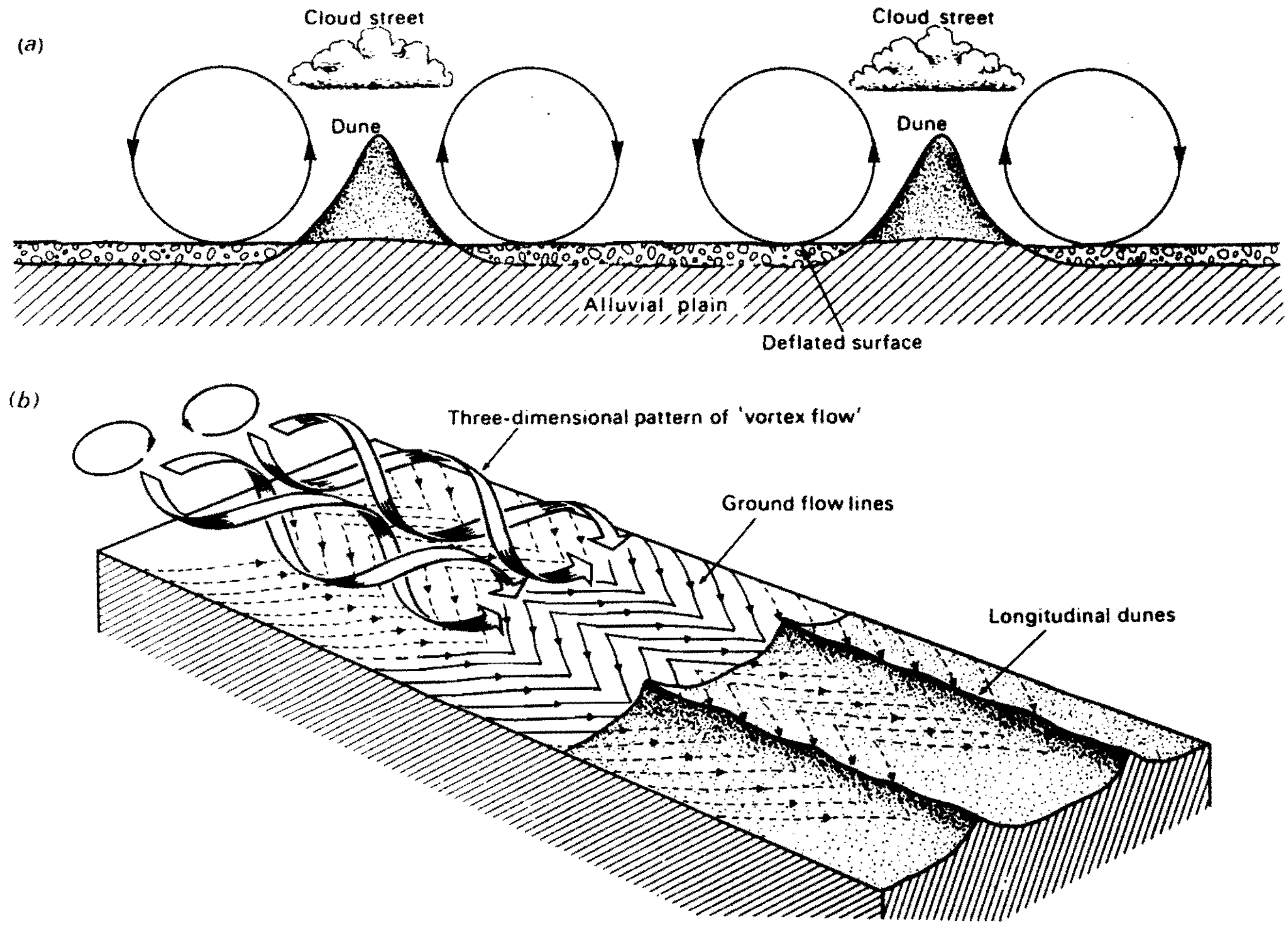

FIG. 5. Diagram of wind in double helical vortices forming regularly spaced, parallel longitudinal dunes (After Goudie and Wilkinson 1977).

When the wind between the linear dunes is of lesser velocity, low sand ridges of coarser grained sand, having no slip faces and often crescentic in plan, are formed in the interdune corridors and are known as zibar (Stone 1967). They are common in the interdune areas, or shuqqan, of three quarters of the Rub' al Khali (Holm 1960).

Where the wind direction is somewhat variable, with alternating winds oblique to their length, the type of linear dunes formed are sigmoidal, sharp-crested dunes. Sigmoidal dunes may occur singly or as com-

between them, and also occur as lines of interconnected pyramidal dunes.

Some linear dunes of draa size, in the southwestern Rub' al Khali, between the towns of Najran and Ash Sharawrah, are straight along their southeastern side but are barbed along their northwestern side by the presence of numerous attached barchans. They are referred to as compound feathered dunes by Breed *et al.* (1977) and Breed and Grow (1979). Other linear dunes in the same area ('Uruq al Kuthayyib) are diver-

FIG. 6. Feather dunes about 200 km east of Sulayyil as shown on Landsat imagery

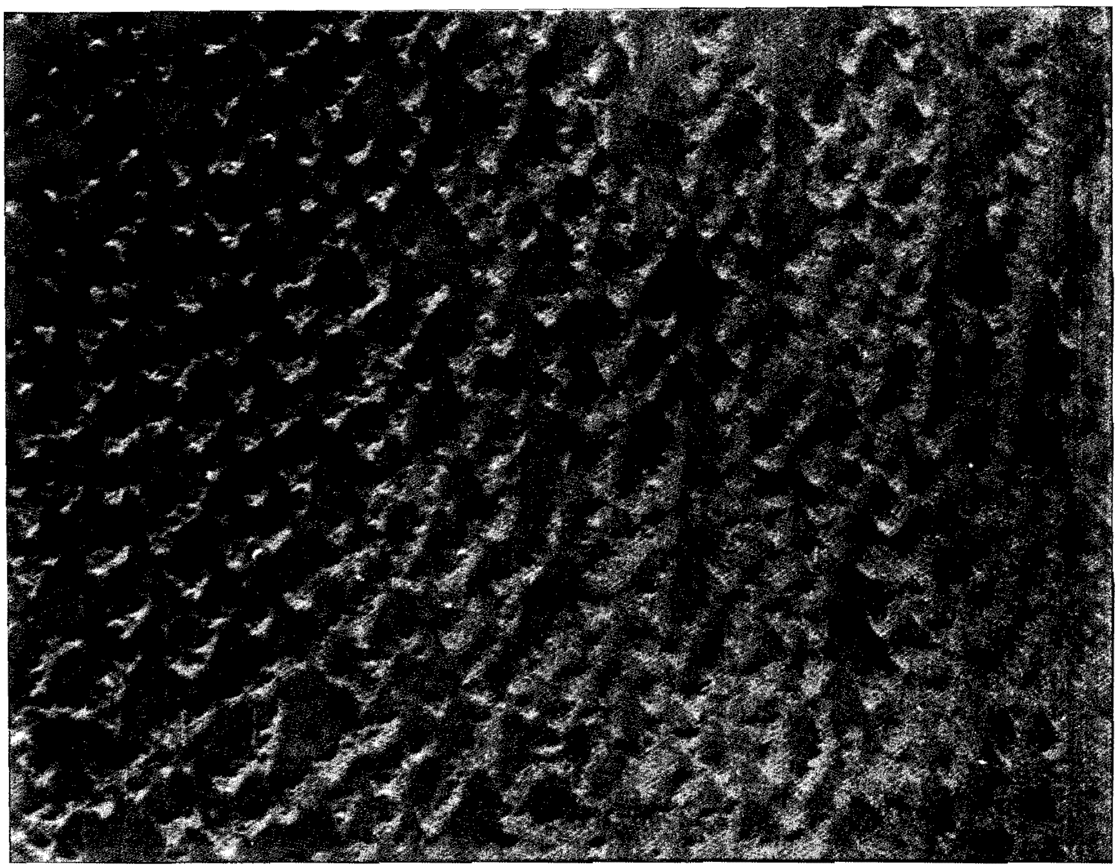

FIG. 7. Linear belts of pyramidal dunes in the Ramlat al Mitan area, eastern Rub' al Khali (Large Format Camera Image 1984).

gent, with a single linear dune branching northeastward into two or three dune ridges (Fig. 8).

A type of linear dune, which is common throughout a large area of the south-central Rub' al Khali, is the fishhook dune (Holm 1960). It consists of a long, linear ridge, forming the shaft with a terminal, crescentic, northeasterly end of apparent transverse origin. These dunes often start as separate crescentic dunes and linear dunes, but they coalesce to give the characteristic fishhook shape, with one or several crescentic parts having slip faces up to 60 meters high (Fig. 9).

In the eastern part of the Rub' al Khali, in the 'Uruq al Mu'taridah, giant crescentic dunes (McKee 1979) up to 230 meters high are developed on a widespread inland sabkha foundation (Fig. 10). Between 19°40'N and 22°00'N, this easternmost part of the Rub' al Khali has predominant winds from the north-northeast during winter and from the southwest in summer (Al-Ansari *et al.* 1988). Some parts of the 'Uruq al Mu'taridah show a fishscale pattern with crescentic elements enclosing sabkha interdune areas, and are called complex crescentic ridges by Breed *et al.* (1979). The source of giant dunes in the northeastern Rub' al Khali is probably from loose and partly cemented sediments (Stadler 1975) deposited by interior wadis flowing southward from the nearby Oman Mountains (Besler 1982), from the stony desert of the Jiddat al Harasis in southeast Oman, and from the shrunken Arabian Gulf of the Late Pleistocene.

Transverse dunes and their varieties, such as akle' dunes, barchans, barchanoid ridges and parabolic

FIG. 8. Divergent dunes in the 'Uruq al Kuthayyib about 180 km ESE of Najran (NASA Satellite Image 1985).

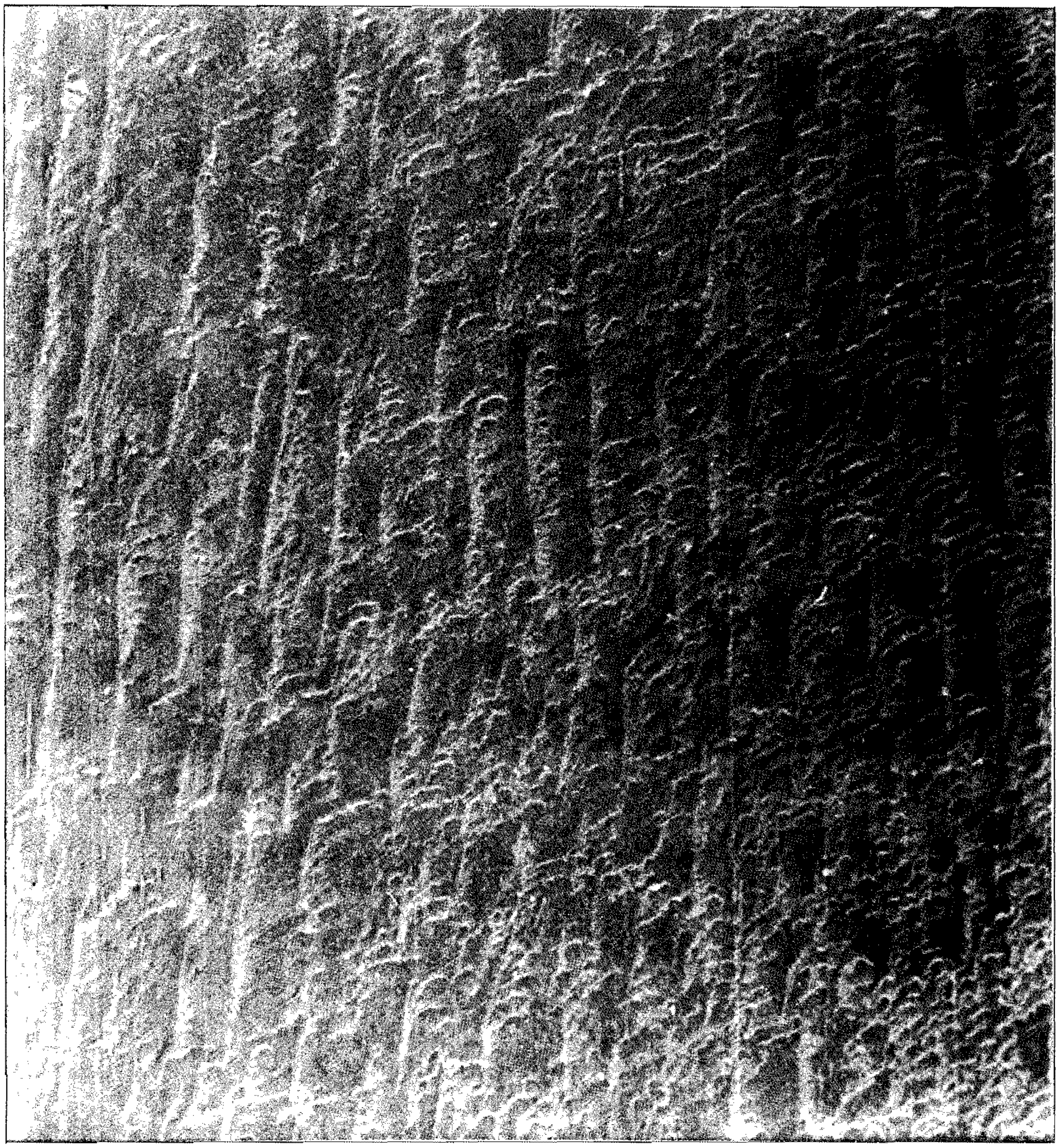

FIG. 9. Fishhook dunes in the south central Rub 'al Khali (Large format Camera Satellite Image 1984).

dunes are relatively minor in the Rub' al Khali, whose dunes are mostly of the linear type. There are, however, some areas where mainly transverse dunes are to be found, as in the north central Rub' al Khali between Lat. 20°30'N and Lat. 21°20'N, as well as between Long. 50°30'E and Long. 51°00'E. These are south of the famous meteorite impact site of Al Hadidah and consist almost entirely of a barchanoid dune ridge complex. Individual barchanoid dune ridges are relatively small and their slip faces are on the south side as dictated by the dominant northerly wind. Barchan type dunes are also probably being converted into longitudinal dunes by the processes explained by Bagnold (1941), Lancaster (1980) and Tsoar (1983).

Akle' type, transverse dunes, with a wavy ridge crest, can be seen around and south of Sabkhat Matti in northwestern U.A.E., together with barchanoid dune ridges and rare individual barchans (Fig. 11). Throughout most of the Rub' al Khali, the plentiful sand supply precludes the existence of large, well-developed individual barchans, except as small bodies in the sabkha-type interdunes of the eastern Rub' al Khali.

Compound crescentic dunes (Fig. 12) have been recognized in parts of the 'Uruq al Mu'ṭariḍah (Lat. 23°N, Long. 54°E) by Breed and Grow (1979) and contain many barchanoid dune ridges. They are best de-

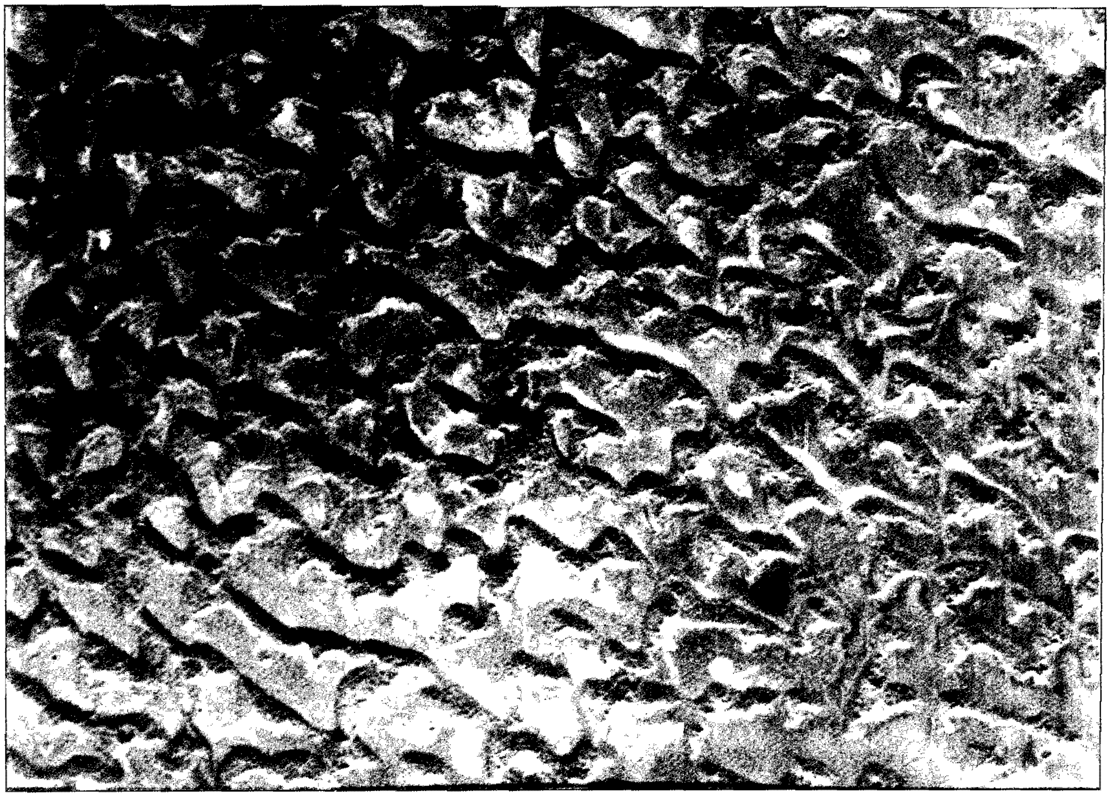

FIG. 10. Giant crescentic dunes in the 'Uruq al Mu'taridah, eastern Rub' al Khali.

FIG. 11. Transverse, wavy akle' dunes, together with barchanoid ridges and small individual barchans, south of Sabkhat Matti, northern Rub' al Khali.

scribed as megabarchans, and in view of their giant size (up to 230 m high), they are considered to have originated in the Pleistocene by Glennie (1970), a view supported here as at least Late Pleistocene in origin. As noted by Bagnold (1941) and Watson (1985). The larger the dune the slower it moves.

around the Compass" (Holm 1960). In the southeastern Rub' al Khali, it is noticeable that individual pyramidal dunes are aligned in rows, *e.g.*, Ramlat Fasad. In interior Dhofar, these dunes are produced by winds blowing inland, either from the south or from the southeast, with their lee side always on the north.

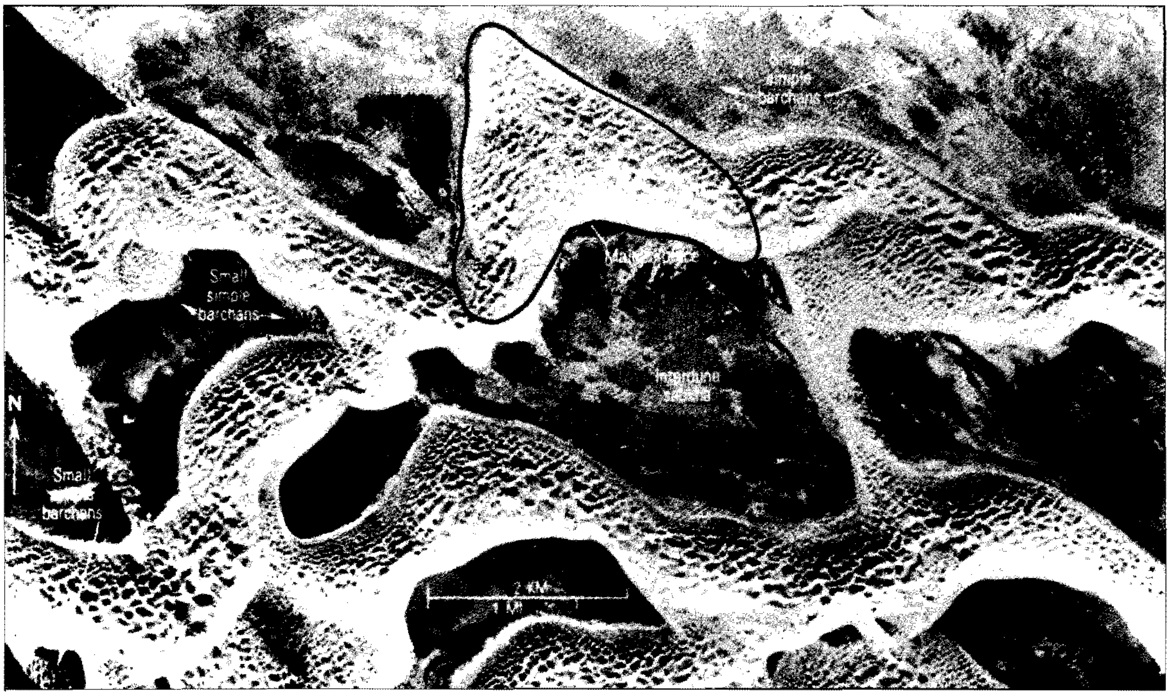

FIG. 12. Megabarchans, or giant compound crescentic dunes in the eastern Rub' al Khali (Breed and Grow 1979).

A large area of barchanoid ridges and compound barchan chains occurs Al Jiwa (Al Liwa) area of the northern Rub' al Khali. They form a broad crescentic area, 100 km long from east to west and up to 50 km wide, which is apparently advancing on the northern end of the giant crescentic dunes, or megabarchans, of 'Uruq al Mu'taridah (Fig. 13).

Solitary dunes consist primarily of pyramidal dunes and domal dunes. The former are often referred to as star dunes or rhourd, but were originally called pyramidal dunes by French scientists in the Sahara of Algeria (Aufrère 1931).

Pyramidal dunes are found mainly along that part of the southeastern Rub' al Khali that borders interior Dhofar (Fig. 14). They appear to form by the convergence of two or more sigmoidal ridges and, after becoming relatively stable, grow by the accretion of drifting sand. These large dunes, often called sand mountains, are from 0.5 to 2 km in diameter and reach heights of 150 m. It has been said that "pyramidal dunes form from sigmoidal dunes when the winds beat

Their alignment is due to a northeast wind, which is part of the general wind circulation in the southern Rub' al Khali. Similar isolated dune massifs, or qa'aid, are known in the Ghanim Sands of the easternmost Rub' al Khali (Bagnold 1951).

Dome dunes, consisting of large, circular or oval, domed sand bodies, up to 2 km in diameter and 60 to 100 m high (Fig. 15), occur in that part of the Rub' al Khali bordering the northern Hadramaut Arch, especially in the Ramlat Umm Gharib and Ramlat Hazar. These dome dunes are apparently due to a relatively restricted sand supply combined with a changeable wind pattern, which locally shifts at random. This type of dune does not occupy any more than a minor fraction of the Rub' al Khali sand desert and is referred to by Holm (1960) as 'tear-drop dunes'.

Sources of Sand for the Rub' al Khali

The sources of the great amounts of siliceous sand which have accumulated in the sand dunes and sand sheets of the Rub' al Khali are several. A large amount

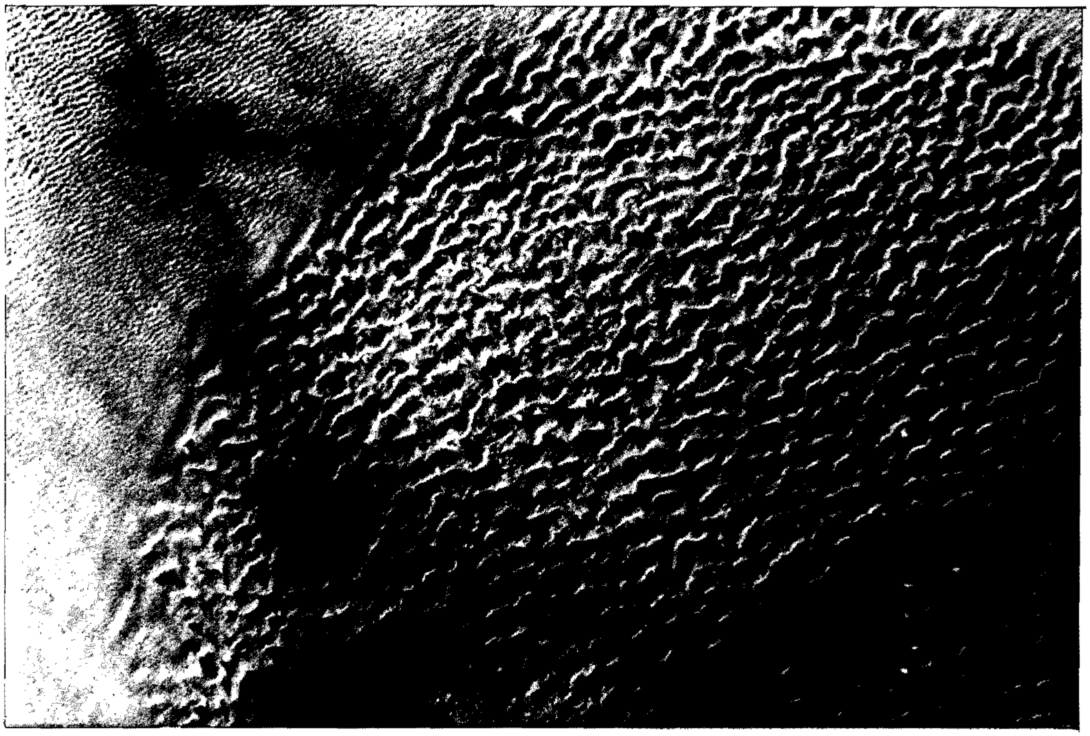

FIG. 13. Compound barchan chains and barchanoid ridges in Al Jiwa area advancing south on megabarchans of 'Uruq al Mu'taridah (Landsat MSS Satellite Image).

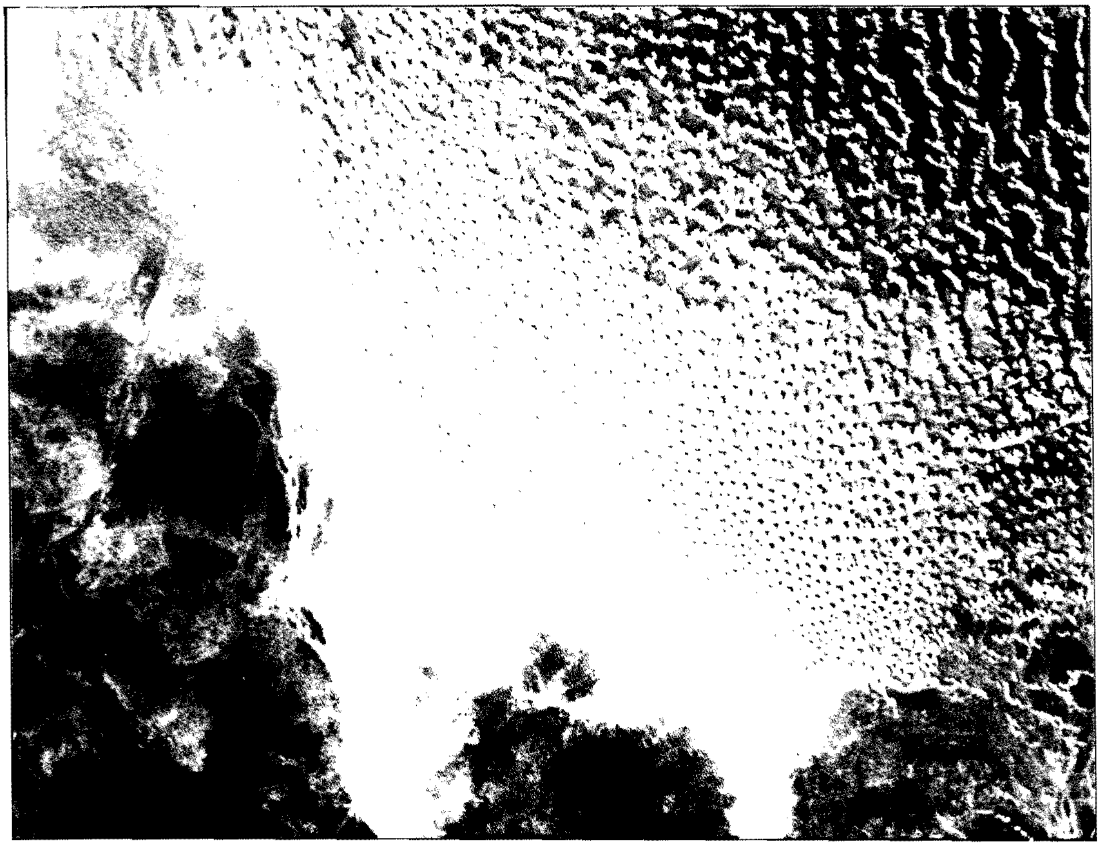

FIG. 14. Pyramidal dunes on the north margin of Dhofar (Landsat MSS Satellite Image).

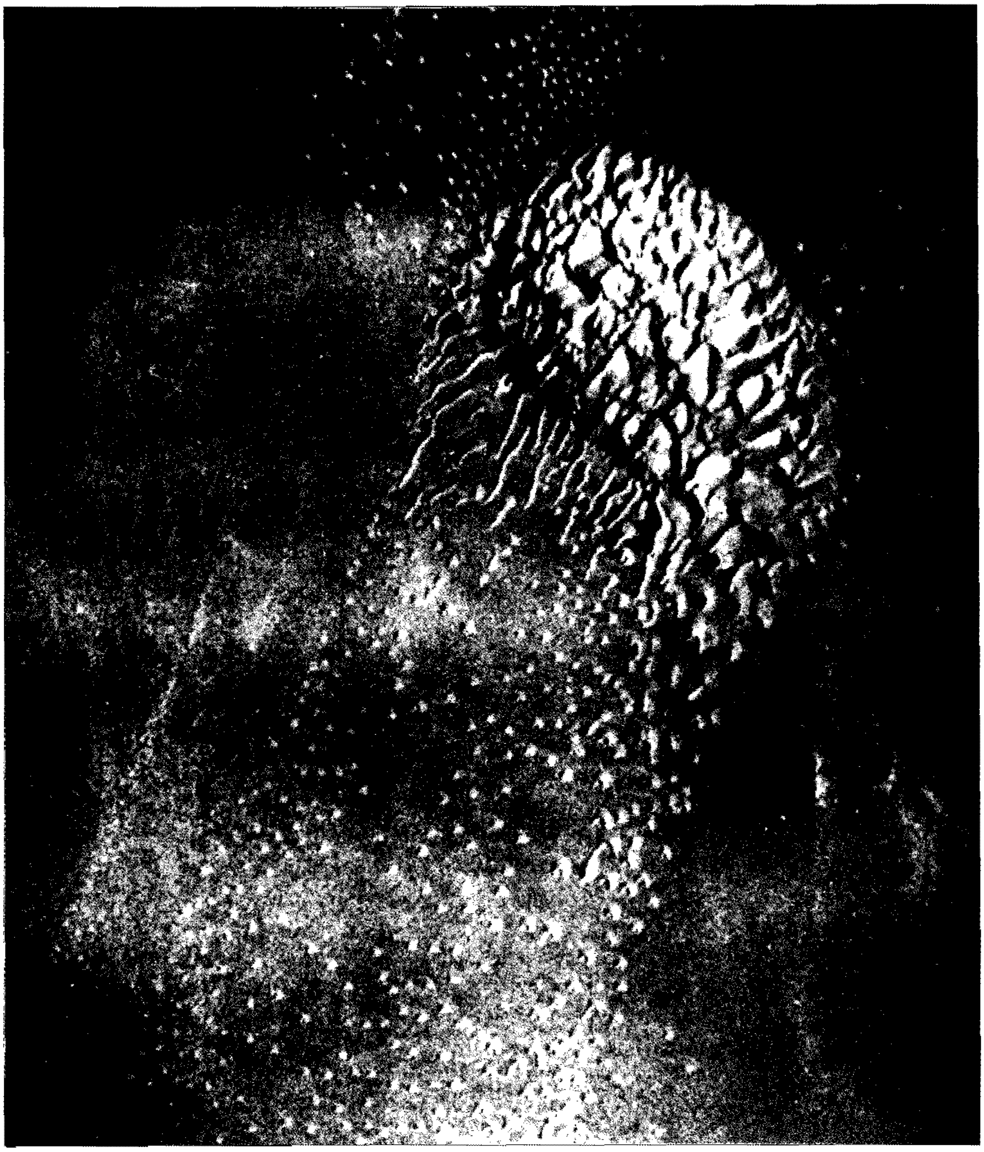

FIG. 15. Dome dunes in Al Ghanim sand of the Easternmost Rub' al Khali (Holm 1960).

of the sand has been eroded originally from the crystalline rocks of the mainly Precambrian Arabian Shield. Much of the eroded sand has been incorporated into widespread clastic formations, such as the Neogene Hadrukh and Hofuf and the Cambro-Ordovician Saq and Wajid formations. As these formations have been weathered and eroded, vast amounts of loose sand have been liberated. Sedimentary analysis by McClure (1984) suggests that much of the sand of the Rub' al Khali was probably derived from a texturally mature sandstone source.

One of the main sources of sand for the Rub' al Khali has been, and continues to be, the sand-filled wadi systems which formed in more pluvial intervals of the Early Quaternary. A good example of these is the Wadi Bishah-Wadi Tathlith-Wadi Dawasir drainage system, which once linked up with Wadi Jawb to extend to the Arabian Gulf (Edgell 1988). Since Wadis Bishah and Tathlith drain a large high area of the Arabian Shield crystalline rocks in Asir Province, they are able to supply large amounts of eroded siliceous sediment to the southern Rub' al Khali. Wadi Najran acts in a similar way, while Wadi Habawnah and Wadi Idimah also supply siliceous sediment eroded from crystalline Precambrian rocks, as well as from erosion of the medium-grained, quartzose Wajid Sandstone. Another source of siliceous sandy sediment is provided by Wadi al Judwal, which is made of eroded Lower Cretaceous sandstones of the Buwaib and

Biyadh Formations and lies in the western part of the Rub' al Khali.

Many wadis draining northward from the Hadramaut Arch have also contributed much sediment to the southern Rub' al Khali and several major wadis in the western Hadramaut consist of eroded sandy Cretaceous Tathlith Formation.

In the eastern and northeastern Rub' al Khali, many steep wadis draining southeastward from the high Oman Mountains have provided vast amounts of alluvium and gravel, and it is probably due to this abundant source that great sand mountains of high crescentic dunes are found nearby (Besler 1982) in the easternmost Rub' al Khali, *i.e.*, in 'Uruq al Mu'ṭariḍah and Al Ghanim Sands.

Due to the prevailing winds circulating from north and northeast along the Dahna (Al-Ansari *et al.* 1988), much sand is collected from various wadis intersecting this long sandy body and is swept into the southwestern Rub' al Khali, just east of As Sulayyil in the 'Uruq al Majari, together with even more sand from the Dahna itself and some eroded from outcrops of the sandy Cretaceous Wasia and Biyadh Formations. The Jafurah Sand Sea acts in a similar manner, conveying sand south-southeast under the predominant shamāl winds into the Sanam Sand of the northwestern Rub' al Khali (Fryberger *et al.* 1981, 1983, 1984), with dune advance rates from 3 to 23 per year. Further proof of long distance eolian sand movement is shown by the very long sand dune ridges, or 'Uruq of the Rub' al Khali, some of which are up to 260 km in length.

Lastly, one must consider the Arabian Gulf, and its much reduced precursors in the Quaternary glacial stages, as a major source for the Middle and Late Pleistocene sand dunes (Shinn 1973), which preceded the present high-crested dunes of the Rub' al Khali. During the major phase of the Quaternary Ice Age, it is known that sea level was reduced (Fig. 16) some 120 m below present sea level (Fairbridge 1961 & 1966, Kassler 1973). Since the present Arabian Gulf is relatively shallow, it is probable that there was no Arabian Gulf at all at that time (17,000 to 25,000 years ago), but there was only a vast alluvial plain, through which streams flowed. These were the forerunners of the present-day Tigris and Euphrates and they found their way southeastward to a –120 m seashore in the Gulf of Oman (Sarnthein 1972). Streams draining the Zagros Ranges, such as the precursors of the Karun, Marun and Mand rivers and their courses on the Arabian Gulf plain, also provided much alluvium, later blown southward to the Rub' al Khali. It is emphasised that all these rivers from Arabia, Iraq and Iran are thought to have provided much sandy sediment to the Rub' al Khali by the action of the shamāl winds on their sandy water courses.

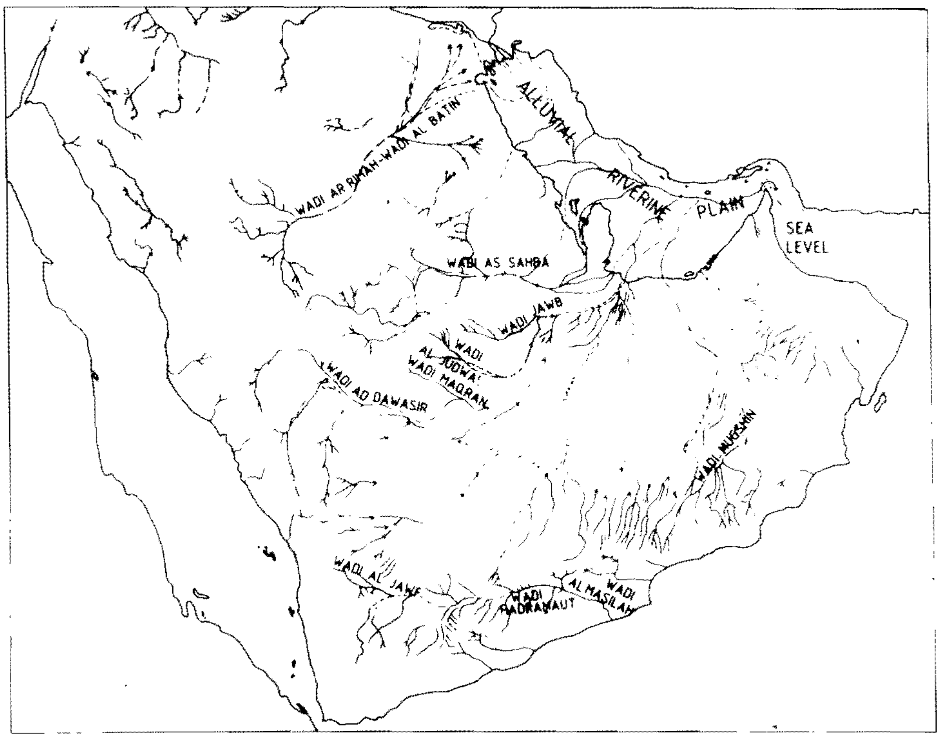

FIG. 16. Sketch map of the Arabian Gulf area during the last glacial maximum about 18,000 years ago showing major Pleistocene drainage systems.

From 17,000 to 5,000 years ago, there was a series of quick advances of sea level, so that the Arabian Gulf reentered its present area. Doornkamp *et al.* (1980), Houbolt (1957) and Kassler (1973) have shown that sea level rose by rapid advances and periodic stillstands to its present level, or slightly above, producing six terraces. During the tens of thousands of years that it took the Arabian Gulf to regain its Late Pleistocene level, large areas of the now submerged Gulf supplied sandy alluvial sediment to Qatar and southeastward to the Rub' al Khali Embayment by means of the prevailing northerly shamāl winds (Shinn 1973). Submerged sand dunes (Fig. 17) have already been noted in the Arabian Gulf (Al-Hinai *et al.* 1987). In addition, the presence of wind-transported coastal ooliths and even shallow water foraminiferids in the Rub' al Khali sands of southern Abu Dhabi (B.H. Purser, personal communication), as well as in the central Rub' al Khali (McClure 1984), is further proof of the continued southward drift of sediments into the Rub' al Khali. The presence of small amounts of heavy minerals in dunes of the southwestern Rub' al Khali is not conclusive evidence that sand dunes originated almost *in situ* (McClure 1984), as smaller heavy mineral particles are carried along with larger quartz grains purely as matter of similar mass. It is often forgotten that Quaternary Ice Age shorelines were quite different from those of today. The Arabian Gulf was a riverine plain, mostly filled with terrigenous sediments, as shown by Seibold *et al.* (1973).

In Qatar, dunes of quartz sand lie in a narrow belt south of Umm Said, having been blown across the Qatar Peninsula by the prevailing, north northwesterly shamāl wind. Almost all the rest of Qatar has no dunes and Shinn (1973) has concluded that the source of sand was on the floor of the Arabian Gulf, but as sea level rose to its present position, the supply of sand

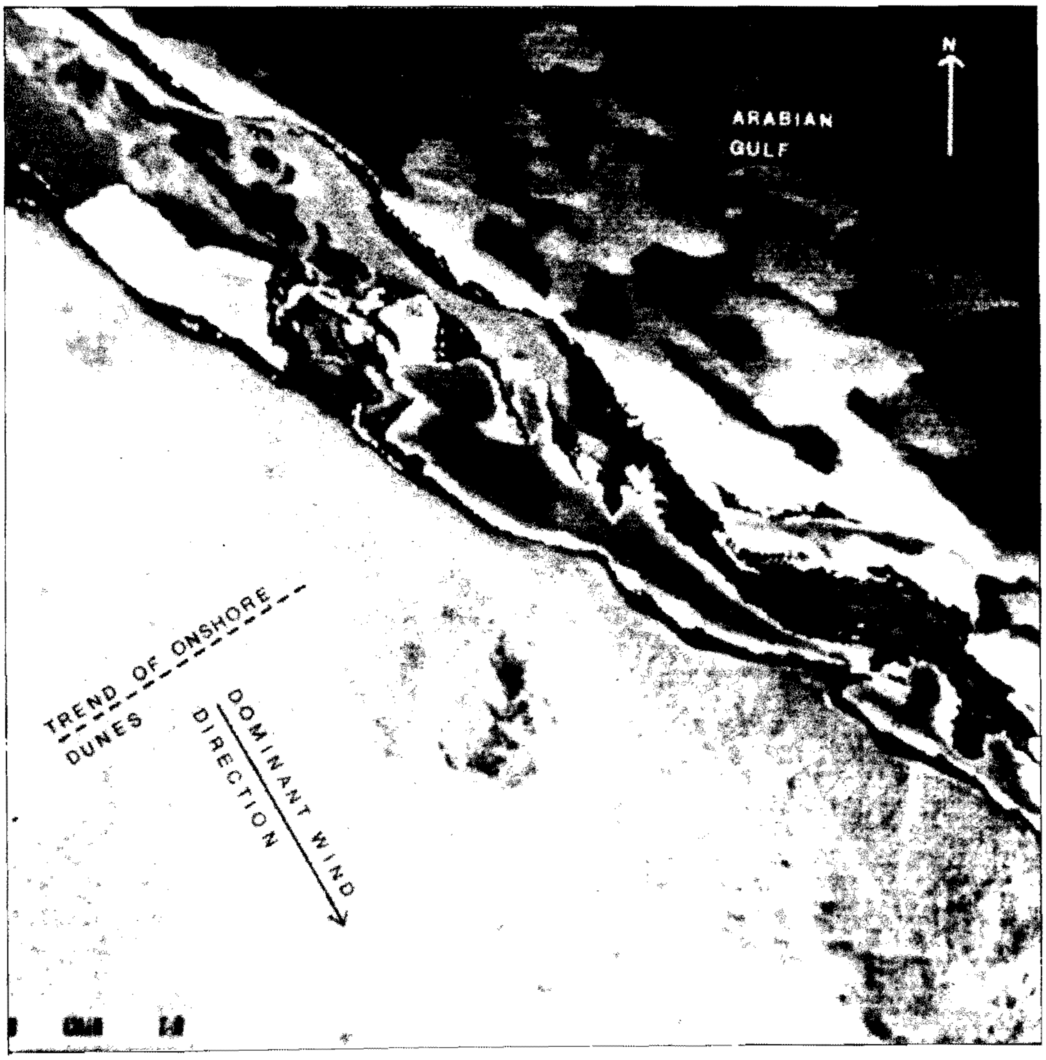

FIG. 17. Submerged sand dunes in the Gulf of Bahrain formed during lower stands of sea level (Al-Hinai *et al.* 1987).

was cut off. This is a good evidence that the ancient, shrunken Arabian Gulf of the Late Pleistocene provided much of the sand which now forms the Rub' al Khali. There is also evidence that the Arabian Gulf may have been as much as 2.5 m higher in the Late Pleistocene and that it retreated in Holocene time (Doornkamp *et al.* 1980). This would only accout for minor marine incursions and the contention of Holm (1960) and Felber *et al.* (1978) that the Arabian Gulf was 150 to 160 m above its present level is clearly untenable, as shown by McClure and Vita-Finzi (1982). Thus, although a great Quaternary marine incursion, viewed by Holm (1960) as responsible for much of the Rub' al Khali Desert, is impossible, it is considered that alluvium and wadi material from the once dried or shrunken Arabian Gulf was blown southward by the prevailing shamāl winds to provide much of the sand now present in the great sand dunes of the Rub' al Khali Desert. The Plio-Pleistocene alluvial fans also provided alluvial debris (McClure 1978) by the erosion of Neogene and Paleozoic siliciclastic sedimentary rocks, in addition to quartzose wadi sand derived from the erosion of the Arabian Shield.

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تطــور صـــحراء الربـــع الخـــالي

ستيورت إدجــل

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المستخلص . يعتبر الربع الخالي أكبر منطقة في العالم مغطاة بالكثبان الرملية ، إذ تبلغ مساحته ٦٤٠,٠٠٠ كم^2 . وتعود نشأته إلى العصر الرابع المتأخر . هذا وقد تم ملاحظة كثبان رملية مستديرة تعود في عمرها إلى عصر البلايستوسين (٧٠٠,٠٠٠ سنة) . ولا يوجد أي دليل على تكوُّن الكثبان الرملية أثناء الجزء الأول من الفترة الرباعية .

وقد تعاقبت فترات مطرة على الربع الخالي في الفترة الواقعة ما بين -١٧,٠٠٠ و -٣٦,٠٠٠ سنة نتج على إثرها عدد من البحيرات في المنطقة الجنوبية الغربية من الربع الخالي . وكذلك وجد عدد من المجاري المائية التي تنساب نحو الخليج العربي . وقد ازدهرت خلال هذه الفترة الحياة النباتية والحيوانية . هذا وقد تم العثور على بقايا أسلحة للإنسان الحجري بالقرب من بعض آثار البحيرات القديمة . كما تم رصد فترة جافة وسطية يتراوح عمرها ما بين -١٠,٠٠٠ و -١٧,٠٠٠ سنة . وكان هناك خلال هذه الفترة القليل من البحيرات ، ثم تبعها فترة مطرة في العصر الهالوسيني المبكر (-٦,٠٠٠ إلى -١٠,٠٠٠ سنة) كثُرت فيها البحيرات مرة أخرى مع بقايا الصَّوَّان النيوليتية ، وكذلك المجاري المائية في الجزء الجنوبي الغربي من الربع الخالي .

أمـا المرحلة المتأخرة من العصر الهالوسيني (-٦,٠٠٠ إلى الوقت الحالي) ، فقد غلب عليها المناخ الشديد الجفـاف مع بعض الفترات الرطبة . وقد أخذت أشكال الكثبان الرملية في منطقة الربع الخالي ، خلال هذه الفترة ، أشكالاً مختلفة ، منها الهلالي والطولي (العروق) . وتغطي الكثبان الرملية مساحة واسعة من الربع الخالي بارتفاعات شاهقة تصل إلى ٢٣٠م ومنفصلة عن بعضها البعض بمساحات واسعة ، وتأخذ أشكالاً مختلفة منها كثبان طولية (ذراع) ، وأخرى تأخذ شكل السيف المـائل ، وكثبان إهليجية الشكل . وتعود نشأة الكثبان الطولية إلى مسار حركتين من الرياح المتعاقبة ، إحداهما من الشمال الشرقي والأخرى من الجنوب الغربي .

أما خلال الـ ٦,٠٠٠ سنة المـاضية ، فلم يُرصد إلا القليل من المجاري المـائية في منطقة الربع الخالي . ويعزي وجود مدن على مشارف الربع الخالي ، مثل قرية الفاو إلى ازدهار الحياة في الفترة الواقعة بين -١٤٠٠ و -٢١٠٠ سنة ، نظرًا لوجود بعض مياه الري المحدودة في المناطق الطرفية من الربع الخالي .

هذا وقد تناولت هذه الدراسة بعض الأنماط التي توجد عليها الكثبان الرملية في الربع الخالي باختصار ، من حيث نشأتها وديناميات تكوُّنها .