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EOLIAN GEOMORPHOLOGY, WIND DIRECTION, AND CLIMATIC CHANGE IN NORTH AFRICA

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ABSTRACT

The North African desert belt is a region of temperature extremes, strong winds, and negligible rainfall. During the Pleistocene, however, there were intervals of more humid conditions. Wind action has been a major geologic process. Erosional effects comprise enclosed basins and various residual rock knobs and ridges, commonly elongated parallel to dominant wind direction. Depositional effects comprise sand streamers, drifts, and dunes. Active dunes may be classed as simple, compound, and complex. Simple dunes include attached lee ridges of sand, barchans, transverse ridges, and "longitudinal" forms. The orientation of the first three of these provides a reliable indication of dominant wind direction, and of the last appears to represent a resultant of winds from a dominant sector. Compound dunes comprise barchan, transverse, and longitudinal types, and are transitional into simple types on the one hand, and complex types on the other. Complex dunes are the most widespread, and show extreme diversity in character. They may be grouped as longitudinal, peaked, domal, ridged, and undifferentiated. They are believed to have been formed by divergent winds, and to have had a complicated development history.

Stabilized or "fossil" dunes occur in a broad belt bordering the Sahara on the south, and represent a former expansion or shift of the desert belt. Where original form has not been too greatly modified by non-eolian processes, dune forms similar to those found farther north in the active stage may be recognized, and it is probable that some of the latter passed through a stabilized state at one

or more times in their history.

INTRODUCTION

The Sahara Desert is the largest on earth, is exceeded by no others in degree and extent of aridity, and probably has the greatest diversity of landforms. Of the latter, those produced by eolian action, although occupying much less than half of the total area, are particularly prominent, and, partly because of the hardships which they impose on the desert traveller, and partly because of their inherent fascination, have been a subject for voluminous writings. From a scientific standpoint, however, knowledge of these features is still in a comparatively rudimentary state. Until the advent of air photography, the diversity of dune morphology was not and could not have been adequately realized, and since photography became available it has been used only to a limited extent. In the project here reported on, opportunity has been provided for exploratory photogeologic study of roughly half of the total area of the Sahara, leading to a degree of perspective on its features and its problems probably not attained previously. The photos used were of the Tri-Metrogon type, dating back to World War II, and numbered roughly 150,000 in all; coverage was mainly in the central and western Sahara.

The phenomena with which this report is concerned are both erosional and depositional, with emphasis on the latter. The depositional forms studied range from simple, well-known dune types to very complex types of highly problematic nature. The former in general can be explained in terms of present climate and present wind systems, but some of the latter must be considered in the light of both present and past climatic environments. In so far as a particular type of dune can first be attributed to a particular wind regime, or other climatic factors, it may then be used as a criterion or indicator for that factor or factors where other records are lacking. Thus for inaccessable areas where no meterological records are available, dune form and orientation may provide significant information not otherwise accessible. It is to questions of this nature that the present report is directed.

PRESENT CLIMATE OF THE SAHARA

General climatic characteristics of the Sahara have been summarized by Kendrew (1953) and mapped by Knoch and Schulze (1956). Precipitation is meager and highly erratic. Mean annual rainfall is less than 0.2 in. in large areas of the central Sahara, does not exceed 1 in. in much larger surrounding areas, and reaches 4 in. only on highlands and around the fringes of the desert proper. However, as noted by Briggs (1960), "Mean annual rainfall figures for the Sahara are all but meaningless....In the first place the variations from year to year are enormous and there are often long periods of complete or practically complete drought...Yearly totals are deceptive also because they include completely ineffectual rainfalls of as little as a single millimeter or even less......

"The most common rate of rainfall (when it does rain) is half an inch or less in twenty-four hours, but truly torrential rains do occur every now and then. At Tamanrasset 1.73 inches fell in three hours in 1950, and 1.42 inches of this came down in only forty minutes. When a downpour of such proportions falls in the desert, powder dry gulleys spring to thundering life as bores of water sometimes several feet high rush down them sweeping away everything in their path."

Relative humidity, in midsummer, "often falls as low as 20 per cent and has been known to drop to as little as 2.3 per cent in the Ahaggar. At Ghat, in the central Sahara, the monthly mean ranges from a low of 20 per cent in August to a high of 54 per cent in January, about the same as Phoenix, Arizona, but a little more vari-- able. The total annual evaporation rate varies roughly from 60 to 140 inches." (Briggs, p. 2-3).

As a consequence of negligible moisture, large areas of the Sahara are barren of vegetation. Other areas are characterized by sparse desert shrub (Shantz and Marbut, 1923; Capot-Rey, 1955, p. 7-9). Bordering the Sahara on the south is a belt of desert grass savanna.

Temperature is high in the summer during daytime, with a recorded maximum of 136°F at Azizia in northwestern Libya. On the surface sand, temperature up to 172° has been reported, but at depths of a few inches this decreases by several tens of degrees. At night, temperature commonly drops 30° to 40°, and occasionally more than 55°, below the daytime maximum. Mean daily maxima well above 100° for extended intervals of time are typical during summer. The monthly mean for July ranges from about 86° to somewhat above 96°. In January, the monthly mean ranges from about 46° to 72°, with a minimum recorded temperature of 20°.

Available data on winds are far from adequate. In general, prevailing winds are mapped as blowing from north to northeast in winter, changing gradually with longitude, and from northeast to northwest in summer, down to about 15° N. latitude, and from opposite directions south of that boundary. However, as shown by Bagnold's work, prevailing winds are meaningless for the study of dune phenomena unless their velocity is at least that of Force 4 on the Beaufort scale; if less than that strength, they are ineffective regardless of duration. Recognizing this fact, Dubief (1952) has computed, for a limited number of stations having suitable records, the actual relative volumes of sand moved by winds from different directions in the Algerian Sahara, and has plotted resultants of sand-moving winds for a larger region. The latter show marked divergences from prevailing winds as usually represented on maps. More data of this type would be most desirable for study of dune morphology.

Sand storms and dust storms are common manifestations of wind action. Although the two are actually quite different in nature, they may occur together, and in published accounts the distinction between them is commonly lost. A true sand storm is described by Bagnold (1941, p. 159): "The whole surface was flowing past us; it surged round our feet, excavating hollows into which they sank unexpectedly as we stood.

"The bulk of the grains flowed as a dense fog, rising no higher than five feet from the ground. Over it we could see each other quite clearly, head and shoulders only, as in a swimming bath."

Briggs (1960, p.7), describing sand storms that probably contained a substantial proportion of dust also, wrote: "In the first such storm that I experienced, near El Golea, the air was so full of sand that from the driver's seat of my desert car I couldn't even see the front end of the vehicle.......

"Although stories of whole caravans swallowed up and buried by sandstorms doubtless belong to the realm of fable, it is a fact that one such storm did destroy fifteen hundred goats and two thousand sheep near El Golea in 1947. Occasionally one sees automobiles come up from the desert with body metal shining, all paint gone, and windshields broken out because they had been so ground by flying sand that the drivers could no longer see through them."

Dust storms are common where fine-grained material is accessible to the wind, and are said to be particularly prominent in the northern part of the Sudan. "Towering pillars of dust rise like a wall to a height of several thousand feet along an almost sharp front about 15 miles long, which advances at about 35 miles an hour." (Kendrew, p. 71). Similar dust storms were common in the Great Plains of the U.S. during the drought of the thirties (Smith, 1940). In southern and central Europe, dust falls from storms originating in North Africa have been known for centuries, and it was estimated that a single storm, in 1901, deposited nearly 2 million tons of dust (Free, 1911).

In North America, partial analogs for Saharran climate are found in Death Valley and the Salton Desert of California, and the continuation of the latter into Baja California (Meigs, 1952).

Detailed comparison of the climate at Yuma with that of northeast Africa is made by Robison (1954).

PAST CLIMATE OF THE SAHARA

Climatic change was virtually world-wide during the Pleistocene, its effects differing in different regions. In the Sahara, these effects were far-reaching, and must be given full consideration in any interpretation of landform development. Although much remains to be learned about the nature and the sequence of the changes, it is known that there were more humid, or pluvial epochs, in sharp contrast to the present arid conditions. Their general aspects have been summarized by Charlesworth (1957) as follows:

"North Africa, which in its flora and fauna, including early man, was an extension of Pleistocene Europe, had a Mediterranean climate. It was in large measure green, fertile and populous: ostriches suggest that pastures carpeted its valleys. The steep-sided wadis of the desert hammada, now dry, had permanent streams....Rivers spread out their sands and gravels from the Atlas Mountains where the depression of the snowline by c. 1400 m denotes an oceanic climate; lakes, river-terraces and travertines existed in Morocco...and tufas, mainly middle paleolithic, grew in the Kharga Oasis from springs....

"Abundant mammalia of Ethiopian and Asian affinties, including elephants, rhinoceroses, zebras, wild asses, giraffes, buffaloes, antelopes, camels, gazelles, lions, hyenas, bears, hippopotamuses and monkeys, inhabited the Barbary states and north-west Africa in an environment now utterly alien...Lion, panther, antelope, gazelle, giraffe, rhinoceros and ostrich...are depicted in cave paintings. The Ethiopian flora, to judge from existing relics, was widespread through the Sahara, including the Hoggar massif, and was accompanied by a lepidopteran fauna....

"Egypt, the recipient of copious rains, was pleasantly diversified with forest and grassland, the home of troops of wild animals. Rain and streams were the chief erosive agencies in the mountains of the Eastern desert and of Sinai....

"Africa's present faunal distribution and development are most plausibly explained by an earlier extension of forests to lower altitudes and over immense areas; trees, bush and grass savannas were much more extensive. The oases then had a higher water level.....

"Wadis or ancient water-courses in West Sahara, which center about Ahaggar (Hoggar) massif and extend from the Atlas to the bend of the Niger, were fashioned by gigantic ancestors of the present puny streams. The regs of this part of Africa, remarkable for their vastness, were the work of wadi streams which filled the terminal basins with alluvium--vast lakes may have existed....

"West Sahara was a steppe...A fossilized human skeleton, of upper paleolithic age, was discovered...400 km northeast of Timbuktu, with freshwater shells, fish, crocodiles and mammals...in breccias, travertines, and stalactite crusts. Pleistocene vertebrates were widespread; a fossil elephant has been found in the Sahara c. 500 km north of Lake Chad."

It is generally accepted that there was more than one major pluvial epoch, and that each was related in some way to a glacial stage

The question as to the exact number is partly a matter of definition, correlation, and grouping, and any really definitive answer is deferred by the fragmentary nature of the data available. The number, extent, magnitude, and chronology of the pluvials, their comparative effects in different geographic areas, and their specific relations to glacial stages, will be a subject for continued investigation for a long time to come. Provisional interpretations, however, are presented by Charlesworth (1957) and by Alimen (1957).

During inter-pluvial epochs, aridity prevailed as it does today, and during at least one interval, desert conditions extended much farther to the south than at present, as testified by the occurrence of a broad belt of stabilized, or "fossil" dunes south of the modern Sahara. Whether the latter represented an overall widening of the desert belt, or only a displacement of both borders in the same direction, and whether it belongs to a general pluvial or arid interval, remain problematical, raising questions related to the broader problem of world-wide displacement of climatic belts by glacial influences (cf. Budel, 1953), and its bearing on interpretation of Pleistocene meteorology and ultimate causes of glaciation. All of these factors must be considered in the interpretation of eolian geomorphology, and the latter, in turn, should contribute to a better understanding of the climatic factors themselves.

EOLIAN EROSIONAL PHENOMENA

Eolian erosional features on a scale such as to be recognizable on the air photos studied for this project comprise deflation basins and wind-eroded humps or ridges. Enclosed basins attributed primarily to eolian erosion have long been known in the Libyan desert, and locally extend below sea level and reach great size (Ball, 1927). The origin of the larger basins is believed to involve the alternating effects of fluvial erosion around the margins, and deflation from the floor.

Evidence as to eolian origin of particular basins is based partly on elimination of other possibilities. Where a completely enclosed basin is encircled by bedrock slopes or bluffs, shows no local structural discordance with surrounding areas, lacks the typical configuration associated with karst topography, and is not known to be underlain by significant thickness of soluble rock at sufficiently shallow depth, eolian origin may be surmised. The occurrence of bedrock knobs or surfaces on the floor of the basin, particularly if they show the effects of eolian erosion, provides supporting evidence, and the association with sand dunes or other effects of wind action is confirmatory. Fig. 1 illustrates a deflation basin on folded strata and Fig. 2 on flat strata.

The criterion value of deflation basins is more or less limited. In general, they indicate only climatic or lithologic conditions favoring eolian erosion. Although best developed in extremely arid regions, they occur also in semi-arid areas, as in the High Plains of central U.S. In such areas, or where now stabilized by moisture, vegetation, etc., they may point to greater aridity at some time in the past (Evans and Meade, 1945). At some places, where a depositional record is preserved in the floor of the basin, this may provide information on geologic history. Only in special cases do deflation basins serve as indicators of wind direction, and this is where an accumulation of identifiable eolian sand or silt is so situated on only one side of the basin as to have had the basin as its only available source.

Residual rock knobs or ridges, left behind and/or shaped by eolian erosion, are found at some places where climatic and lithologic conditions are especially favorable for wind action. Local relief ranges from a few feet to perhaps a few tens of feet, and minor, undrained hollows are commonly associated. Form varies with size; the larger ones tend to be irregular in contour, while the smaller ones, under ideal conditions, display a smoothed and rounded surface, and a streamlined, elongate ovoid outline (Fig.3). They have been observed on both flat and tilted sedimentary rocks, and on the latter may be either parallel or transverse to strike; external form truncates internal bedding and jointing. Dune sand is commonly associated, and trailing ridges or streamers of sand are sometimes aligned on the downwind side. At many places, these features are grouped in elongate belts or irregular "swarms," and where the elongation is pronounced, the parallelism of individual ridges produces a distinctive topographic "grain." Surface drainage generally is lacking in areas of wind-eroded ridges, but where minor drainage lines do occur, the trend of the ridges is indifferent to their pattern. The features described above are best developed under conditions of extreme aridity, but minor examples have been described from the deserts of southwestern U.S. (Blackwelder, 1931, 1934).

The knobs and ridges resulting from eolian erosion serve as indicators mainly of the prolonged intensity of wind action, particularly where they occur on relatively resistant rock. Where parallelism of elongated forms is pronounced, and demonstrably independent of any structural control, it serves also to record the direction of the effective winds. Where that characteristic is lacking, winds of variable direction are suggested.

GENERAL OUTLINE OF DUNE DEVELOPMENT

In considering dunes and their relation to climatic factors, it is well to begin with a brief resume of the general condi ions of dune development (Smith, 1940, 1949). Active dune building may progress either in the presence or in the absence of vegetation. Granting a source of sand and a wind capable of moving it, the only requirement is some factor to arrest sand movement and cause accumulation. Vegetation is one such factor, and its role in dune building may be seen along many coastal areas in humid regions. In semi-arid regions also, vegetation may be the controlling factor in causing sand accumulation, where a suitable balance exists between the amount of sand supplied and the capacity of the vegetation to withstand it. In all cases, the dune forms developed under the influence of vegetation are distinctive and readily recognizable.

In more arid regions, where vegetation is absent or ineffective, sand accumulation is controlled by other factors, mainly topographic obstacles, moisture, or sand traps - sandy surfaces which tend to arrest more sand, and thus grow and perpetuate themselves. A wide variety of dune types is produced, as discussed in a later section of this report.

Primary dunes formed under of either of the above conditions may become stabilized and rendered inactive by the invasion of vegetation, as a result of climatic change. Once the bare sand surface is covered and protected from further wind action, a different set of processes comes into action, and an eluvial phase of development is initiated. Weathering and gravitational slope processes cause gradual blurring and modification of the original dune forms, and, working through stages of youth, maturity, and old age, finally obliterate the initial forms, if uninterrupted.

The eluvial development may be interrupted at any stage, however, by a reverse change in climate, leading to weakening of the vegetative cover and renewal of wind attack. Given time enough, this may have far-reaching effects, and a new generation of secondary dunes may be produced. But, this in turn, may be interrupted by still another swing of the climatic pendulum such as to establish stabilization once more. These alternations may be repeated many times, with numerous variations. Only if the later episodes of eolian activity are successively shorter or less severe, is it likely that remnants of the earlier dune forms will be preserved. Since far-reaching climatic fluctuations have taken place in the Sahara, and the larger dune masses must have required a long time for their building, the effects of climatic change cannot be ignored in any interpretation of present dune morphology. Differences in dune age, in fact, have been inferred from contrasting color of the sands at different places (Alimen, 1957, p. 137), but the full implications of this seem not to have been investigated.

ACTIVE DUNES

Active dunes may be either primary forms in their initial phase of development, or secondary forms resulting from the rejuvenation and reworking of once-stabilized dunes. Evidences of the latter type of origin may or may not be recognizable from morphology alone, depending on the extent of reworking, but the possibility must always be considered, particularly in the case of the more complicated dune forms and patterns.

From the standpoint of morphology alone, active dunes may be classified in general terms as simple, compound, or complex. Simple forms are those of unitary nature, not divisible into clearly defined component parts. Barchans are typical of this group. Compound forms are those in which a number of similar simple forms of concordant arrangement are apparently united to make up a larger dune mass having the same general shape and trend, or are superimposed on the latter compound barchans are illustrative. Complex dunes, on the other hand, are made up of component parts dissimilar in character and/or discordant in their relations to one another or to the overall form. Most of the Saharran dunes fall in this category, which includes a multiplicity of pyramidal, peaked, branching, radiating, and intersecting forms.

Simple dunes. Simple dunes comprise various sand streamers and drifts, attached lee ridges, barchans, transverse dunes, and "longitudinal" dune ridges. Sand streamers are relatively thin, ribbon-or banner-like accumulations of sand downwind from localized source areas or from topographic constrictions (Fig. 4). They may cross minor stream courses without interruption or deviation. Where long, straight, parallel, and separated by relatively sand-free strips, they serve to indicate constancy and direction of sand-moving winds. Sand drifts are thicker and more irregular, and commonly are localized by bedrock relief features. Where advancing uphill, the term, "climbing dune" may be applicable, and where passing over the ridge or crest of a hill, the terms, "falling dune," or "sand glacier," may be used. Both varieties are prominent in some parts of the Sahara, and examples are found also in the Mojave Desert of the U.S. Dunes of this sort are suggestive of wind direction only in a very generalized way, if at all. However, where they invade or inundate stream-carved topography on a significant scale, climatic change is indicated (Fig. 5).

Lee dunes are long, narrow, tapering sand ridges attached to and extending downwind from rock knobs or salient points (Fig.6), the wind shadows of which initiate sand accumulation. Where the crest is straight, sharp, and symmetrical, and size is too large to allow complete reshaping by seasonal changes in wind, these features serve as reliable indicators of dominant wind direction. Where the crest is curved, sinuous, or asymmetric, however, divergent winds are suggested, with the trend of the ridge probably representing their resultant.

The barchan is one of the best known types of dunes, although by no means the most widely distributed. The ideal form is symmetrically crescentic, in ground plan with horns pointing downwind, and asymmetric in axial profile, with a relatively moderate slope on the convex side, and a steep slope, or slip face, on the concave side (Fig 2). Size and proportions range widely, variations of and departures from the ideal form are innumerable, and transitions into other types of dunes are not unusual. Morphologic variations commonly observed include axial asymmetry of moderate to extreme degree, irregularities or discontinuities in the curvature of the concave side, and distortions produced by axial or lateral fusion of dunes of different sizes. Other types of dunes into which transitions occur include compound barchans, transverse dunes, and longitudinal dunes.

Symmetrical barchans where too large to be remodeled by seasonal shifts in wind regime, are indicative of dominantly unidirectional winds blowing in the direction pointed by the horns of the dune. Where a clearly defined wind shadow, or dark, sand-free strip, extends downwind from the barchan (Fig. 7) additional confirmation is provided. Where found, the arrangement of barchans in long, straight, narrow, "trains," aligned axially, provides further confirmation of wind direction. Asymmetric barchans are interpreted to represent divergence from the dominant wind direction, but detailed analysis is needed to appraise the amount and duration of the divergence.

Transverse dune ridges are comparatively uncommon in North Africa, but do occur locally. As the name implies, they are elongated transverse to dominant wind direction. The cross profile displays the same degree of asymmetry as the barchan, and all stages of gradation between barchans and transverse dunes may be found in close proximity. Dunes of this type commonly occur parallel and closely spaced, making for a wave-like appearance (Fig. 8). Individual ridges vary from more or less straight to curved and irregular; a moderate degree of sinuosity or scalloping is common. Where relatively straight and regular, a dominant wind from a direction approximately perpendicular to the average trend of the ridges is suggested, and additional evidence commonly can be found in associated barchans. Pronounced irregularities, on the other hand, with convergence, divergence, junction, and division of individual ridges, or development of reticular patterns, point to divergent winds from a broader sector. At the present state of knowledge, interpretation of the range of divergence is problematic, but further studies may delimit the possibilities.

The term, "longitudinal," has been applied to a variety of more or less symmetrical dune ridges known or supposed to trend parallel to prevailing wind direction. Different varieties probably are formed in different ways, and one certainly is developed in the presence of vegetation; the latter, however, is excluded from the present discussion. The simple longitudinal dunes considered here, in their ideal form, are long, relatively straight and narrow sand ridges lacking marked or systemmatic asymmetry (Fig. 9). Although a degree of asymmetry is noticeable at some places, it generally is discontinuous, and gives the impression of being readily reversible by a shift in wind direction. The ratio of height to width is much greater than for the normal transverse dune, and side slopes are much steeper than those on the windward side of a transverse dune. The sides may display minor irregularities, including beaded, crenulate, serrate, and barbed forms. The crest may show minor departures from the rectilinear trend, with cuspate, sinuous, or irregular deviations. Where the crest is more broadly curved, however, the distinctive character of the longitudinal dune is lost. Dunes of the longitudinal type occur both on bare ground and on preexisting dunesand surfaces. At a few places they are aligned with and appear to be extensions of lee ridges attached to rock knobs. In general, they tend to occur in groups (Fig. 10), parallel, subparallel, moderately divergent or en echelon in trend. Locally, barchans occur side by side with them. Group patterns show great variety, and constitute a separate subject for study, beyond the scope of this report.

Longitudinal dunes of the type considered here are best explained as produced by a sort of shepherding effect of alternating, convergent winds, an interpretation particularized by Bagnold (1941a). Minor morphologic details may be inferred to record the effects only of the last strong wind, but the general trend may be assumed to represent the resultant force of the different winds which play a part. The angular spread and relative strength of the effective winds are separate questions, less easily answered. However, on photos of suitable scale and quality, faint linear streaks of sand projecting obliquely outward from the sides of the ridge, in fishbone pattern, appear locally to indicate a spread of up to nearly 90° in wind directions.

<u>Compound dunes</u>. Dunes which occur in compound form comprise barchan, transverse, and longitudinal forms, although the latter generally show at least some tendency to complexity. Compound barchans are comparatively rare, and have been reported previously only from Peru (Smith, 1956; Simons, 1956). They have been found in North Africa at relatively few places, but locally are well developed. The general form is that of an over-size barchan (Fig. 11), and displays morphologic variations similar to those of the ordinary barchan. Superimposed on the larger form are much smaller barchans or transverse ridges, and there is a full range of gradation between the smaller and the larger forms. Downwind from the horns narrow, elongate trains or narrow fans of smaller barchans are common. Numerous simple barchans of smaller size and random distribution commonly occur in close proximity, and some may be observed in process of riding up onto the larger form. The significance of the compound barchan in terms of wind direction is similar to that of the simple barchan.

Compound transverse dunes also are comparatively uncommon, and have received virtually no attention in previous literature. The general form and pattern are akin to those of the simple transverse dune, but scaled up by the order of ten or more. Superimposed on the major forms are subordinate transverse dunes having essentially the same trend (Fig. 12). It is not clear whether dunes of this type represent a first-generation or a second-generation phenomenon. The latter possibility certainly cannot be dismissed, and would imply that the minor transverse dunes are a product of secondary reworking of a once-stabilized but now reactiviated primary form of large scale; without data on internal structure - buried soils etc. - this question would be difficult to answer. In any event, this type of dune appears to indicate relative constancy in direction of the dominant winds for a long interval of time.

Compound longitudinal dunes are perhaps less clearly defined than the above types, and are gradational into closely-spaced groupings of individual dunes, on the one hand, and into complex types, on the other. The term applies best to the relatively uncommon occurrences where bundles of subparallel simple dune ridges more or less coalesced together to make up much larger sand ridges having the same general trend, or are superimposed on such a ridge (Fig.13). Individual ridges may diverge at low angles from one or both sides of the main mass. The assemblage may narrow down lengthwise to a single simple ridge, or may spread out in a brush-like or pinnate pattern. Some of the compound longitudinal dunes appear certainly to be primary features, but others may represent superficial reworking of older, once-stabilized dune masses. Significance of compound form in terms of wind direction is somewhat ambiguous, and evidence as to that factor is perhaps best studied in the associated simple ridges.

Complex dunes. Complex dunes are by far the most widespread type in the Sahara, and morphologic diversity is extreme. Although various Arabic terms are widely used in the French literature, and a supposedly genetic classification has been proposed by Aufrère (1933), on the basis of hypothetical interplay of winds from different directions, a purely descriptive treatment in familiar terms seems preferable here. Four broad classes of complex dunes may be distinguished, all gradational into one another: longitudinal, peaked, domal, and ridges; others may be referred to only as undifferentiated. The longitudinal class is similar to the compound longitudinal dune, but with added complications and variations. The subordinate or unitary dune ridges lie diagonal or transverse to the trend of the larger form (Fig. 14), and may show discordant trends among themselves. This type of compound dune is not widespread. It might be either a first- or second- generation feature, and, if the latter, might indicate a shift in dominant wind direction between the earlier and the later sand-moving episodes.

Peaked dune complexes are extremely widespread in the Sahara, and occur in innumerable variations and associations. The characteristic feature is a culminating peak or cluster of lesser peaks, from which curved or branching ridges radiate out on all sides. The peak itself may be rudely pyramidal, tent-shaped, or star-shaped (Fig.15); together with the auxiliary ridges, it may suggest the appearance of a spider or octopus. Size ranges widely, with heights up to hundreds of feet; small, embryonic peaks and intermediate sizes may occur within a few miles of the larger, more massive ones (Fig. 16). Peaked dunes are closely spaced and crowded in some areas, and more widely spaced in others. In the latter situation, they may be separated either by areas of bare, flat ground, or by sand waves or other varieties of lower-relief sand surfaces. Where more closely spaced, the individual peaks may either show a random distribution, may be linked together in elongate chains, or, together with associated subordinant ridges, may form more or less irregular network pattern. At some places, peaked dunes are clearly seen to be superimposed on older, formerly-stabilized masses of sand; at others, the smaller simpler, ones appear to be of first-generation origin. It seems impossible to explain peaked dunes without assuming pronounced differences in the direction of sand-moving winds, but whether the differences are on a short-term or a long-term basis, what the extent of divergence is, and what the relative strength and duration of the winds from different directions amounts to, remain subjects for continued study. Probably a large sand peak itself would tend to produce some local deviations in wind direction.

The domal dune complex might be considered as more subdued variant of the peaked dune, and is comparatively rare. It is made up of a broad, rudely dome-shaped mass of sand, covered with, and commonly bordered by, irregular minor ridges of complicated pattern (Fig. 17). Similar forms have been described from Arabia by Holm (1960). In some places, these dunes are clearly secondary, but elsewhere they might be primary.

The ridged dune complex is a more or less elongate, generally steep-sided massif of sand, topped and/or flanked by a complicated array of irregular second-order ridges (Fig. 18). The latter are diverse in size, shape, and trend, are commonly intricate in pattern, and locally enclose small bowl-shaped or horseshoe-shaped depressions. Peaked forms may occur on the major crests, but are subordinate in proportion to the mass as a whole. Some of the above sand ranges are relatively long and straight, though with variations in height and width. Others, however, show irregular curves, and jogs, and offsets, converging, diverging, branching, and rejoining so as to enclose broad hollows, corridors, or basins. Dunes of this general category undoubtedly have had a long and complicated history, but the record is extremely puzzling.

STABILIZED DUNES

The active dunes of the Sahara pass southward into a broad, though discontinuous belt of stabilized dunes, extending across more than 5 degrees of latitude (Niehoff, 1917; Chudeau, 1920; Capot-Rey, 1953, Carte V; Grove, 1958). These dunes represent a former expansion or shift of the desert belt, and must be included in any consideration of the problems of the Sahara. It is probable that some of the now active dunes of the latter area were produced by the reworking of older forms such as those now found in the stabilized belt.

The range of characteristics displayed in the stabilized belt may be best described in terms of an eluvial cycle of development, first worked out by the writer in studying the stabilized dunes of the Great Plains of the U.S. (Smith, 1940, 1951), and referred to elsewhere in this report. This cycle begins as soon as a cover of vegetation is sufficiently continuous to check further wind attack. At that point, processes of degradation come into play. Weathering, soil building, creep, rain wash, and gulleying begin their work. Silt and clay are produced by chemical weathering of silicates, and organic material is added by plant growth. During the initial, or youthful stage, minor irregularities tend to be effaced, the steeper slopes are reduced, and contours are rounded out and simplified. Maturity may be said to have been reached when the entire dune presents a smooth and regular appearance. During maturity, relief is decreased, slopes are further reduced, initial asymmetry is erased, the soil zone becomes thicker and more stable, and typical dune morphology gradually wastes away. Old age begins when the original dune form has become unrecognizable, and the landscape shows only a gently undulatory appearance, with shallow depressions or temporary ponds marking the position of the original inter-dune troughs or hollows. If conditions are suitable, a consequent drainage system, may be established during the latter part of the developmental cycle, and a trellis pattern is common where the initial dune ridges were regular and parallel.

The eluvial cycle may be interrupted at any stage by thinning or destruction of the plant cover, leading to reactivation of eolian erosion and sand movement. At first, this is of a spotty and piecemeal nature, producing minor secondary forms, of distinctive appearance. But if given time and opportunity, these grow larger, merge together, and gradually rework the older sand into new forms that come to dominate the scene, and may assume the same forms as the original dunes before stabilization. Restablization, however, may arrest this phase of development at any point, and further alternations between the two processes may ensue. If these are on a descending scale, the topography becomes increasingly complicated, and finer in texture.

Examples of all parts of the above sequence are represented in the stabilized dune belt of North Africa. Both longitudinal (Fig.19) and transverse dunes (Fig. 20), some probably of compound or complex origin, may be recognized in the earlier stages of eluvial development, and dunes of indeterminate origin are found in the later stages. The interpretation of wind direction responsible for the building of the original dunes obviously has its limitations. Only where eluvial modification is still early in the cycle is external dune form sufficiently clear to serve as an indicator. In later stages, the pattern and the spacing of inter-dune swales may be all that remain to provide a tenuous sort of circumstantial evidence.

CONCLUSIONS

The Sahara is an ideal natural laboratory for the study of eolian phenomena, and air photography provides an ideal method of investigation. Eolian erosion is seen to have been a major geologic process, as evidenced by the immense volume of sand which it supplied to the great dune fields, but its distinctive marks on the topography are comparatively limited in extent, though locally prominent. In the dune fields, the cumulative effects of wind action are most prominently displayed, and its versatility clearly shown. The diversity in dune form, size, and pattern is extreme, but the recurrence of simpler forms in different combinations provides a partial basis for systematization. The relation of the simpler forms to wind direction is known in general, but needs further particularization, particularly in the case of variants from ideal types, and groupings of individuals.

Systematic regional studies of dune orientation should enlarge or refine present knowledge of wind regime over broad areas.

The relation of the more complex dunes to wind direction is less well known, and is in need of much further study. More detailed analysis of and synthesis from existing data should be helpful, but much new data is needed. Detailed records of wind velocity and direction for selected spots would be most helpful, particularly if correlated with seasonal modifications of dune forms, as recorded by ground observations and/or large-scale air photography at frequent intervals. Additional data on internal structure of various dune types would be useful also, but would be very difficult for the larger forms.

The larger dune complexes of the Sahara probably have been built up, discontinuously, through a sequence of climatic alternations, which may have included shifts in wind direction. Much is to be learned from the photogeologic approach, particularly if air photography in color should become available to differentiate dune sands of different ages on the basis of color differences reported in the literature. Correlation of photogeologic data with stratigraphic, paleontologic, and archeologic evidence should then contribute to more definitive interpretation of Pleistocene events in the Sahara.

Analogs for some of the simpler types of Saharran dunes, and possibly for some others as well, occur in western U.S.

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Fig. 1. Deflation basin on crest of structural dome. Numerous similar topographic basins on structural highs were observed in the same general area, and one in a structural trough. Note absence of any discordance with surrounding structures. The basin can be explained only by erosion, with removal of material in an uphill direction.

Fig. 2. Deflation basin and barchan field. Note variations in size and shape of barchans, and multiple forms produced by merging of individuals. The basin is attributed to deflation by elimination of other possible modes of origin. The minor gulleying around the margins suggests that water played a part in carrying detritus to the floor for easy pickup by the wind.

Fig. 3. Wind-eroded ridges on gently dipping strata. Note smooth, rounded form on the smaller knobs and ridges, tendency toward ovoid outline, distinctive topographic grain, and transection of fractures trending across the grain.

Fig. 4. Sand streamers aligned with wind direction and trending indifferently across minor drainage lines.

Fig. 5. Irregular sand drifts, with some dune ridges, choking valleys and inundating stream-carved topography. A change of process is indicated and a change of climate implied.

Fig. 6. Lee dune ridges localized by wind shadow of rock salients, and pointing in the direction of the dominant wind. The one that is curved suggests local topographic control on wind movement.

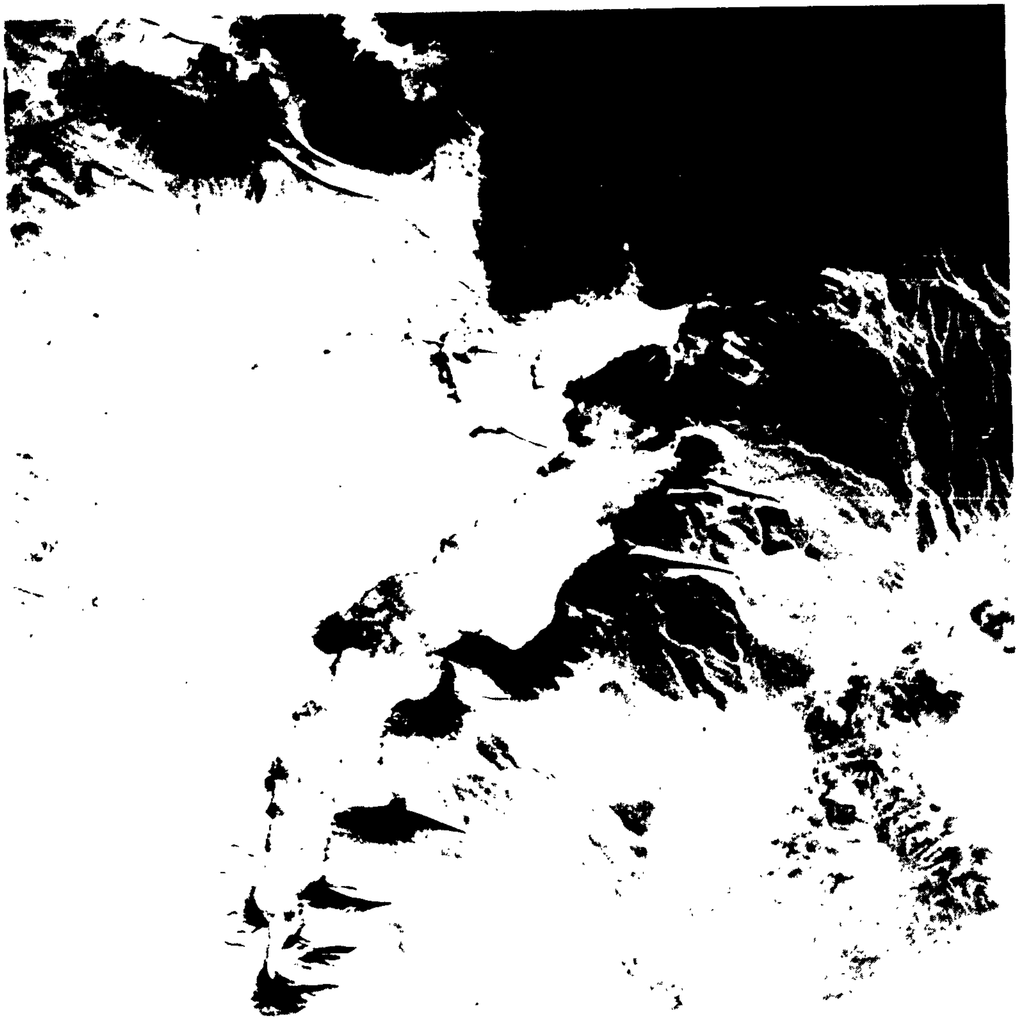


Fig. 7. Wind shadows leeward from barchan dunes, indicating constancy of wind direction. Darker areas are sand-free, and lighter areas are sand-veneered.

Fig. 8. Locking downwind over field of closely-spaced transverse dune ridges. Note transitions to multiple barchans, and minor irregularities of the individual ridges.

Fig. 9. Typical "longitudinal" dune ridges, superimposed on older subdued and probably semi-stabilized dunes. Note steepness of sides and lack of systematic asymmetry.

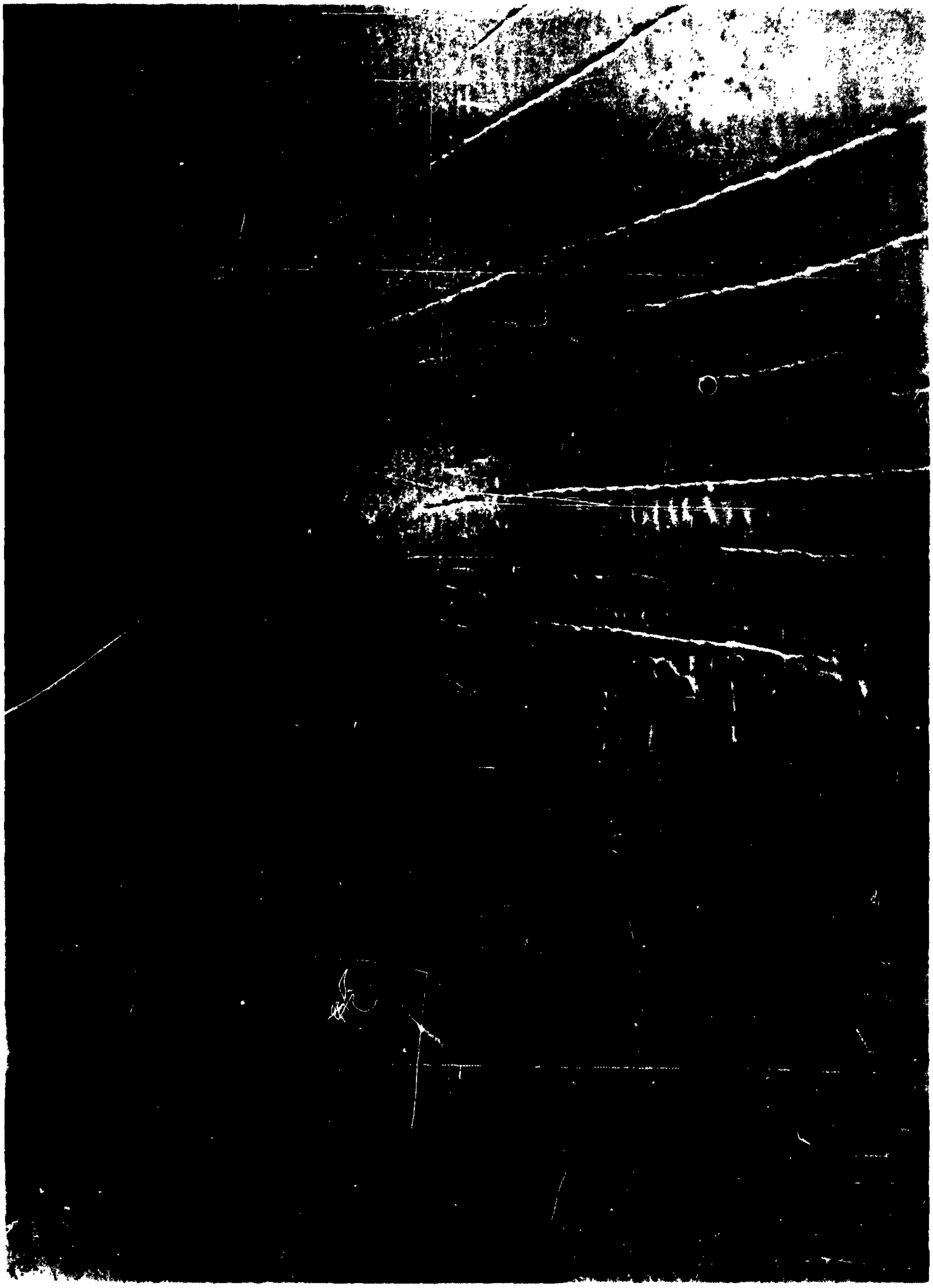


Fig. 10. Typical patterns assumed by groupings of longitudinal dunes.

Fig. 11. Compound barchans in coastal desert. The one toward the bottom is distorted by the drag of its windward "twin," partly obscured by a cloud. Note typical trains of minor barchans downwind from the horns of the major forms. The crowded assembly of sand ridges nearest the beach is made up of transverse dunes, with a tendency toward compound form on the landward side.

Fig. 12. Large, compound transverse dunes, more or less overriding one another, in typical pattern. The relatively smooth areas are flattish inter-dune basins.

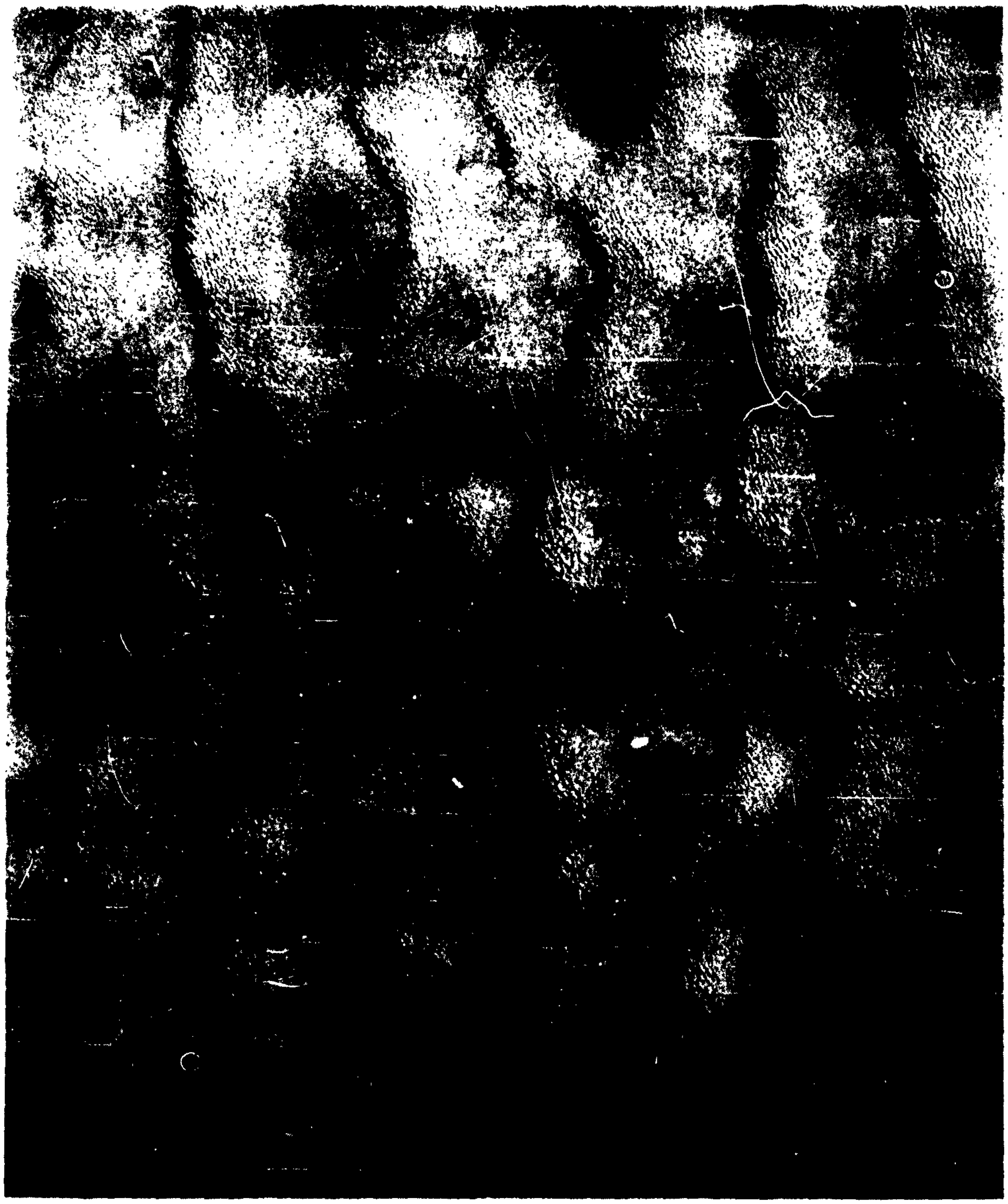


Fig. 13. Compound longitudinal dunes, separated by wind-eroded ground. Note subparallelism of the minor ridges to the major ridge.

Fig. 14. Complex longitudinal dunes alternating with strips of intricately eroded desert floor. Note discordance between trends of minor and major ridge forms.

Fig. 15. Dune field dominated by closely-spaced peaked complexes in random pattern.

Fig. 16. Widely-spaced peaked dunes of different sizes, surrounded by minor dune ridges of low relief. The smaller peaks are believed to represent embryonic forms.

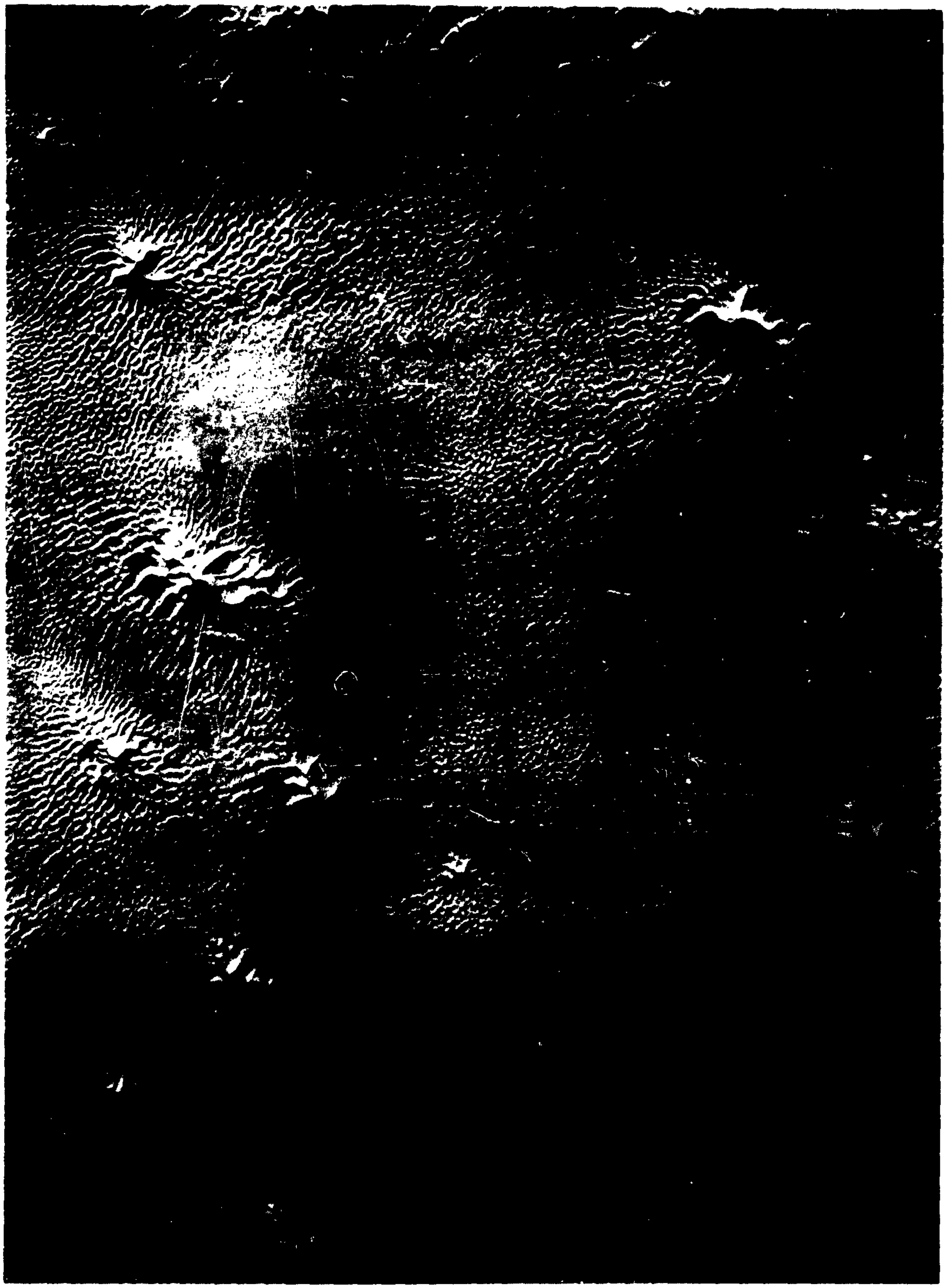
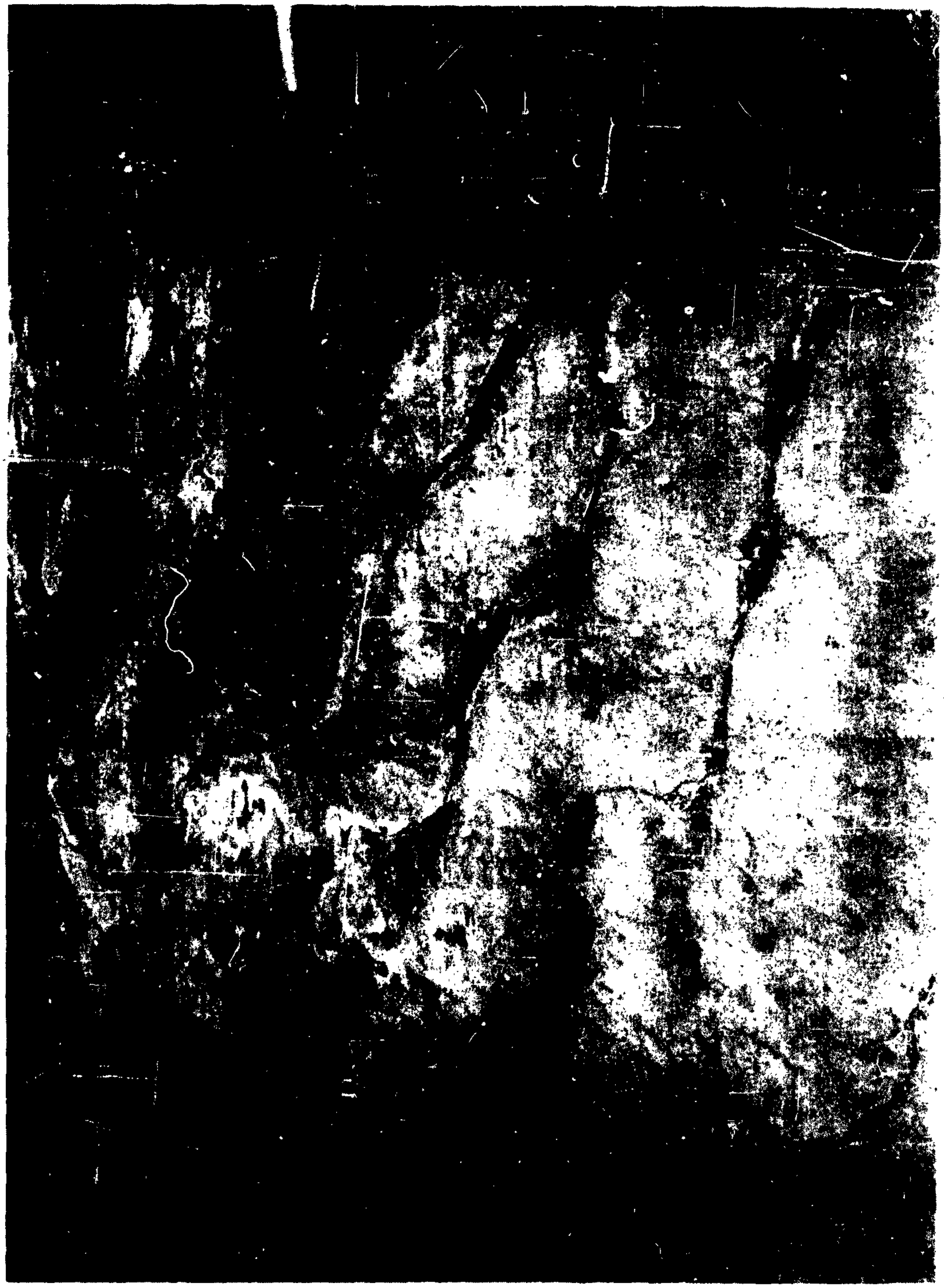


Fig. 17. Domal dune complexes of Medusa-head aspect.

Fig. 18. Assemblage of ridged dune complexes. They might be described as "homogeneous in their heterogeneity." Note range in form from irregular, short, stubby masses to long and relatively straight ranges.

Fig. 19. Stabilized longitudinal dunes, probably of compound or complex origin. Note minor gulleys on sides, indicative of sufficient soil development to allow runoff to concentrate.

Fig. 20. Large, massive stabilized dunes in the mature stage of eluvial development. The size, form, and pattern suggest origin as compound transverse dunes. Drainage lines are consequent on inter-dune troughs.



Air Force Cambridge Research Laboratories, Laurence G. Hanscom Field, Bedford, Mass.
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The North African desert belt is a region of temperature extremes, strong winds, and negligible rainfall. During the Pleistocene, however, there were intervals of more humid conditions. Wind action has been a major geologic process. Erosional effects comprise enclosed basins and various residual rock knobs and ridges, commonly elongated parallel to dominant wind direction. Depositional effects comprise sand streamers, drifts, and dunes. Active dunes may be classed as simple, compound, and complex. Simple dunes include attached lee ridges of sand, barchans, transverse ridges, and "longitudinal" forms. The Orientation of the first three of these provides a reliable indication of dominant wind direction, and of the last appears to represent a resultant of wind from a dominant sector. Compound dunes comprise barchan, transverse, and longitudinal types, and are transitional into simple types on the one hand, and complex types on the other. Complex dunes are the most widespread, and show extreme diversity in character. They may be grouped as longitudinal, peaked, domal, ridged, and undifferentiated. They are believed to have been formed by divergent winds, and to have had a complicated development history. Stabilized or "fossil" dunes occur in a broad belt bordering the Sahara on the south, and represent a former expansion or shift of the desert belt. Where original form has not been too greatly modified by non-eolian processes, dune forms similar to those found farther north in the active stage may be recognized, and it is probable that some of the latter passed through a stabilized state at one or more times in their history.

1. Eolian Geomorphology
2. Wind Direction
3. Climatic Change
4. North Africa
I. AFSC Project 7628, Task 762805
II. Contract 19(628)296
III. University of Mass., Amherst, Mass.
IV. H. T. U. Smith
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