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CURRENT PROBLEMS IN RESEARCH

Desert Geomorphology in the Arabian Peninsula

Distinctive land forms provide new clues to the Pleistocene and Recent history of a desert region.

Donald August Holm

Discovery that natural resources of oil and minerals abound in desert regions is the reason for the recent penetration of the great deserts; it has resulted in learning how to cope with the problems of living and working in an arid environment. Exploration in general has accelerated rapidly since World War II, and in the case of the deserts, modern explorers have discarded the ancient modes of living and moving through these regions. The camel has been supplanted by the motor car, the powerful tractor truck, and the airplane; the simple wool tent has been displaced by air-conditioned trailers and portable living quarters. Water supply for exploration has been taken out of the realm of the chance finding of isolated water holes and placed on a dependable basis with the aid of hydrogeology, drilling, and pumping equipment. Mapping by the traditional methods has been reinforced by aerial photographic coverage and geodetic controls. Photogeology has become an important tool for the field geologist, enabling him to check and identify the geology of critical areas on the ground and to carry out mapping operations in greater detail and with pin-point thoroughness.

The author is a senior geologist with the Arabian American Oil Company, Dhahran, Saudi Arabia.

In early stages of exploration in Arabia, two- or three-man surface geology field parties moved through the country with Badawin guides, but as exploration advanced, other methods were utilized. The shift from the small surface geological party to the large structure-drilling group meant a substantial increase in the logistics problem. Transportation of drilling units and their accompanying camping equipment across great distances of difficult terrain required knowledge of the surface of the area penetrated. Today, as drilling and geophysical crews carry out their programs in the Rub' al Khali (one of the largest sand deserts in the world), they are drawing on the knowledge gained by their predecessors during the last 27 years. In addition, their problems can be simplified by systematic studies of terrain and trafficability preceding their entry into the unknown parts of the Rub' al Khali. The earlier approach to the problems of logistics, with the ever-present need to get to the next location, was the necessarily pragmatic approach of trial and error.

In the pragmatic process one learns something of sand dunes in the course of getting trucks stuck in the sand, and something of the saline flats on the Persian Gulf coastal plains, where such flats can engulf the unwary driver and his truck without warning. Hard experience with soft sands and *sabkhah*'s (saline flats on coastal plains) taught field men to recognize the danger of these invitingly smooth sand plains and to avoid them for more passable terrains.

In general, though reports assessing oil potentials leave little room for geomorphic description, over the years, in the moving back and forth across the sand and rock areas of the peninsula, the details of land forms have come to fit together and the broader questions of origin have gradually emerged.

In the present stage of accumulated information, many of the geomorphic problems in the Arabian peninsula present more questions than answers: What factors contribute to the emplacement of large sandy deserts? What causes the great variety in sand-dune shapes? What factors control the size of dunes? Can the movement of sand be controlled by applying knowledge of the natural behavior and characteristics of the moving sand itself? What causes broad gravel plains in Arabia? How old is the Persian Gulf and what features are identified that are pertinent to its geomorphic history? How do *sabkhah*'s form? Did the main wadi systems that dissect the steppes of the Najd once flow westward instead of toward the east?

These and other questions constantly badger the field men as they move across the surface of the peninsula, aware of the details but without time to integrate them into a whole. Let us consider some of the facts that have been observed in connection with these problems.

The Emplacement of Large Sandy Deserts

At least one-fourth to one-third of the land area of arid regions is covered with sand. The Arabian peninsula, with a total area estimated at 1,060,000 square miles, has sand cover on at least 300,000 square miles. The Rub' al Khali alone has an area of 230,000 square miles. The interior *nafud*'s (*1*) and the

Dahna make up most of the rest (see Fig. 1). Why do these *nafud*'s accumulate where they do?

Aeolian processes are active today and probably were active during times following glacial maxima in the Pleistocene. There may have been alternations of dry and moist climates. In support of this assumption, the discovery of the remains of *Hippopotamus* (*2*) and water buffalo in deposits underlying sand dunes in the southwestern Rub' al Khali indicates that there was a moist climate preceding deposition of the sand dunes. Whether this was a Pleistocene or an earlier climate is at the moment not known. Observation of dune patterns in two widely separated areas suggests that at least two dune cycles have been in operation: (i) in the western Rub' al Khali south of Wadi Dawasir, and (ii) in the north central Dahna, north of Rumah.

Where do these large sandy deserts occur? In the Arabian peninsula they are found in areas of low relief, frequently in long, narrow, low plains bounded by scarps and dip slopes (in the Najd) or in broad basins of low relief like the Great Nafud and the Rub' al Khali (*3*, *4*). Why does sand accumulate on plains? Probably gravity has as much to do with it as the wind. Dunes, as a rule, do not form on elevated landscapes, because of a principle, stated by Bagnold (*5*, p. 201), that "the rate of removal or deposition per unit area at any point on the surface is proportional to the tangent of the angle of inclination of the surface at that point." This is true whether the slope is on a dune or a hillside. An increase in angle of slope increases the wind velocity and the capacity of the air to carry sand. A decrease in angle of slope causes a drop in velocity so that sand is deposited. Sand is carried upslope over mountains and through passes and deposited on the slopes below. As long as the tangent of the angle of slope is negative, there must be deposition. Thus, sand is more easily deposited on descending slopes and low places than on uplands.

The sources of sand for the *nafud*'s and Rub' al Khali have been, and still are, numerous. The primary sources are crystalline rocks exposed in the uplands of the peninsula. From them, wadis carry alluvium to flood plains and deltas in the lowlands, where aeolian processes winnow out the sand and transport it. Strand lines of lakes and the sea are other potential primary sources of sand. Secondary sources are outcrops of sandstones upwind from dune fields and gravel plains in which unconsolidated clastic sediments are partly protected by the veneer of gravel, often a rich source of sand. Dune fields also lose sand to others downwind. The wind thus assumes a major role in the distribution of sand and its concentration in *nafud*'s and other sandy deserts.

The wind regime of the Arabian peninsula is complex in detail but simple in the broad view. The region lies within the trade-wind belt of the Northern Hemisphere. Westerlies from the Mediterranean enter the region in the northwest and travel toward the Persian Gulf and then swing south and southwest through the Rub' al Khali, toward the Yemen. The air masses of the shamal (*6*) appear to divide south of the Trucial Coast along the 53rd meridian, part bending off to the southeast, the rest back to the southwest. The effect of the monsoons is in the opposite direction, providing a reversal of winds for the southern Rub' al Khali at least.

The wind regime in the Najd is less well understood, primarily for lack of information. However, the *nafud*'s in the north central Najd respond to a wind regime that encompasses winds from every point on the circle, with formation of dome-shaped dunes, pyramidal dunes, and many variations of the sigmoidal dune (*4*). In the eastern Rub' al Khali, a similar regime gives rise to thousands of pyramidal dunes.

Twice a year, in December–January and May–June, the shamal season of northwest winds occurs. The length of the shamal season varies from year to year but may range from a few days to 50 or more. It is similar to the khamsin of Egypt. The shamal is familiar to all residents of the Persian Gulf region as the time of year when the air is filled with dust and sand. The winter shamal is less noticeable because of cooler and moister weather. The main movements of sand in the coastal plains of the Eastern Province appear to occur in the shamal seasons, with a rate of 38 percent of the total dune movement for the year (*7*).

The spring wind regime is complex. In the Najd it is extremely variable in direction and intensity, ranging from southwest to all parts of the compass and from zephyrs to storms and gales. The Rub' al Khali likewise has a variable spring wind regime, with easterly zephyrs alternating with southeast gales and shamals. In the southeastern Rub' al Khali field parties report winds from all directions. Occasional gales arise with velocities up to 75 miles per hour. The periods of high winds are those in which mass movements of aeolian sand are greatest.

The Great Nafud receives winds dominantly from the west, but there are less frequent reversals from the east, and locally within the Nafud there are occasionally winds of variable direction. Little is known about the Great Nafud and its climate. Observations about it are derived almost entirely from an examination of the dune patterns on aerial photographs.

Broad sandstone outcrops that lie upwind and west of the Great Nafud supply sand. The Dahna and the *nafud*'s west of it apparently derive sand from the Great Nafud and are nourished, in addition, by the alluvial deposits brought down by Wadi ar-Rimah to the region between Buraidah and 'Unayzah. The gravel plains bordering Wadi al-Batin have contributed sand to the dune areas south of them. The southern Dahna, the Jafurah, and the western Rub' al Khali have all been nourished by material from gravel plains. The Rub' al Khali probably derives sand from highlands on three sides, as well as from the coastal dunes and beach deposits of the southern Persian Gulf.

What we know of the wind regime for the peninsula, scanty as the data are, points to sand accumulation in two large basins, with elongate *nafud*'s connecting them, and additional concentrations in the coastal areas downwind from the Persian Gulf.

The Great Variety of Dune Shapes

A study of aerial photographs of sand-dune regions in Arabia reveals a large variety of dune shapes. The variety and complexity of dune patterns in the Rub' al Khali is far greater than is generally realized (Fig. 2). The *nafud*'s of the Najd have dune complexes that appear to be peculiar to that region (*4*). The Great Nafud has the unique crescentic hollows described originally by Blunt (*8*) (Fig. 3). There are also linear complexes and simple transverse dunes, with a few scattered pyramidal dunes in the southeastern part. The Dahna, with its great arc more than 1200 kilometers in length, has had a complex history, which has affected dune shapes. Its north-central part is perhaps most interesting. Here there are sigmoidal dunes (*9*), tuning-fork dunes, linear dunes, and pyramidal dunes (*10*) in a perplexing array.

The most important factor in the shaping of dunes is the wind and its pattern, with the relative supply of loose sand next in importance. A change or shift in the wind shifts sand, either removing it or depositing it. The shape of a dune changes constantly while the dune bulk is increasing or waning. A slight change in the dune surface shifts the course of the sand stream. Shifting winds are more effective than constant winds in producing variety of dune shape. Turbulence appears where wind streams are mixed by passage over or around an obstacle. Turbulence is a very effective tool of dune sculpture, whether acting at high or low velocities.

Streamlined flow in one direction tends to build barchan dunes. Reversal of the wind direction tends to destroy the barchan by cutting off the top of the slipface and building a new one with a convex arc down wind on the back of the old one. Shifting the wind to a side quarter tends to shift the dune sideways, intensifying the slipface on the windward horn and rounding it off on the leeward horn. A shift to 45° tends to elongate the opposite horn [contrary to Bagnold (5, p. 223)] to form an incipient linear dune. If the winds are alternating, roughly equal, and from opposite directions, the barchan is transformed into a sigmoidal dune (Fig. 4).

Pyramidal dunes form from sigmoidal dunes when the winds beat around the compass. If a sand-laden wind intensifies from one quarter, it will modify pyramidal dunes into incipient giant crescents, by piling sand on the windward side. Under slightly different conditions (perhaps lower velocities), small sigmoidal dunes detach themselves from the pyramidal dune and migrate across the floor. The process of sigmoidal dunes merging with and detaching from the pyramidal dune is one of the most fascinating actions in the desert.

The sigmoidal dune joins in other ways to form linear dunes of great complexity. One of the most peculiar and unique is the "hooked dune," so-called from its resemblance to a fishhook or a shepherd's crook. Badawin of the south-

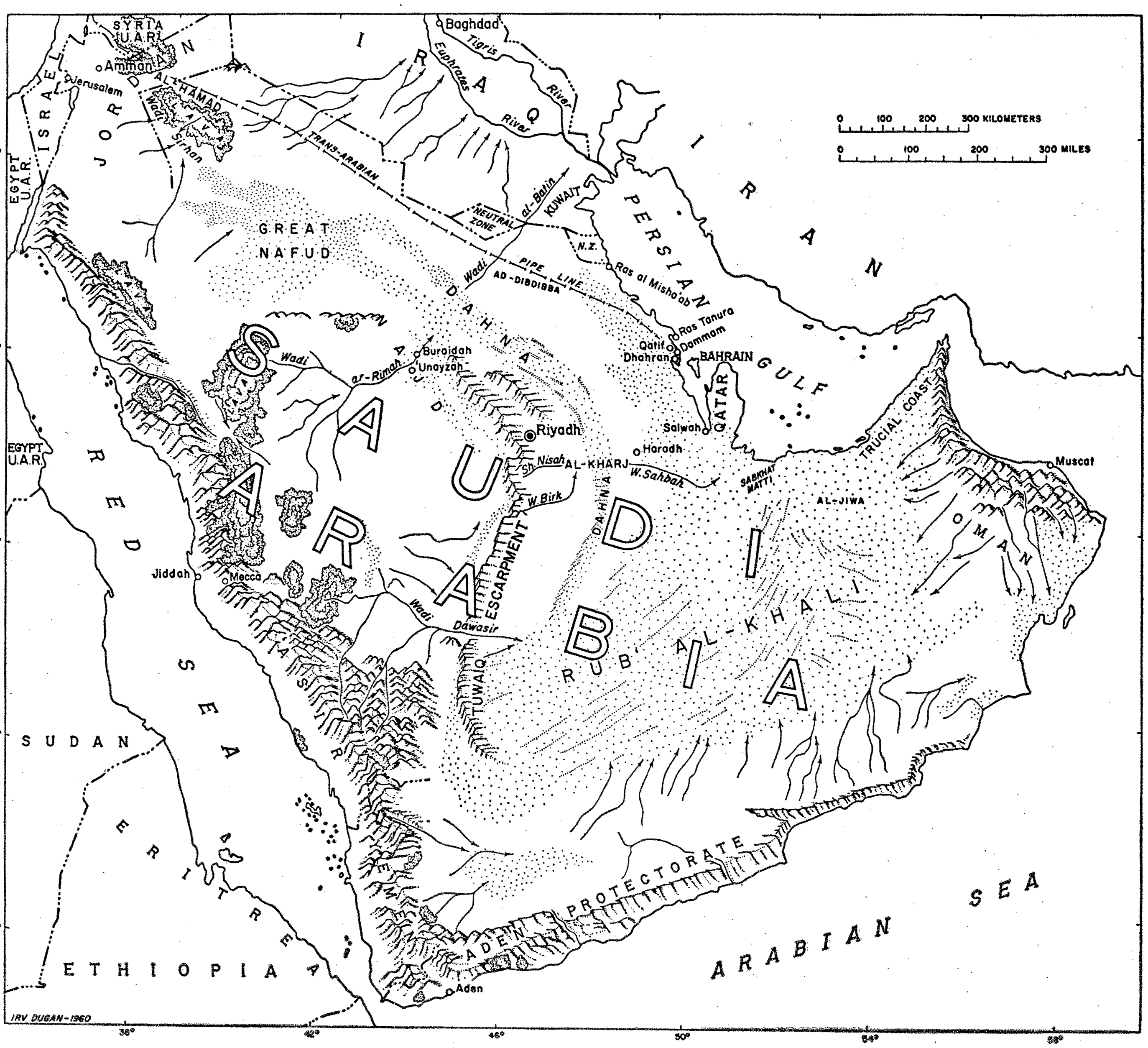

Fig. 1. The Arabian peninsula.

ern Rub' al Khali, where this form occurs, call it "curved or wandering," with such names as *'irq ma'kuf, 'irq muta'akkif* or *'irq muhayyar*, drawn from resemblances to the curled tail of the saluki dog (*11*). The hooked dune has two parts, a long sinuous sigmoidal ridge, forming the shaft, and a well-defined crescent, forming the hook. The hooked dune in the Rub' al Khali is usually oriented with the shaft pointing down wind or southwest. There is a gradual change in form and complexity of the hooked dune as one goes toward the northeast. The shafts or linear elements become shortened to the length of a kilometer or less, and the slipface widens and joins with several others to form a double or triple hook. The physical relief of this variety of the hooked dune is greater than in the simpler forms, and the dunes are spaced much closer together. The hooked dune is the product of north, northeast, and southeast winds, in that order of importance. It predominates in the southern Rub' al Khali and is not known elsewhere in Arabia.

Other dune complexes too numerous to describe are the giant crescentic massifs of the Jiwa area (Fig. 5), dome-shaped dunes (*4*), long linear complexes of sigmoidal ridges in branching or coalescing patterns, chevron-shaped ridges in linear belts, pyramidal dunes shaped like four-pointed paper pinwheels, and the ubiquitous rolling transverse ridge without slipface, called by the Badawin *zibar*, which is present in many interdune areas and which in the central Rub' al Khali is a dominant form. It is out of order to include the *zibar* in dune complexes, but it was mentioned in this connection, because it is a form of low relief that develops in between many complexes and, in particular, in the low areas between linear belts. *Zibar* forms a hard, smooth sand surface traversable by motor vehicles.

The shape of dunes is also affected by the presence or absence of moisture and vegetation. Rainfall may saturate the dunes to a depth of half a meter. This is enough to germinate seeds or spores if the air temperature approaches 80°F. Water works upward by capillary action into the bases of dunes from *sabkhah* floors beneath, or into dunes from underlying aquifers. Where the moisture supply is relatively constant, perennial shrubs with long roots can establish themselves. Sand areas with moisture and vegetation lose the definite and clean forms of dunes and become intricate hummocks and narrow passages of erratic shape.

The presence of certain shrubs or xerophytic plants is indicative of camel-grazing lands, and many parts of the desert have been named by Badawin accordingly. The names also indicate

Fig. 2. Transverse and linear dune complexes, due to frequent wind changes, and exploration party camp in eastern Rub' al Khali. Aerial view looking northwest. [Arabian American Oil Co.]

something of the topographic form. Thus, *zibar* is rolling, trafficable, smooth, firm sand, without permanent vegetal cover. *Marbakh* is similar in form but carries a scattered cover of a perennial shrub, *'abl* (*Calligonum comosum*) and occasionally a sedge (*Cyperus conglomeratus*) called *'andab*. *Marbakh* tends to deflate slowly and thus loses relief, in comparison with barren sand dunes nearby. Shrubs on the side slopes of pyramidal dunes and large linear complexes tend to stabilize the slope until they are covered by freely moving sand. Every obstacle in the path of the sand stream deflects the stream and is a potential cause of a change in dune shape.

The spacing and relief of dunes are contributing factors to the shapes of dunes. Low relief causes less turbulence in the air stream than high relief, and therefore less change in dune form.

The equilibrium of a sand dune is like a delicate chemical state of equilibrium; the slightest change in the conditions involves changes in the state of equilibrium. Studies in petrology and sedimentology of aeolian sands and investigations of micrometeorology of the air stream passing over dune surfaces are recommended.

The size of dunes varies greatly. There does appear, however, to be a limit of maximum height for any given dune field. The limiting factors have been discussed by Bagnold (*5*, chap. 12).

The size of dunes is not always governed by the shape, as there are small crescentic dunes a few meters high, and tens of meters wide, and others of similar shape a hundred times as large. Pyramidal dunes are seldom less than 50 meters in height and range up to more than 150 meters, with diameters of 1 to 2 kilometers. Sigmoidal dunes vary from tiny sharp ridges, a few meters high to huge ridges 100 meters high. Tiny "tear-drop" dunes 10 to 15 meters in diameter are found along the southern boundary of the Rub' al Khali (Fig. 6). These are so small that they are not resolvable on aerial photographs with a scale of 1:60,000, though on photographs of scale 1:10,000 they may be studied in detail. A broad band of long, high parallel linear dunes ('uruq) (*12*) forms the southern part of the Rub' al Khali westward of the 50th meridian; it is called " 'Uruq al-Qa'amiyat" (Fig. 7). The ridges attain heights of 100 meters or more, stretch to lengths of 20 to 200 kilometers, and are usually 1 to 2 kilometers wide. The upper surfaces of the ridges are covered with a complex of branching linear and sigmoidal dunes, where local relief is usually less than 50 meters. Dune massifs in the eastern Rub' al Khali with heights of 500 to 700 feet (153 to 213 meters, are reported by Thesiger (*13*). Unverified verbal reports of dunes with heights of 1000 feet (330 meters) have been received, but to date, no surveyed heights greater than 200 meters have been recorded.

Dunes in the Great Nafud have been reported by field parties to be 100 meters high and described as gigantic (*14*). I have surveyed pyramidal dunes in the north central Dahna with heights of 150 to 170 meters.

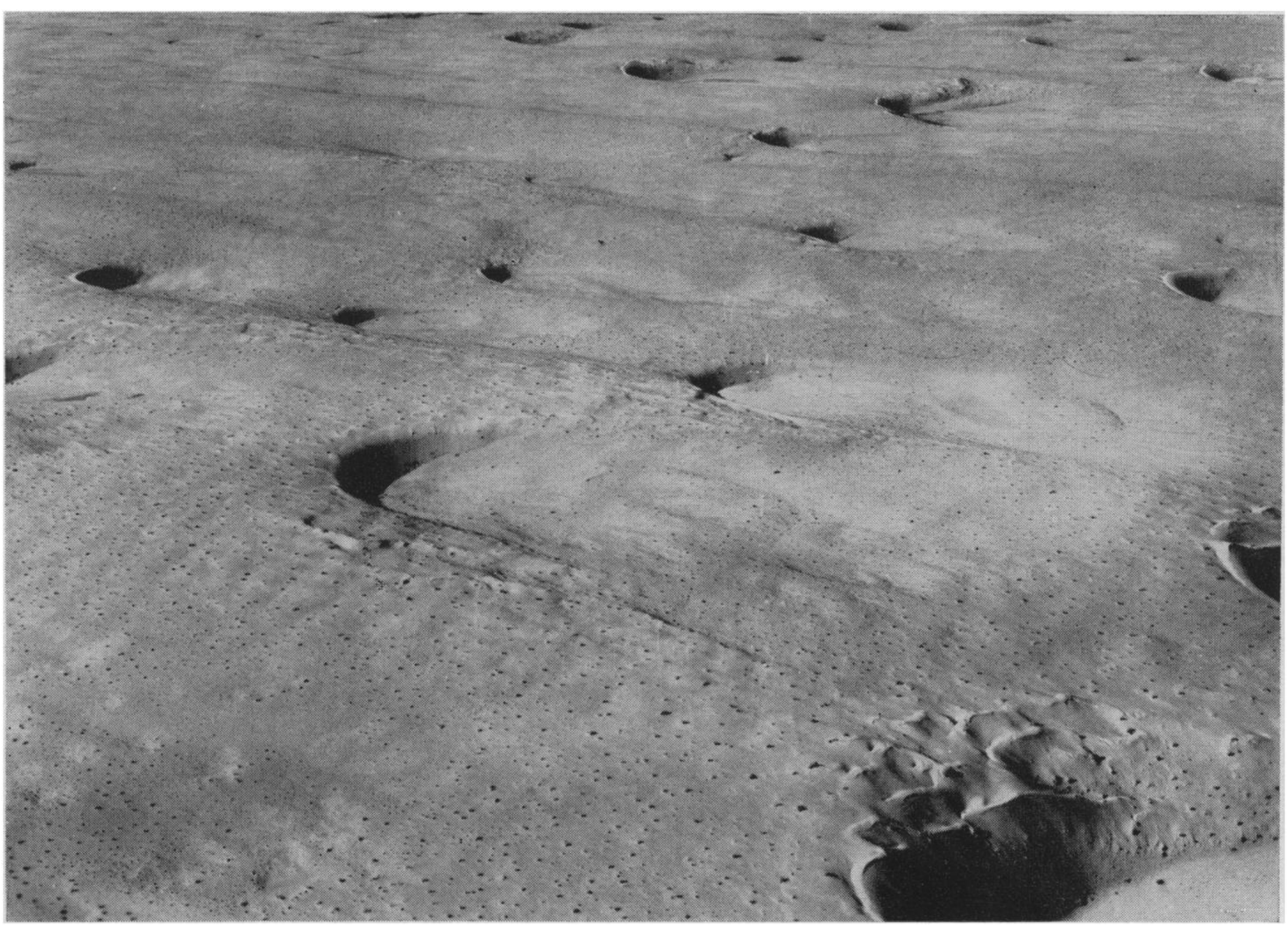

Fig. 3. Giant crescentic hollows and slipfaces in the Great Nafud, looking northwest. [Arabian American Oil Co.]

Sand Control

The problem of sand control may become crucial where industrial installations, houses, power lines, roads, railroads, walls, airstrips, and communities have been built in the path of moving aeolian sand. The immediate problem is that of protecting installations from influx of drift sand. No less important is the matter of stabilizing or breaking up sand dunes before they encroach upon an installation.

Utilization of plant cover to stabilize sand is an old, well-known method, much publicized in Europe, and used by Arabs near Buraidah for several hundreds of years. Plant control is hardly feasible in many arid lands for lack of water. Artificial procedures have been devised, such as sand fencing, based on the principle of the snow fence, and the oiling of sand dunes and surfaces with a high-gravity, waxy, penetrating oil (*15*).

Geomorphic methods of sand control have been suggested by Barclay (*16*) and Bagnold (*5*, pp. 36, 71, 153–159, 169, 170, 180, Fig. 53). Both propose spreading gravel or pebbles on a sand surface to reduce sand movement. Bagnold advocates spreading pebbles on dunes as a method of "killing them." Actually, any material the size of pebbles, such as loose aggregates, shells, broken glass, pottery, or cinders, and even dry camel dung will serve the purpose.

Origins of Gravel Plains

Gravel plains in Arabia are either alluvial or residual.

Alluvial gravel plains may be divided into several kinds: (i) river deltas; (ii) river flood plains; (iii) intermittent stream flood deposits; (iv) fans; and (v) bolson deposits.

Residual gravel plains are the product of weathering and deflation of conglomerates.

There are also regoliths, or residual stone desert plains, where there has been no transportation of pebbles or cobbles but concentration in place by weathering and deflation of cherty limestones or similar rocks composed of hard and soft materials.

The climate of Arabia today is so arid (less than 100 millimeters of precipitation annually) that integrated river systems capable of flowing to the sea are practically nonexistent. The wadis in Pleistocene times were undoubtedly less intermittent than today, and a few of them apparently reached the sea. Among the latter, the Wadi ar-Rimah–Wadi al-Batin system (continuous, although the former is now clogged by *nafud*'s) is one of the larger systems, reaching from headwaters in northwest Najd to the Tigris-Euphrates Valley in southern Iraq.

The Rimah-Batin Wadi system, during one of the major pluvial periods of the Pleistocene, apparently carried rushing floods loaded with rock debris, eroded from the crystalline uplands and the sedimentary steppes of the northern Najd. The floods cut narrow, steep-walled canyons through limestone plateaus and then, as the floods spread out on the coastal plains, dropped their loads in a great, delta-shaped area called ad-Dibdibba, which reaches from its apex at 28°N and 45°30′E almost to the southwest edge of the Tigris-Euphrates Valley. The surface of this triangle is a gently sloping gravel plain, bisected by the trough of the present-day Wadi al-Batin. The gradient across this plain is 1.2 meters per kilometer. Its surface is covered with gravel trains divergent from the apex toward the outer edge. Other gravel beds have been observed in the valley walls of Wadi al-Batin, and also in wells drilled through the gravel. Cobbles and pebbles show a gradual decrease in size toward the outer edge. The materials that compose them are quartz, igneous rocks, metamorphic rocks, and limestones, with finer sediments interspersed. Deflation by winds has smoothed the plain into a very flat, gently undulating surface, veneered with gravel, and when dry, it is traversable by vehicles in any direction. Because of the deltaic shape, the distribu-

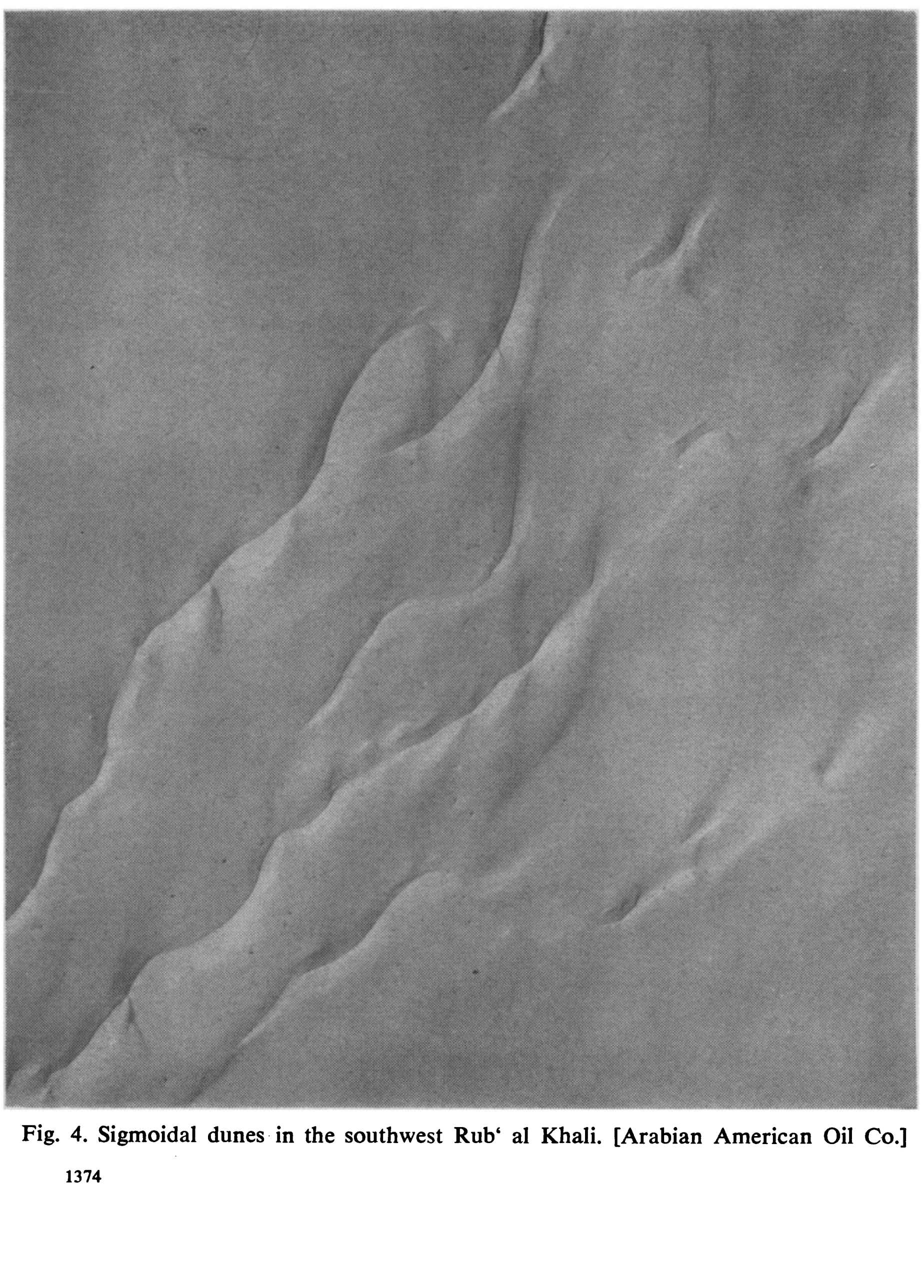

Fig. 4. Sigmoidal dunes in the southwest Rub' al Khali. [Arabian American Oil Co.]

tion of alluvium, and its position between a wadi system and the coastal plain of a hypothetical Pleistocene Sea, the plain is classified as a delta.

The Nisah-Sahbah wadi system—which drains the central Tuwaiq Plateau, runs eastward just north of the 24th parallel, and breaks out of the confines of the interior steppes at Haradh—has deposited a similar gravel plain with even more marked characteristics of deltaic origin. The apex is at Haradh, and from this point a series of divergent gravel trains fan out toward the Persian Gulf. The margins of the plain have been indented by subsequent inroads of the sea, but aerial reconnaissance has enabled us to trace some of the gravel trains across Qatar and around the southern end of Qatar to the western edge of Sabkhat Matti. The gradient across this plain varies from 1.02 to 0.88 meter per kilometer. The trench of a younger Wadi Sahbah (now choked with sands of the Jafurah) cuts across the plain from Haradh southeastward and out to the Gulf just southeast of Qatar. The gravel trains are protected from deflation by the concentration of cobbles and pebbles in the ancient channels, so the trains now stand a few meters above the surrounding plains as inverted courses. The marginal areas of the plain show the results of dissection by a younger cycle of erosion, and this has been more drastic than dissection of the Wadi al-Batin delta. The shape of the plain, approaching that of the Greek letter *delta*, and the divergent fanning of gravel trains, along with the grading of sediments toward the Persian Gulf, suggests that this, too, can be classified as a delta. The presence of foreset beds of sands and silts at several places along the margins beneath the gravels further suggests a deltaic origin.

A third wadi system, that of the Wadi Dawasir, has deposited a broad, gently sloping gravel plain, parts of which reach to the southern borders of the Sahbah delta near Wadi Jaub. The analogy is suggestive, but as the Dawasir plains are largely covered by sand dunes of the northwestern Rub' al Khali, the origin remains questionable at present. Philby (*17*) suggested that Dawasir and perhaps other systems in the southwest in previous times may have reached across the intervening areas to the Persian Gulf.

River flood plains in Arabia are less conspicuous than the deltaic plains. The ancient course of Wadi al-Atj, which drained the northern Tuwaiq plateau and departed from the steppes near Ma'aqala, left gravel trains, deposits of red and brown sands, and other alluvium (now erratically exposed where erosion has uncovered them) in a widening band that extends northeast from Ma'aqala almost to the southern edge of ad-Dibdibba plains. The Pleistocene history of this wadi system is obscured by sand dunes and recent deposits which cover its lower reaches. The evidence does not fully support the existence of a deltaic plain, but does suggest the possibility of a flood plain.

There is another gravel feature, the Wari'ah gravel ridge, which is quite a puzzle. This ridge is about 100 kilometers long and 1 to 2 kilometers wide and extends east and west, along the southern margin of ad-Dibdibba. It is protected from erosion by the heavy cover of coarse-to-medium cobbles and pebbles, and it stands about 10 to 20 meters above the surrounding plain. F. S. Vidal and I found a few crude, rolled artifacts in the gravels in 1958. Wari'ah seems to be the remains of an old stream course heading east, but very little else is known of it.

Many long, narrow, and smooth gravel plains are found below the Tuwaiq, Dhruma, Khuff, and Tawil escarpments that can be classified as intermittent stream deposits.

Fans frequently develop where intermittent streams debouch from steep scarps onto flatlands below. There are many recent fans below the Tuwaiq scarp. Gravel fans which have been separated from the parent scarp are found on the south side of Wadi Sahbah, east of al-Kharj. These are composed mainly of limestone debris, derived from uplands to the south. (I

Fig. 5. Giant crescentic dune complex, 2 to 5 kilometers across, in northeast Rub' al Khali. [Arabian American Oil Co.]

found a single, crude, rolled artifact of quartzite there in 1953.) Alluvial fans and pediments form around the bases of mountains in the crystalline complex of the Arabian shield, where relief and steep slopes are adequate for their formation.

Bolson deposits accumulate in enclosed basins with centripetal drainage. There are thousands of centripetal basins in Arabia, in sedimentary rocks as well as in the crystalline basement. I am most familiar with those found in the sedimentary areas, where relief is moderate and the dry lakes in the basins have reached maturity as silt flats. The Arabic name for these silt flats is *khabari* (singular, *khabra*). Gravels are seldom visible except in the margins, but where they are exposed by erosion, they are seen to underlie the silts, occasionally in several layers.

Residual gravel plains are formed from the weathering and deflation of conglomerates. The Biyadh plain, which extends southward from Wadi Sahbah to Wadi Dawasir as a white, quartz-pebble plain, has been derived from a quartz-pebble conglomerate and sandstone which has been weathered and deflated in place. A similar plain covered with quartz-pebbles is located southwest of Majma'a in the Sudair region of the northern Tuwaiq.

The residuum left by the weathering and erosion of cherty limestones in al-Hamad in northwest Arabia forms plains sometimes miscalled gravel plains. As the residual chips of chert have not been transported by water but merely became concentrated in place by removal of the softer matrix, the terms *regolith* or *residuum* seem more applicable. Al-Hamad forms the stony plains of the great Syrian Desert, a truly inhospitable region to the traveler in the old days before motor cars and deep-water wells were available.

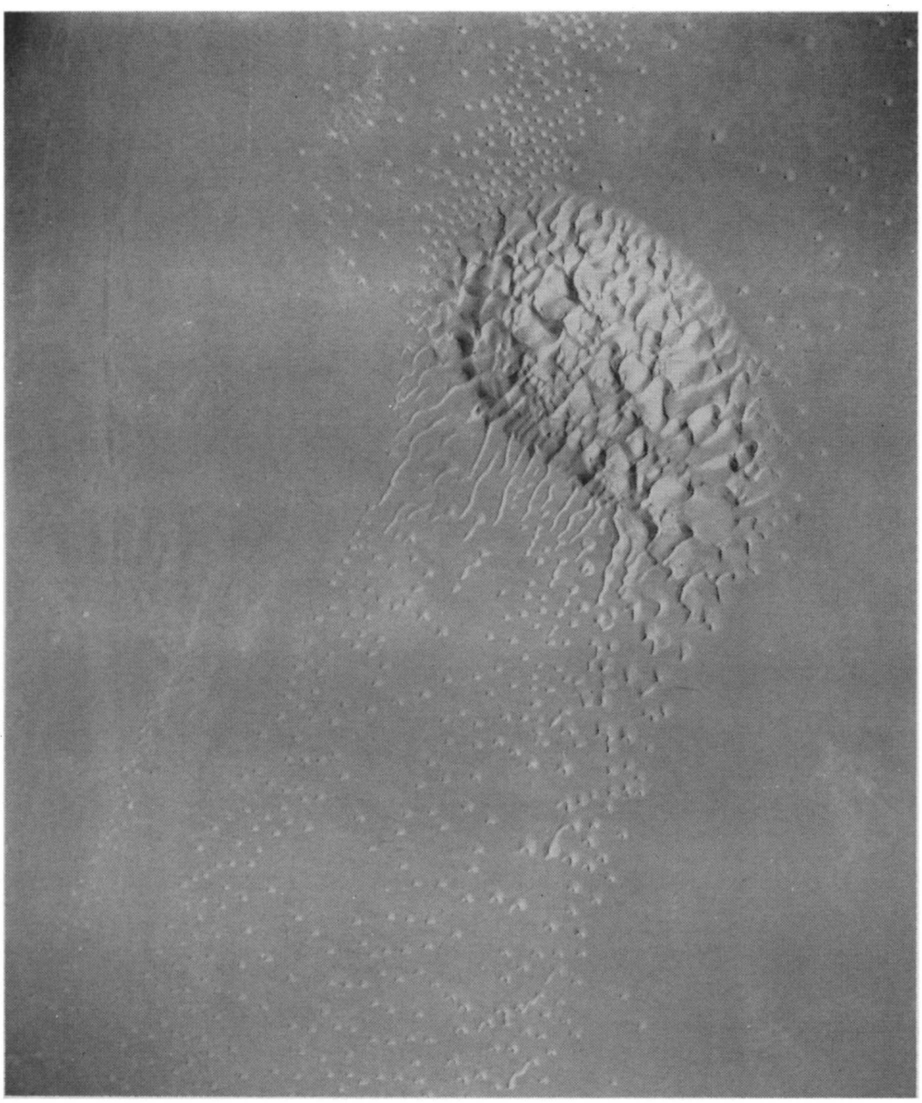

Fig. 6. Tear-drop dunes, small sigmoidal dunes, barchans, and an elliptical dome-shaped dune with smaller dunes streaming off down wind. Winds from north northeast and east southeast. Southern Rub' al Khali. [Arabian American Oil Co.]

Gravel plains are significant in the deserts for several reasons. One is important to the modern exploration geologist. Gravel plains may cover broad areas of rock formations he wishes to explore. This means that structure drilling and geophysical methods of exploration are required, with greater demands on the budget. Another reason is that gravel plains are good trafficable surfaces for motor transport, and airstrips for light aircraft are easily prepared.

Age and Geomorphic History of the Persian Gulf

The absence of terraces on the Arabian side of the Persian Gulf is conspicuous. There are, however, traces of higher stands of sea level in the form of shell beds, serpulite reefs, and calcarenites, at several levels. East-facing cliffs in the Eastern Province, as opposed to west-facing cliffs in the Najd, and possible wave-cut benches on Jibal Dhahran, on Jabal Barri, and in the southwestern part of Qatar suggest the possibility of higher sea levels in Recent or Pleistocene times. Lees (*18*) mentions terraces on the west side of the mountains of Oman at 1230 feet (and mentions that the northern end of this mountain range, the Musandum Peninsula, is submerged, forming a drowned coast). The coast lines of the Eastern Province and Trucial Coast are largely "emergent." Shingle, in what appears to be a beach remnant near Nibak at the eastern edge of the Sahbah deltaic gravel plains, stands at an elevation of about 110 meters.

Sabkhah's (*19*) (discussed below) are found inland from the coast at elevations up to 150 meters near Hofuf. *Sabkhah*'s are being formed today along the coast by aeolian sand filling embayments. If the high *sabkhah*'s are formed by the same process, it is logical to assume that there were embayments of the Gulf at the higher levels.

The lowest of the shell beds is found 1.5 to 2 meters above sea level, along the coast between Ras al-Misha'ab and Salwah, and again along the Trucial Coast. It appears to be undisturbed by movements of the crust. It may be equivalent to wave-cut benches in rock in the harbor at Maskat, at a similar low level. The bench in the Eastern Province carries abundant small *Tur-*

ritella-like shells and serpulite reefs. It is quarried for light aggregate, used in roofing and in seal-coating of asphalt paving in Dhahran. Cornwall (*20*) may have had this level in mind in his assumption of a recession of 5 to 10 feet in historic times. More accurate dating of this shell horizon would be helpful.

The next higher marine deposit is a calcarenite composed of miliolites, calcareous pellets, and quartz sand, interbedded with dune sands. The calcarenite is cemented by calcium carbonate. It forms low cliffs along the shore from Ras Tanura to Ras al-Misha'ab. Remnants of the formation are found on the northeast side of Jabal Barri, in the vicinity of Qatif, and at Jabal Muraiqibat, south of Dammam. It forms stacks and islands as well as part of the coastal plain of the Trucial Coast. It laps on the Tertiary surface of al-Baynunah, south of the Trucial Coast. Farther north, it borders remnants of *sabkhah*'s in the area east of Hofuf and in Wadi al-Miyah. Beds of the calcarenite have been found in cores taken at Ras Tanura (Najma), and it is thought to dip under Recent deposits on the floor of the Persian Gulf.

The calcarenite has been given an informal name, "Bahr formation," from its first observed occurrence in Jabal Bahr, offshore from the village of Jubail (*21*).

The Bahr formation, in addition to the outcrops mentioned above, underlies sand dunes on the coastal plain between Ras al-Misha'ab and Ras Tanura. Its presence can be detected by the occurrence of white calcareous or quartz sands. When the Safaniyah-Ras Tanura pipeline was constructed, Bahr formation was exposed frequently by the ditching machine. It was found bordering some of the *sabkhah*'s which extend inland from the coast, and in other areas where its presence was suspected, holes bored with a post-hole auger were used to determine its presence. White dunes, derived from the Bahr formation, occur commonly from Dhahran southward to Salwah and are sharply differentiated from dunes of the Jafurah by the change in color from white to golden tan.

There are references in the literature (*22*) to occurrences of a miliolite of Pleistocene age, on islands in the Persian Gulf and on the coast of Maskat. It would be interesting to know if these are correlative with the Bahr formation.

Further study and mapping of the Bahr formation would clarify Pleistocene history of the Persian Gulf.

The evidence for a higher stand of Persian Gulf waters provided by east-facing cliffs and wave-cut benches needs careful study. The exact relationships of these features to possible marine sediments of Pleistocene age are not known. An advance of the sea to the base of these cliffs at an elevation of at least 150 meters is clearly possible. Evidence for tilting towards the

Fig. 7. 'Uruq al-Qa'amiyat in southwestern Rub' al Khali, looking northeast. [Arabian American Oil Co.]

north is suggested by north-south alignment of *sabkhah*'s, with slopes inclined gently to the north.

The deltas of the Wadi al-Batin and Wadi Sahbah systems seem to indicate the possibility of an even higher advance of the sea at an earlier stage of the Pleistocene. The elevation of the apex of the Batin delta is 400 meters, and at the outer edge the elevation is approximately 100 meters—a difference of 300 meters in 250 kilometers, or a gradient of 1.2 m/km. The gradient of the floor of Wadi al-Batin is 1.12 m/km, too low for water to flow except in periods of very heavy rainfall. Water stands on the surface of the gravel plain and only flows for a short time after very heavy rains, when low places have been filled to overflowing. This seems to suggest the possibility that slight tilting to the southwest has reduced the gradient from that at the time the delta formed. A much steeper gradient than 1.2 m/km seems necessary for the transport of cobbles of the size found in the gravels.

A similar situation exists in the Sahbah delta. The elevation at the apex near Haradh is 300 meters and at the edge of the delta at Khashm Umm Huwaidh the elevation is 110 meters, a difference of 190 meters in 185 kilometers, or a gradient of 1.02 m/km. From Haradh to another point on the edge of the delta, near Ras Mushayrib where the elevation is 35 meters, the difference is 265 meters in 300 kilometers, or a gradient of 0.88 m/km. Again, the gradient seems too low for the transport of the cobbles found at the delta margin, so the question arises, "Was there tilting to the west and, if so, how much?"

A summary of geomorphic features suggests the possibility of higher stands of sea level in the Eastern Province of Saudi Arabia. These features are: (i) a low-level shell-and-serpulite bench; (ii) outcrops of the Bahr formation from sea level or below to 150 meters above; (iii) *sabkhah*'s from sea level to 150 meters above; (iv) wave-cut cliffs and benches inland; and (v) deltas of probable early Pleistocene wadis.

How Do Sabkhahs Form?

The *sabkhah* problem has two interesting aspects—one, purely geomorphic in the genesis of a coastal land form; the other, the relation of the *sabkhah* to the deposition of salts and evaporites intercalated with sediments in thin layers.

The *sabkhah* is a saline flat. The name is from the Arabic, and use of the term should be restricted to coastal regions. Saline flats in the interior basins, akin to playas of the American Southwest, are known by another Arabic word, *mamlahah* (*19*). The *mamlahah*, though often classed as a dry lake, differs from the type of interior basin called *khabra*, which has no salts or evaporites but is filled entirely with silts.

There are two types of *sabkhah*'s on the Arabian coast: (i) arenaceous, filled with sand, and (ii) argillaceous, filled with clay. The arenaceous *sabkhah* is formed by the filling with aeolian sand of an embayment of the sea and by the reworking of this sand filling by waves and currents. The process can be observed today south of Dhahran at Dohat Dhalum, particularly on a windy day. Many of the *sabkhah*'s along the coast show growth lines in subparallel arcs, marking former positions of the shore line. The surface of the arenaceous *sabkhah* is quite flat and smooth, with low gradients, of less than 0.5 m/km. During dry periods, capillary water in the sand evaporates and concentrates to a very saline brine, with eventual precipitation of salts near the surface. After rains, water stands on the surface, owing to saturation and high-tide levels. Water level subsides in dry weather to 0.3 to 1.0 meter below the surface. Water rising through pore space in the sand coats the grains, increases lubrication, and develops into a soft quicksand of low bearing strength. Evaporation of standing water on an arenaceous *sabkhah* forms salt crystals as a coating on the surface and sometimes forms a thick armor plate of salt. If this salty armor is buried by aeolian sand, it may be preserved until dissolved by a rise in water level.

Argillaceous *sabkhah*'s are formed as the result of the manufacture of calcareous mud by algae or other organisms in shallow coastal embayments. The process can be observed in Tarut Bay, and in the coastal *sabkhah*'s near Khursaniyah. The mud is wet, soft, and sticky, has very low bearing strength, and flows under pressure. Aeolian sand blown across the surface sticks to the mud and forms a layer seldom more than 1 meter thick. A layer of dry sand 1 meter thick, lying on soft mud, will support the weight of a moving light truck. Once wet, the sand softens, like quicksand, so that a heavy vehicle, and sometimes a light one, will sink through until it rests on its frame. A thin sandy crust may appear to be safe but should be tested carefully before one tries to drive out upon it. The surface layer of an argillaceous *sabkhah*, when not covered by sand, dries in summer heat. Where packed by traffic in the roadways, it hardens to the consistency of asphalt. Away from the roadways, the surface is generally unsafe, whether wet or dry.

Argillaceous *sabkhah*'s occur between Tarut Bay and Ras al-Misha'ab and are also numerous on the Trucial Coast. Sabkhah Matti, one of the largest in Arabia, is a compound *sabkhah*, both sandy and argillaceous. In both regions there are *sabkhah*'s with a surface which appears to be only mud but which, on testing, proves to be underlain by a firm subcrust. The latter may be a strong, thick layer of salt or gypsum or, more rarely, a layer of hardpan.

The *sabkhah* as a depositional source of salt, particularly in the case of intercalated layers of salt and sediment, receives little consideration from chemical theorists on salt formation. It is not unlikely that some ancient saline deposits, such as Permian red beds and salts, may have been formed in an environment similar to that of the *sabkhah*. I recall examining the cores from a wildcat exploratory well in eastern Arizona, with nearly 400 feet of intercalated red sandstone, siltstone, and salt. No layer was more than 1 foot thick, despite the fact that recovery of the core was high (*23*).

Tilting of the Arabian Craton

It is generally assumed that the Arabian Craton was tilted toward the sedimentary basin now occupied by the Persian Gulf through most of geological time since the Precambrian. Historical geological evidence supports this concept. However, in probable Pleistocene times, when the great wadis cut their courses in several limestone plateaus, several major wadi channels were cut through the Tuwaiq plateau, leaving canyons that are wider at the western ends than at the eastern ends. Wadi Birk, Wadi Dawasir (in the south), and three troughs cut through the central Tuwaiq—namely, Sha'ib Nisah, Sha'ib al 'Ausat, and Sha'ib Lihah—are all wider at the western ends than at the eastern. It has been assumed, as normal, that these wadis flowed eastward toward the Gulf. Were the notches, shaped like gigantic *V*'s, cut at the western ends of these canyons the results of normal stream erosion cutting into a dip slope that dipped downstream? Or did the streams originate in Tertiary times as west-flowing rivers, when the Afro-Arabian shield had not been uplifted?

In conclusion, the desert geomorphologist today finds that the desert is susceptible to systemic land-form analysis. Every land form in the desert has significance, if we can but determine what it means. Desert geomorphologists of the future, many of whom may come from the Middle East, will discover that there are still geomorphic frontiers in the Arabian deserts (*24*).

References and Notes

1. *Nafud* is the Arabic word for a large sandy desert, used mainly in the Najd.
2. A lower right molar tooth of *Hippopotamus* was found in 1955 by William Reiss, in the southwest Rub' al Khali, in beds underlying the dune sands. It resembled a specimen of *H. antiquus* in the Heidelberg Museum. Leakey, of the Coryndom Museum, Nairobi (personal communication), suggested that it might be identified as *H. gorgops* if more of the skull, with eye sockets, could be found. The specimen has disappeared from the Arabian American Oil Co. collections.
3. See map No. I-270-B-1 of the Arabian Peninsula (1:2,000,000) in *Miscellaneous Geological Investigations*, published (1958) by the U.S. Geological Survey and the Arabian American Oil Co., under the joint sponsorship of the Kingdom of Saudi Arabia and the U.S. Department of State, and maps Nos. I-213-B and I-214-B (1:500,000) in the same series (1959).
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18. G. M. Lees, *Geograph. J.* **71**, 441 (1928).
19. W. E. Mulligan, Arabist with the Arabian Research Division of the Arabian American Oil Co., is my authority for the definition of *sabkhah* as saline flats on coastal plains, and of *mamlahah* as saline flats or basins with centripetal drainage, in the interior of the peninsula, synonymous with *playa* as used in the western United States.
20. P. B. Cornwall, *Geograph. J.* **107**, 31 (1946).
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22. G. E. Pilgrim, "The geology of the Persian Gulf and adjoining portions of Persia and Arabia," *Mem. Geol. Survey India* (1906), vol. 34, pt. 4, pp. 7, 54; H. J. Carter, "Memorandum on geology of the southeastern coast of Arabia," *Geol. Papers on Western India* (1857), pp. 33–34, 94–95.
23. The well was Franco-Arizona No. 1, located near St. Johns, Ariz. (1939–1940). The cores were from the Permian Supai formation.

24. This article is published by permission of the Arabian American Oil Co. General statements on climate and winds are derived from the company's meteorological records on file in Dhahran and from personal observation. Grateful acknowledgment is made to my colleagues, particularly G. P. Crombie, E. L. Elberg, Jr., L. F. Ramirez, and N. M. Layne, for many valuable discussions; to O. A. Seager, for support of this study; to I. A. Dugan for the sketch map; and to my wife, Esther A. Holm, for critical editing.

Specific Transport of Oxygen Through Hemoglobin Solutions

Why is this transport abolished when opposed by a slight back pressure of oxygen?

E. Hemmingsen and P. F. Scholander

It has recently been shown that under certain steady-state conditions oxygen moves several times faster through hemoglobin solutions than through water. In these experiments the solution was held in a Millipore membrane, above which was air at varying pressures and below which was moist vacuum. It was found that the nitrogen flux in all cases was strictly proportional to the diffusion pressure, but that the oxygen flux was enhanced. At air pressure of 1 atmosphere the oxygen-nitrogen ratio was almost double that of water, and at 1/12 atmosphere it was eight times higher than that of water. The following simple numerical relation prevailed in each case: Total oxygen flux = oxygen diffusion + a constant. Or, to express it more empirically: Total oxygen flux = nitrogen diffusion × 0.56 + a constant, where 0.56 is the O_2/N_2 ratio in the hemoglobin-free solution.

This was interpreted to mean that the oxygen flux proceeds via two separate routes—namely, a simple Fick's diffusion through the solution and a specific transport which is mediated by the hemoglobin. The latter is constant over a wide pressure range, increases with the concentration of the hemoglobin until the viscosity becomes excessive, and is abolished when the pigment is oxidized to methemoglobin. Suspensions of intact red cells and solutions of myoglobin show a similar effect (*1*).

These results were obtained by a gasometric technique which required that a near-vacuum be maintained below the membrane; it could not be used to study gas flow into a system containing oxygen of various tensions. In a muscle, zero or near-zero oxygen tension is relevant enough, but this would very rarely apply to the blood. The question therefore presented itself: What happens to oxygen transport through hemoglobin when the low pressure is elevated? In order to answer this question a new approach was needed, and it was highly desirable, also, to determine the state of oxygen saturation in the membrane at various pressures.

The authors are members of the staff of the Scripps Institution of Oceanography, University of California, La Jolla.