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SALTATION VS. SOIL STABILIZATION: TWO PROCESSES DETERMINING THE CHARACTER OF SURFACES IN ARID REGIONS

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SUMMARY

In satellite images of sandy areas in arid regions disturbed (crumbled) surfaces appear much brighter than stabilized soil. From observations of Landsat satellite images that show directional surface features along the dominant wind direction, two theses are inferred concerning eolian erosion and transport: (1) transport is dominantly a near-surface phenomenon of saltation rather than of aerodynamic entrainment and later deposition; (2) both the disturbed surface characteristics in the saltating regions (saltation formations in our terminology) and the stability of the crusted soil in the quiescent regions are locally self-perpetuating.

Thesis (1) is suggested by the appearance of the zones in the lee of protrusions from the surface, or even a river, that constitute obstacles (across the dominant wind directon) to particle flow. In the lee of a ridge between two "streaks" or in the lee of a protruding outcropping within a "sheet", one finds darker zones, in contrast to the adjacent bright saltation formation. These darker zones are laterally uniform, and have to be interpreted as stable, quiescent areas of non-deposition and non-erosion.

Thesis (2) is inferred from (i) the sharpness of the transition in the reflectivity at the boundaries (parallel to the dominant wind direction) between the bright "streaks" or "sheets" and the darker stable surface, and (ii) the constant width of some long quiescent areas in the wind-shadow of an isolated obstacle. Variability of wind direction, in any season of any strength, should have produced a gradual boundary. The disturbed and the stable surfaces are therefore interpreted as locally a bi-stable situation: an occasional wind will produce no effect over a stable surface, which tends to be "immune" to the eolian influences, whereas the surface in a saltation formation is prone to be disturbed anew by a comparable wind. The bi-stable situation is linked to positive feedback mechanisms; the most important mechanism appears to be the cohesion of the crusted surface. Such a surface can be broken only by high energy impact. The feedback mechanisms have implications for designing measures to reduce the danger of dust storms.

1. INTRODUCTION: AERODYNAMIC ENTRAINMENT, SALTATION AND SALTATION FORMATIONS

In satellite images of arid regions, the areas of unstable, mobile sand are recognized as such by their brightness, in comparison with the darker, more stabilized surfaces. The reduced reflectivity of the stabilized areas stems from accumulation of plant debris on the surface, from crusting of the surface (often influenced by algae), from shadowing effects of plants (whether live or dead, but remaining in situ) and, in many locations, from an accumulation of pebbles and stones on the surface (desert pavement or lag surface). The unstable sand areas quite often are bounded by roughly parallel lines, like the banks of a river. Such areas are identified and analyzed in this paper as "saltation formations".

Soil erosion can be categorized according to the relative importance of particle interaction (exchange of kinetic energy) and aerodynamic forces. In **aerodynamic entrainment**,

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soil particles are lifted from the surface directly by the force of the wind. In **saltation, particles** ejected from the surface fall a short distance beyond their initial position, usually with enough force to dislodge other particles. Those in turn impact the ground, continuing the process of flow. Saltation is commonly initiated by aerodynamic entrainment, but it also can be initiated by mechanical impact (from passage of a vehicle or herd of animals, for instance). The process is sustained by the force exerted by the wind on the soil particles along their short (several centimeters or a few decimeters long) and low (approximately 1 cm high) trajectories, which results in their acceleration. This addition of energy counteracts the kinetic energy losses by inelastic impacts. The threshold wind velocity to maintain the saltation (impact or dynamic threshold) is lower than the threshold for aerodynamic entrainment (BAGNOLD 1941, OWEN 1964). Saltation can continue the flow of sand even if the wind speed falls below the aerodynamic entrainment threshold (fluid threshold) but remains above the impact threshold velocity (BAGNOLD 1941). As indicated by satellite observations of dust storms in progress (OTTERMAN 1978) and also discussed here, saltation is the dominant mechanism of soil movement in arid regions. The unstable sands, dunes, sheets or stringers, appear in the satellite imagery as formations hundreds of meters to tens of kilometers wide and from a few to a few hundred kilometers long.

From the examination of the configurations of the bright saltation formations versus the dark, stable areas, two theses are developed:

(1) On a macroscale (hundreds of meters to tens of kilometers), the main surface disturbing process is the near-surface flow of sand by saltation;

(2) The saltation formations and the stable areas (which by comparison are immune to the eolian influences) are discrete and locally self-perpetuating surface conditions.

Theses 1, that saltation is the dominant process relative to aerodynamic entrainment, is based on observation, on a macroscale, of the transition from unstable to stable soil characteristics in the lee of obstacles to saltation. The saltation formations terminate whenever the flow of the sand grains cannot continue, that is, at barriers such as a river or a cliff. (In the lee of these barriers to the flow of particles, the surface winds are not reduced and are possibly enhanced.) This observation is only an extension of BAGNOLD's work (1941), his studies on a microscale of the termination of saltation.

It is observed, in addition, that the areas in the lee of protrusions (isolated hills) constitute essentially uniform quiescent zones. These characteristics can be expected in such zones, sheltered from the flow of particles, if saltation is the dominant process. (This contrasts with the situation on a microscale, i.e. 10's cm, where objects such as shrubs or small trees trap the sand and cause an accumulation behind the object. The sand, in this case, can be deposited from either saltating or aerodynamically entrained particles.) Were aerodynamic entrainment/deposition dominant, complex patterns would occur, linked to the patterns of vortices developed in boundary layer flows: erosion occurs where turbulent eddies form axes parallel to the direction of airflow (these may merge into a horseshoe vortex pattern, depending on wind speed), and deposition occurs in nonturbulent zones (SEDNEY 1973). Related patterns were produced in wind tunnel simulation of eolian processes on Mars, under contitions of aerodynamic entrainment. Bilobate zones show relative erosion in the lee of craters, which may merge into a single triangular zone at higher wind speeds. Sand deposits form on the wind-facing side of the crater and in trilobate zones on the leeward side (GREELEY et al. 1974). In our macroscale observations, we do not see any such alternating patterns of erosion and deposition.

Thesis 2, the tendency for both the saltating areas and the stabilized areas to be self-perpetuating, is deduced from the sharpness of the reflectivity boundaries, and narrowness of the saltation "rivers", that parallel the effective surface wind direction. These boundaries could be expected to be gradual and diffuse, reflecting changes, however slight, in the wind direction from one soil disturbance incident to another. Broader fan or cone-shaped streaks are generally absent. The sharpness and elongated narrowness of the reflectivity boundaries lends support to an either-or situation (explainable only by one or more positive feedback mechanisms, discussed below) which causes the local persistance of either a saltation formation or a stabilized surface, each one as a self-perpetuating state.

Regions of stability or instability exist over long time periods. This leads to the development of quite different ecosystems, involving differences in plants and micro-organisms in those two types of surfaces. The soil also forms part of the ecosystem and develops differently in stable as compared to unstable (saltating) regions. In stable regions, the fine size fraction of the soil is retained and organic matter has a chance to accumulate. On the other hand, in saltating formations, fine particles are created by abrasion, but these are removed by selective deflation, so that large sizes are dominant.

Various examples of saltation formations are described and discussed below. Observations are presented of the abrupt termination of saltation formations by topographic features, such as an outcrop, an isolated hill, or a river, that interrupt the flow of saltating grains. A possible example of anthropogenic activity initiating saltation is briefly discussed. Reflectivity measurements from the Landsat digital tapes (see Figure 1 for the index map) are presented to illustrate the pronounced brightness contrasts across the "banks" separating stabilized and mobile terrain. The sharpness of the boundary between these two kinds of surface and the postulated either–or situation are explained by positive-feedback mechanisms that contribute to the stability of the nonsaltating regions: surface crusting – both inorganic and biogenic, retention of fine particles and organic debris, and enhanced surface roughness.

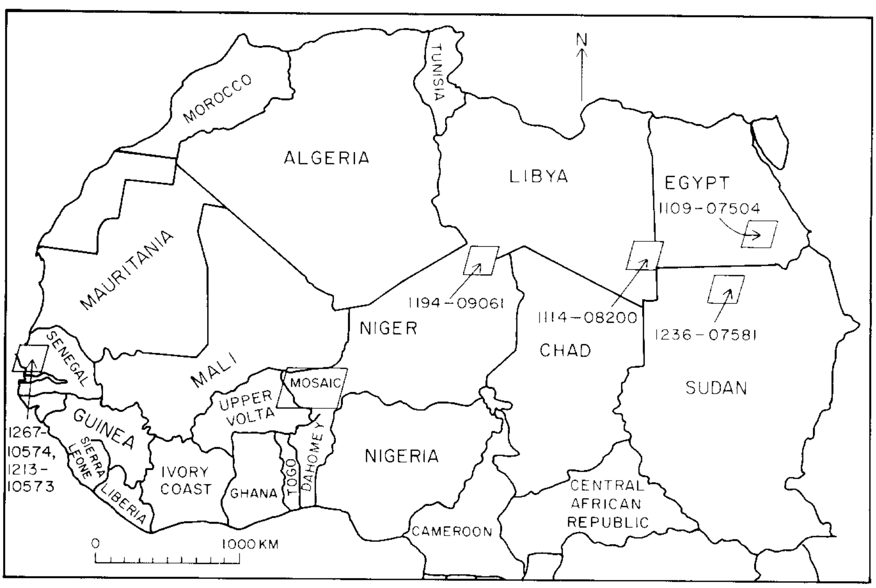


Fig. 1: Index map of Landsat imagery used in this paper.

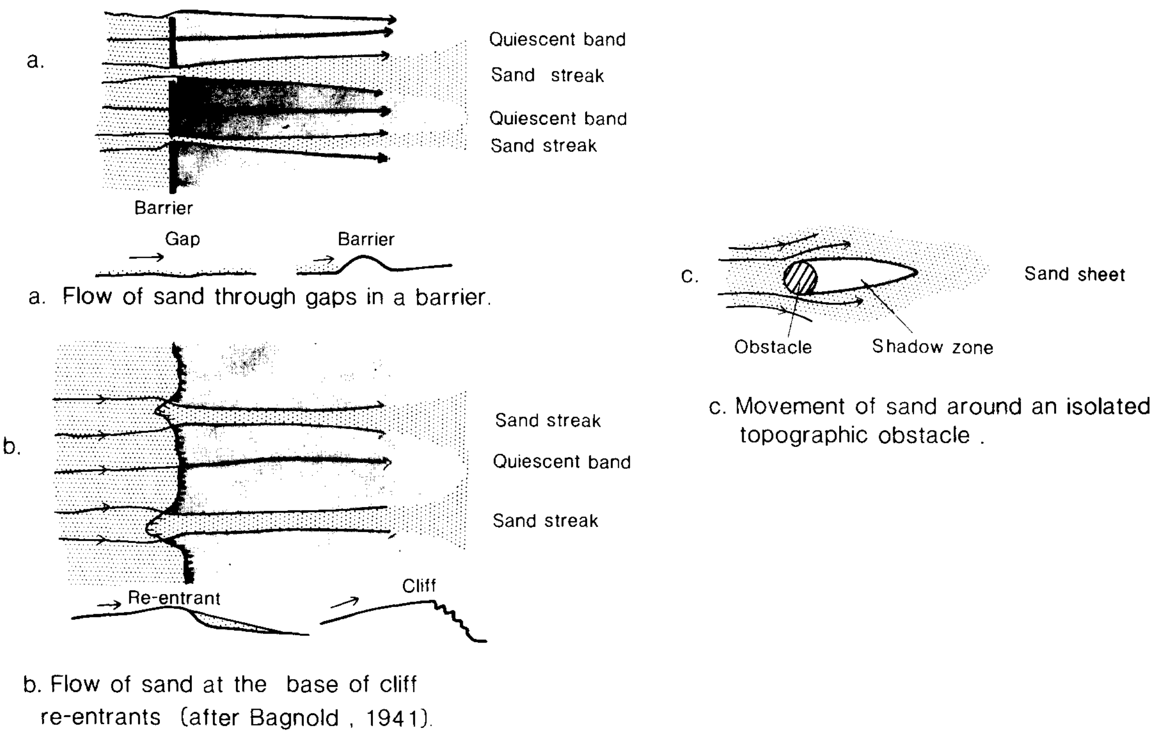


Fig. 2: The relation of saltation formations to topographic obstacles.

2. OBSERVATIONS OF SALTATION FORMATION VS. STABILIZED AREAS

2.1. SAND FLOW THROUGH GAPS IN A BARRIER

The first category of saltation formation is where sand flows through gaps (canyons, arroyos, valleys) in a topographic barrier (ridges, cuestas, escarpments). On Landsat imagery it can be observed that the sand has been funneled through re-entrants (on either upslope and downslope sides) of a plateau and through topographic gaps in the rock outcrops, forming elongate, linear sand streaks. Drifts also accumulate on the downwind base of cliffs, but only near re-entrants or side canyons (Figure 2b, after BAGNOLD 1941). In the lee of a ridge or any other barrier that prevents the sand from migrating downwind by saltation, there is a contrasting stable, quiescent band of non-deposition and non-erosion (Figure 2a, after BAGNOLD 1941).

Pure entrainment would have led to erosion (deflation) on the exposed high plateaus, where the winds are generally stronger than at the base of the cliffs, and to settling of airborne particles in bright, uniform blankets in the more sheltered valleys. This is contrary to the actual observations (Photo 1, Fig. 3). Apparently, the migration of sand grains is not controlled by the strength of the wind, but by the **continuity of near-surface particle flow**. Whenever there is a break in the continuity, caused by a topographic barrier, a quiescent zone forms in the lee of the barrier. The relatively gentle slopes along both upwind and downwind re-entrants in the plateau escarpment do not act as insurmountable barriers to the migration of sand along the effective wind direction. Only steep irregular cliffs obstruct the saltation process (Figure 2b). Thus the bright sand stringers are seen in cliff re-entrants, but the dark quiescent zones occur to the lee of the steep cliffs.

These features can be observed in Landsat images of the area between the Plateau du Mangueni and Plateau du Djado, along the Niger–Libya border, south of the Marzuk sand sea (Landsat 1194-09061, Feb. 2, 1973, Photo 1, Figure 3). The Plateau du Mangueni and Plateau du Djado form the southern rim of the concentric cuestas and escarpments enclosing the Marzuk basin, and consists of Cretaceous Nubian sandstone, post-Tassilian limestone and Paleozoic sandstone, shale and limestone. Sand filling the Marzuk Erg is predominantly quartz. Grain sizes are distributed bimodally, with most of the sand grains more than 0.35 mm (coarse) and some less than 0.1 mm (very fine). At the western margin of the sand sea, the grains are uniformly fine (BREED et al., 1979). The northern and western parts of the basin comprise active, barchanoid dunes. Fields of barchan dunes occur on the northern side of the Plateau du Mangueni.

Winds have carried sand southward over the southeastern rim of the Marzuk basin in long parallel streaks (Photo 1, Figure 3). The streaks contrast with the darker, more stable areas (in part sandy-pebble pavements or lag deposits) of the smooth, intermountain plains on the southern edge of Libya's Marzuk basin. The sand streaks are up to 40 km long and fairly narrow (1-2 km wide) and tend to widen downwind, whereas the darker, quiescent bands, which occur in the lee of barriers, in between the sand streaks, are broader originally (2-3 km) but ultimately taper downwind. The streaks can be traced from the sand-covered plains into northeast-trending slopes of the plateaus. They are more prominent in the southeast escarpments, in the downwind direction. The occurrence and development of the streaks is obviously controlled by the narrow breaks (gaps) in the outcrops. Bright streaks are especially noticeable on the plateau south of Emi Fezzan and on the Plateau du Djado (Photo 1).

The sand may be derived from more than one source. Some of the sand in the Marzuk basin appear to have been carried southwest by the prevailing winds, from sources in the Great Sand Sea (Egypt) and Calanscio sand sea (eastern Libya) as determined from the orientation of saltation formations (Figure 4). The Al Haruj al Aswad mountains (Tertiary mafic volcanics near P_3, upper right, Figure 4) have acted as a partial barrier to this southwest migration of sand, but the low eastern margin of the Marzuk basin may not have prevented some sand from crossing into the basin and thence onto the Plateau du Mangueni from the northwest. On the other hand, PESCE (1968) believes that most of the sand was derived locally by fluvial erosion of the sandstone ridges surrounding the Marzuk basin*. However, the original source of the sand does not affect our observations.

A second area where sand is funneled through gaps in cliffs may be observed along the 300 m high escarpment, west of Aswan, Egypt (Landsat 1109-07504, Nov. 9, 1972, Photo 2). The prevailing surface wind direction is from the northwest (N39°W, 141° azim.), as measured from the orientation of sand streaks on the leeward side of the cliffs (see also Figure 4). Thus the linear dune, only a few kilometers farther, at the base of the cliff, but at an elevation of 100 m, in the Nile valley (25°N and 32.4°E) is oriented in a more southerly direction by 24° (N15°W, or 165° azim.), reflecting the control of the prevailing surface winds by the valley.

* Traces of dried-out river channels may still be observed on Landsat imagery (Photo 1).

Photo 1: Plateau du Mangueni and Plateau du Djado, Niger–Libya border, (Landsat scene 1194-09061; Feb. 2, 1973). This scene illustrates the funneling of sand streaks and stringers through cliff re-entrants on plateaus and through gaps in outcrops.

2.2. FLOW OF SALTATION SHEETS AROUND ISOLATED TOPOGRAPHIC OBSTACLES

The situation is different when the movement of saltating sand is impeded by an isolated topographic protuberance on an otherwise flat plain. The sand sheets are diverted by a topographic obstacle: the saltating particles flow around it, leaving a dark quiescent shadow zone, which tapers downwind (Figure 2c). This shadow zone is uniformly dark on the scale of our observations and shows none of the complex patterns that are associated with airflow around obstacles (linked to the patterns of vortices in the boundary layer flow, see INTRODUC-

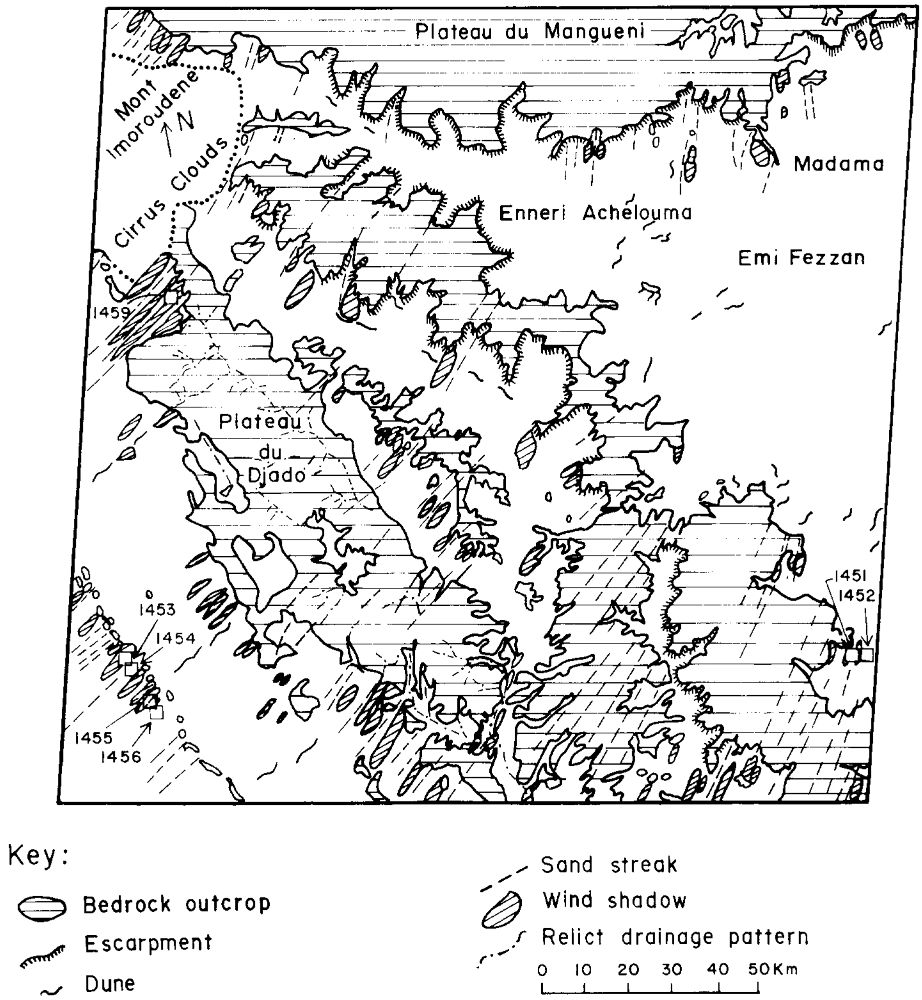


Fig. 3: Schematic drawing showing the relation of the sand streaks and the shadow zones to gaps in topographic barriers, same area as Photo 1.

TION). It can be noted that on a small scale, erosion and deposition patterns have been observed in the lee of the Amboy crater by GREELEY & IVERSEN (1978). A pronounced, recent deposition of airborne particles (which can be expected to be strongest in the lee of obstacles because of reduction in flow velocity, BAGNOLD 1941) would show up as a bright area. Inasmuch as we fail to observe these effects, they must be a minor influence when compared to the absence of the saltation activity in the shadow zone.

Dark shadow zones are observed in the lee of isolated outcrops southwest of the Plateau du Djado and at the base of southern cliffs (downwind) of the plateau. These represent stable zones, with some pebbly lag pavements, which do not participate in the saltation.

. Still better examples of these features may be observed between Jebel Uweinat and Gilf

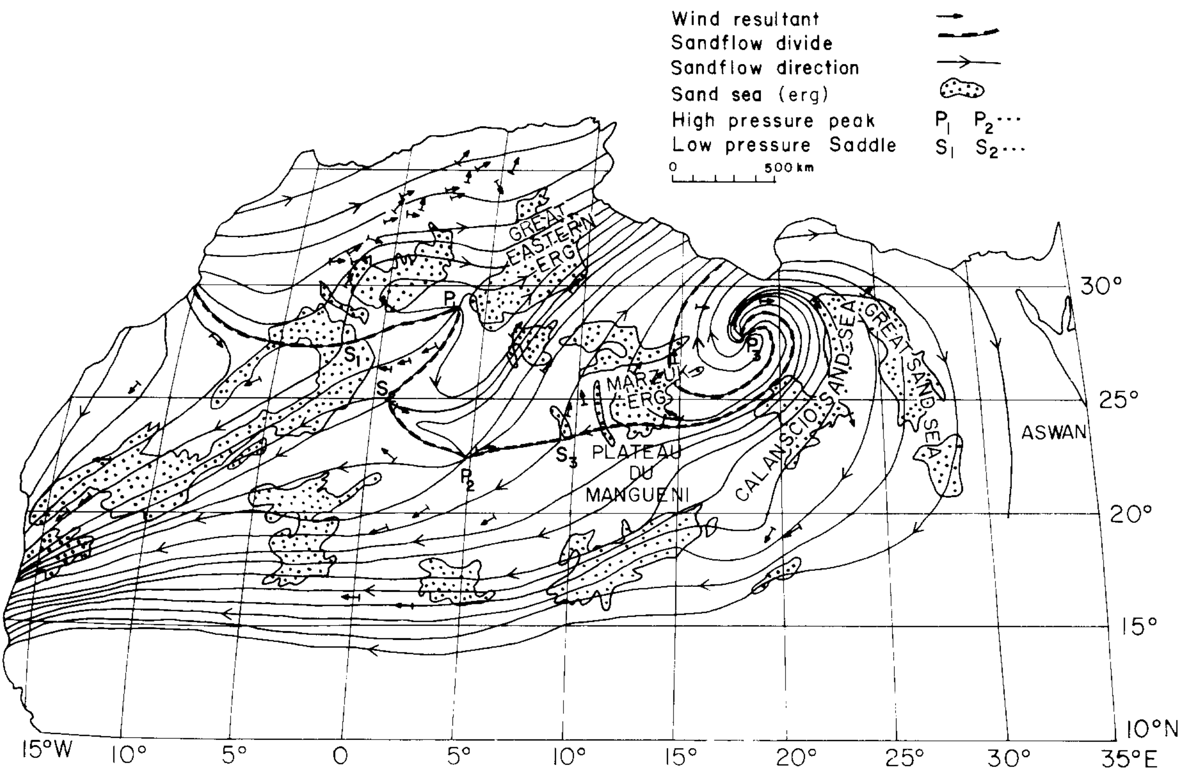


Fig. 4: Prevailing wind directions and sand streams in the Sahara (after WILSON 1971).

Kebir, at the border between Libya, Egypt and Sudan (Landsat 1114-08200; Nov. 14, 1972; Photo 3, Figure 5, lower right). The area is at the eastern edge of the Kufra basin, which is marked by an upwarp of Precambrian and Paleozoic rocks. The prominent mountains – Jebel Uweinat (elev. 1934 m), Jebel Arkenu (elev. 1435 m), Jebel Babein (elev. 1104 m) and Jebel el Bahri are Precambrian granitic ring-dike and dome intrusions. Isolated Tertiary basaltic volcanos, such as Hagher el Garda, are scattered over the region (CONANT & GOUDARZI 1964, PESCE 1968, ISSAWI 1980).

The sand originates in the Western Desert of Egypt, south of the Siwa depression, and has accumulated into enormous compound linear dunes, topped by sharp-crested longitudinal (seif) dunes that are actively migrating south, under the influence of the prevailing winds (El–BAZ et al. 1979). The sand is blown south through a gap – El Agaba – in the Gilf Kebir (Great Wall) – a plateau of Jurassic–Cretaceous sandstone.

Dunes of the Western Desert consist chiefly of well-rounded quartz grains derived from sandstone and from unconsolidated alluvium. Dune sands are well-sorted, with diameters ranging from 0.12 to 0.5 mm (fine to medium), whereas particles in the flat sand sheets from the southern part of the Western Desert have a bimodal distribution, with peak diameters between 1-2 mm (coarse) and 0.66-0.25 mm (very fine to fine).

The saltation formations south of Gilf Kebir consist of both dunes and broad sheets (Fig. 5). The sheets are like a river of sand that diverges and flows past the "islands" of Jebel

Photo 2: Another example of sand funneled through gaps in cliffs west of Aswan, Egypt (Landsat 1109-07504; Nov. 9, 1972). Note also the change in orientation of the long, linear dune west of the Nile relative to the sand streaks on the plateau, illustrating the shift in surface wind direction induced by the local topography. Scale: 185 × 185 km.

Arkenu and Jebel Uweinat, down a gentle regional slope of 0.004.

Field studies (EL–BAZ et al. 1979, 1980) have shown that the shadow zone in the lee of these mountains is covered with irregularly-shaped dark rock fragments, derived by mass-wasting from the nearby mountains. Although smaller, lighter-colored chips and sand grains are scattered between and under the dark fragments, the latter predominate. The shadow zones are elongate, up to 20-40 km long, occasionally tear-drop-shaped, and taper downwind from a maximum width of 15-20 km (the dimensions vary according to the size of the obstacle). The shape of the shadow zone is determined by the sifting of the mobile sand rather than the fairly stable pebbly surface. Changes of up to 2.5 km in the position of the borders of the sand sheets have been observed over a six-year period on Landsat imagery (EL–BAZ et al. 1979).

Photo 3: Jebel Uweinat (lower right-hand corner), Jebel Arkenu and Jebel Babein, Libya–Egypt border (Landsat 1114-08200; Nov. 14, 1972). Examples of the development of quiescent zones in the lee of isolated topographic obstacles (the mountains).

The shadow zones of the Jebel Uweinat area represent a relatively quiescent, dormant region, not participating in the saltation processes. The absence of loose bright sand in the shadow zone supports the thesis that saltation is the mechanism forming the sheets. If the sand were transported predominantly as airborne particles, the reduction of the forward wind velocity in turbulent eddies created by the presence of the obstacle would cause the sand grains to settle in the zone of reduced air velocity in its lee, as discussed. This would result in accumulation of freshly deposited, bright sand in the lee of the topographic feature, which has not been observed.

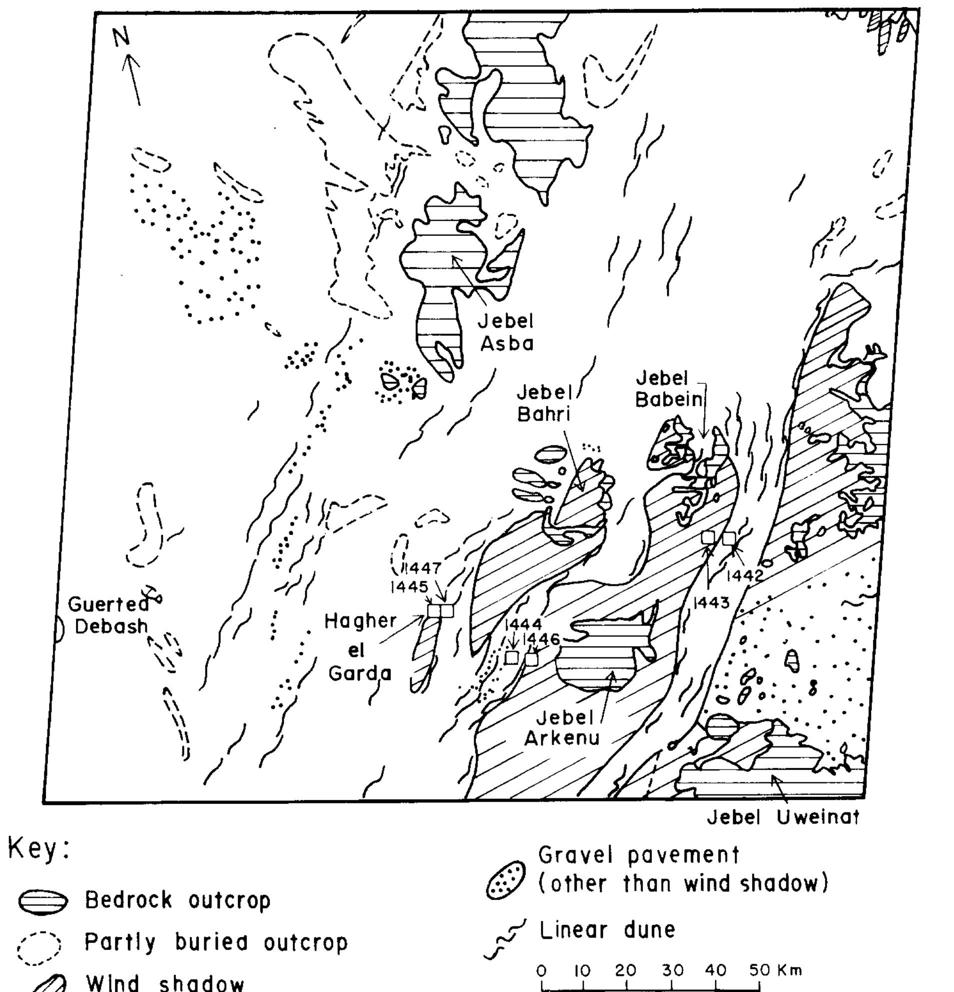


Fig. 5: Schematic sketch showing the relation of quiescent shadow zones and linear dunes to the mountains.

2.3. TERMINATION OF A SALTATION FORMATION BY THE RIVER NILE

Sand sheets are observed to terminate abruptly at the east-west bend in the Nile between Kosha and Abri, Sudan (20°30'N; 30°30'E; Landsat scene 1236-07581, Mar. 16, 1973) although the sheets continue to flow south, to the west and south of this river bend (Photo 4). The river has apparently acted as a barrier to saltation. Although some hills directly south of the Nile at the bend may have also formed a topographic impediment to saltation, the river itself has prevented sand from crossing, as can be seen by the much lower reflectivities on the river islands directly in the path of the sand, but which appear to be relatively sand-free. Good examples of long, narrow, dark, wind shadows in the lee of two prominent, isolated dark, elongated (volcanic?) outcrops are also seen on Photo 4.

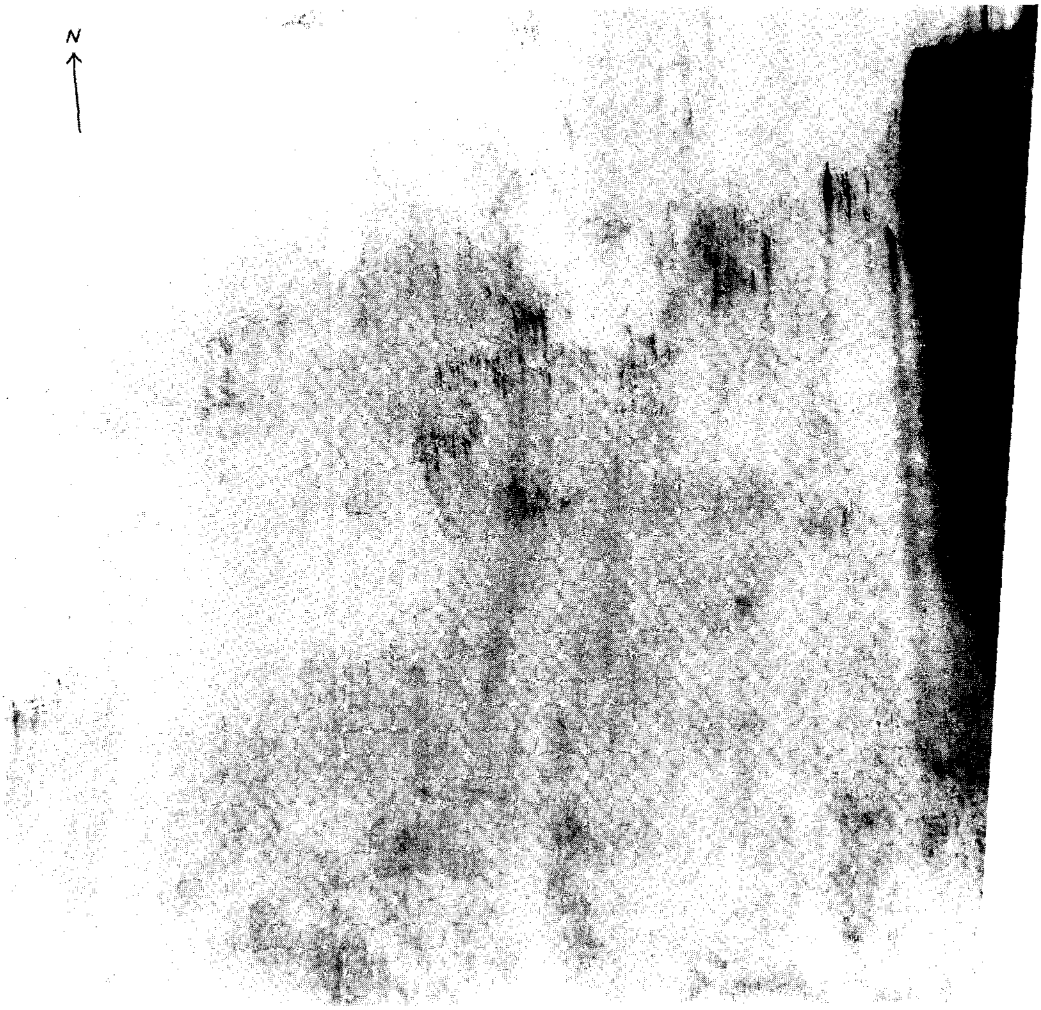


Photo 4: Bend in Nile River between Kosha and Abri, Sudan (Landsat 1236-07581; Mar. 16, 1973). Truncation of southward flow of sand by the river. Note absence of sand in river islands. Also several examples of shadow zones (dark areas) in the lee of isolated outcrops. Scale: 185 × 185 km.

2.4. SALTATION SHEETS POSSILY INFLUENCED BY MAN'S ACTIVITIES

Saltation formations (fossil dunes and sheets) may become partially stabilized as a result of climatic and environmental changes over geologic time. However, these formations remain vulnerable to eolian deflation under certain circumstances, such as anthropogenic disruption of the vegetation cover, or favourable orientation of erodible material with respect to the prevailing wind system.

An example of an area where all of these factors are present is in western Senegal, north of the Saloum River (Landsat 1212-10573, Feb. 21, 1973, Photo 5). The region is underlain by nearly horizontal, undeformed late Cretaceous to middle Eocene sedimentary rocks,

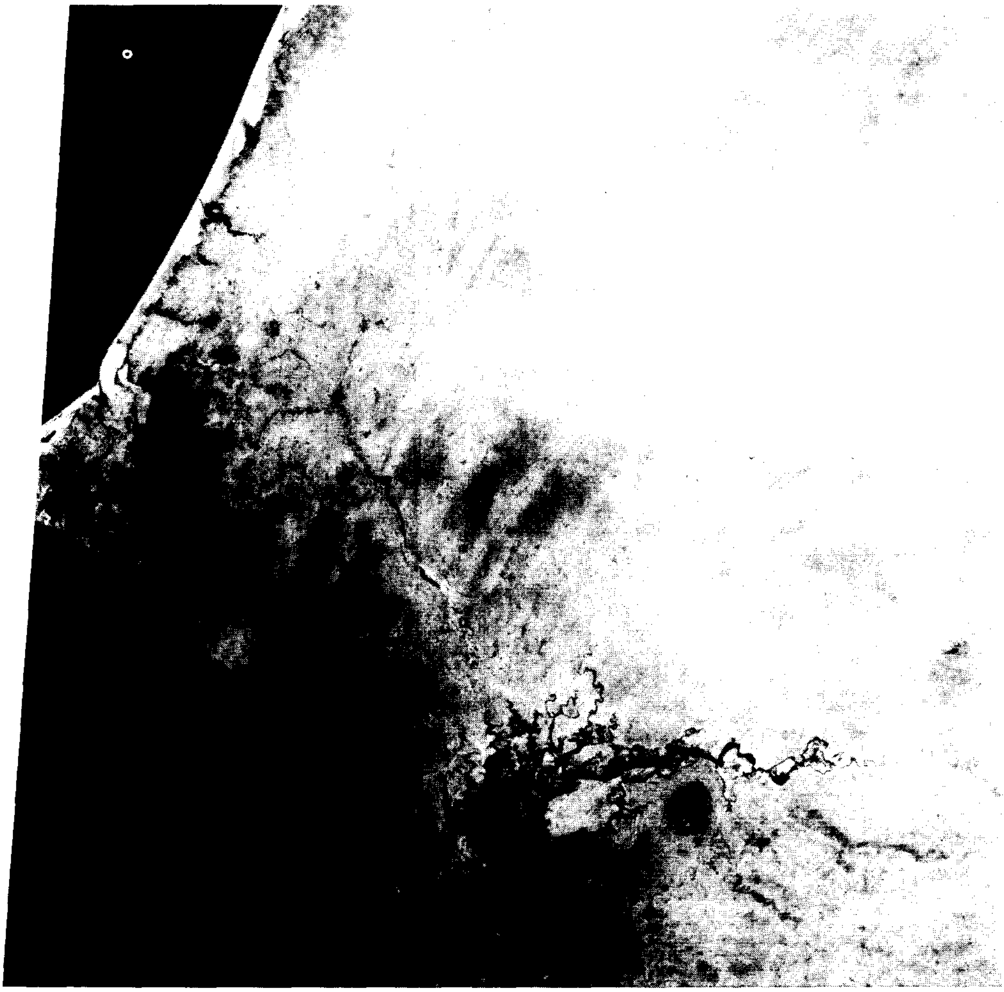
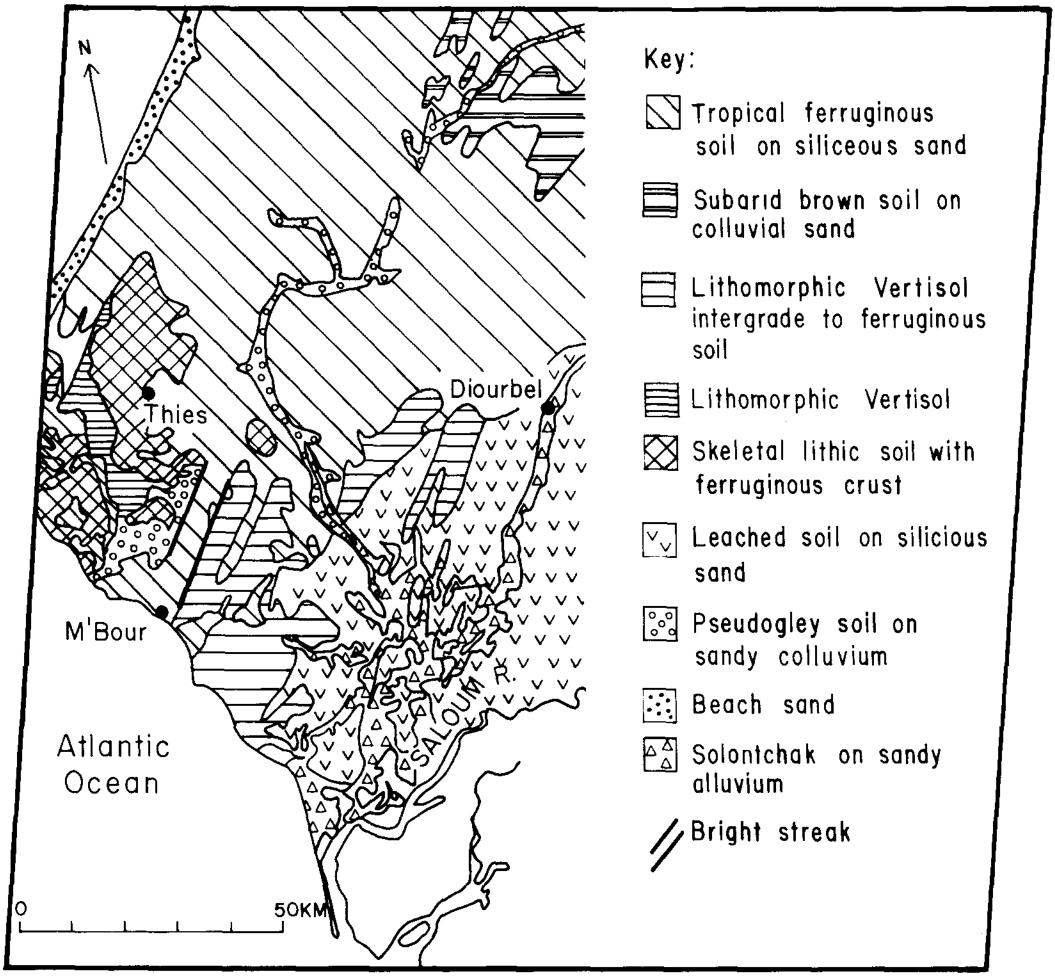


Photo 5: Western Senegal (Landsat 1267-10574; Apr. 16, 1973). Bright NE–SW trending linear streaks with sharp reflectivity boundaries. The streaks extend from M'Bour on the Atlantic Coast to an area east of Thies. The bright streaks probably represent fossil sand dunes (compare Photo 5, Figs. 6a-c). The streaks seem to be source of the dust plumes extending southward across the Atlantic.

mostly limestone and marl. Volcanic rocks (Miocene to Quaternary) occur on the tip of the Cap Vert peninsula, near Dakar, and in scattered, isolated volcanoes around Thies (Carte GEOL. SENEGAL ET GAMBIE 1962). A dune erg once extended as far south as the Saloum valley (MAIGNIEN 1965). Sahelian Africa was extremely arid during the culmination of the last (Würm) glaciation, 20,000 to 15,000 years ago (STREET & GROVE 1976, CLIMAP STUDY 1976). Vast areas of the Sahel are covered by fossil dunes from this period (GROVE & WARREN 1968). The dry period was succeeded by a wetter stage, probably corresponding to the end of the last Ice Age. Sea-level rose 5500-5000 years ago, flooding the Senegal River 250 km inland and depositing quantities of beach sand. During the last few thousand years, the sea has regressed and the beach sand has been blown by the



F.g. 6a: Soil map of same area as Photo 5 (after MAIGNIEN 1965). Note how bright streaks are parallel to and coincide with soil boundaries.

wind into the coastal "dune jaunes" (GROVE & WARREN 1968, BREED et al. 1979, FAURE 1980).

The prevailing wind direction, at latitudes 13° to 17°N, during the dry winter months is NNE to NE, parallel to the Quaternary red dunes. At these latitudes, the wind shifts to SW, as the Intertropical Convergence Zone (ITCZ) moves north during the summer monsoon months.

A NE–SW trending linear bright streak with sharply defined boundaries (about 35 km long and 6-10 km wide) is observed on Landsat imagery, extending from M'Bour on the Atlantic coast to an area east of Thies (Photo 5, Fig. 6a-c). A less pronounced band (about 15 km long and 3-4 km wide), lies parallel and to the east of the first. Although the continuity cannot be definitely established, faint lineations with the same trend occur north of Diourbel

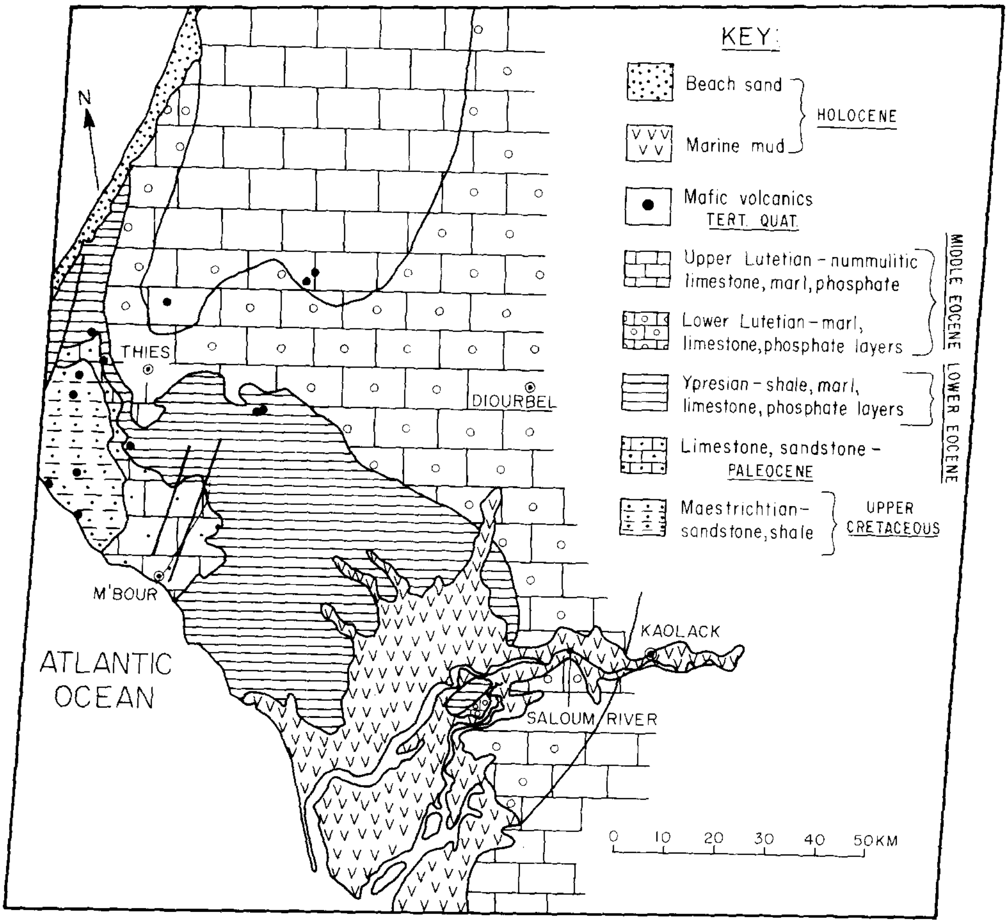


Fig. 6b: Geologic map of same areas as Photo 5 (after CARTE GEOL. DE SENEGAL ET GAMBIE 1962). Note how bright streak crosses geological contacts nearly at right angles.

in northern Senegal (Photo 5, Fig. 6a-c). The lineations probably represent the "fixed red dunes" of Quaternary age, which can be traced northward into Mauritania, where dunes parallel to the prevailing NNE to NE wind directions are still active (BREED et al. 1979).

The bright streaks do not show correlation with geologic features, which trend north to northwest in this area, nearly perpendiculat to the soil type boundaries and to the streaks (Fig. 6a-c). The streaks lie on tropical ferruginous soil that has developed over silicious sand, which represents transported material, i.e., fossil saltation formations, since the bedrock is chiefly limestone and marl. The darker, vegetated regions flanking the streaks (Figs. 6a, b) occur on several soil types including lithomorphic vertisols, intergrading with ferruginous soil – marl, and on alluvium (MAIGNIEN 1965). The darker more elevated areas near Thies are forested; the medium gray tones represent savannah or brush. West of Thies, the vegetation boundaries lie parallel to the geologic and soil contacts. The boundaries between bright and dark terrain may have been partially modified by agricultural practices such as

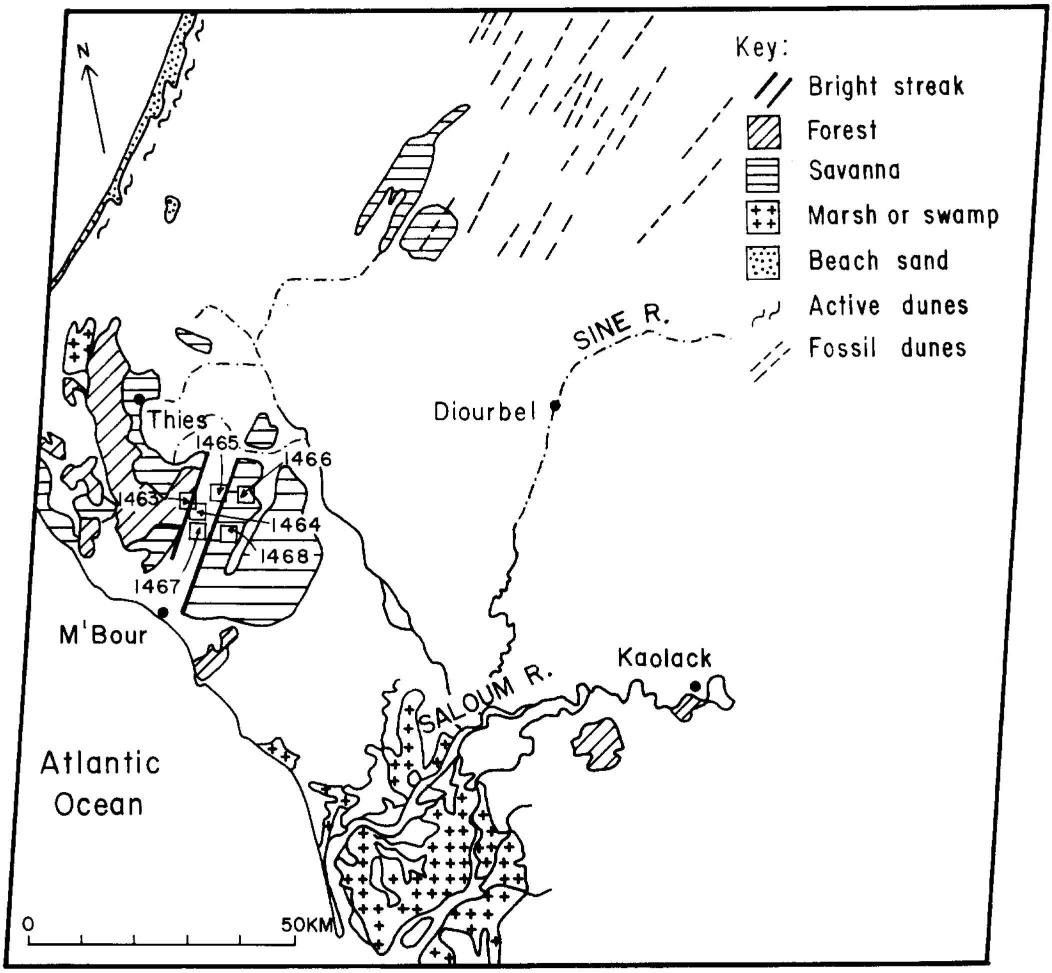


Fig. 6c: Simplified vegetation map of same area (after CARTE DE LA VEG. DE L'AFRIQUE OCCIDENTAL FRAN., Thies quad., 1950).

peanut farming.

The sandy, tropical ferruginous soils are vulnerable to wind deflation, particularly because of the peanut farming and burning of vegetation which expose the bare surface to the NE winds during the dry season (McLEOD et al. 1977). That deflation actually takes place is demonstrated by the dust plumes extending over the coast near M'Bour (Photo 5; Landsat 1267-10574, April 16, 1973). This dust storm occurred at the end of the dry season during the Sahel drought of the early 1970's. The dust is derived from the area of the bright streak. When the sand begins to saltate, the saltating grains dislodge fine clay-sized particles that are then carried in suspension by the wind. Furthermore, collisions between saltating grains can comminute friable mineral particles, providing additional material that can be removed in suspension.

In western Senegal, in summary, the fossil saltation formations originated in the ex-

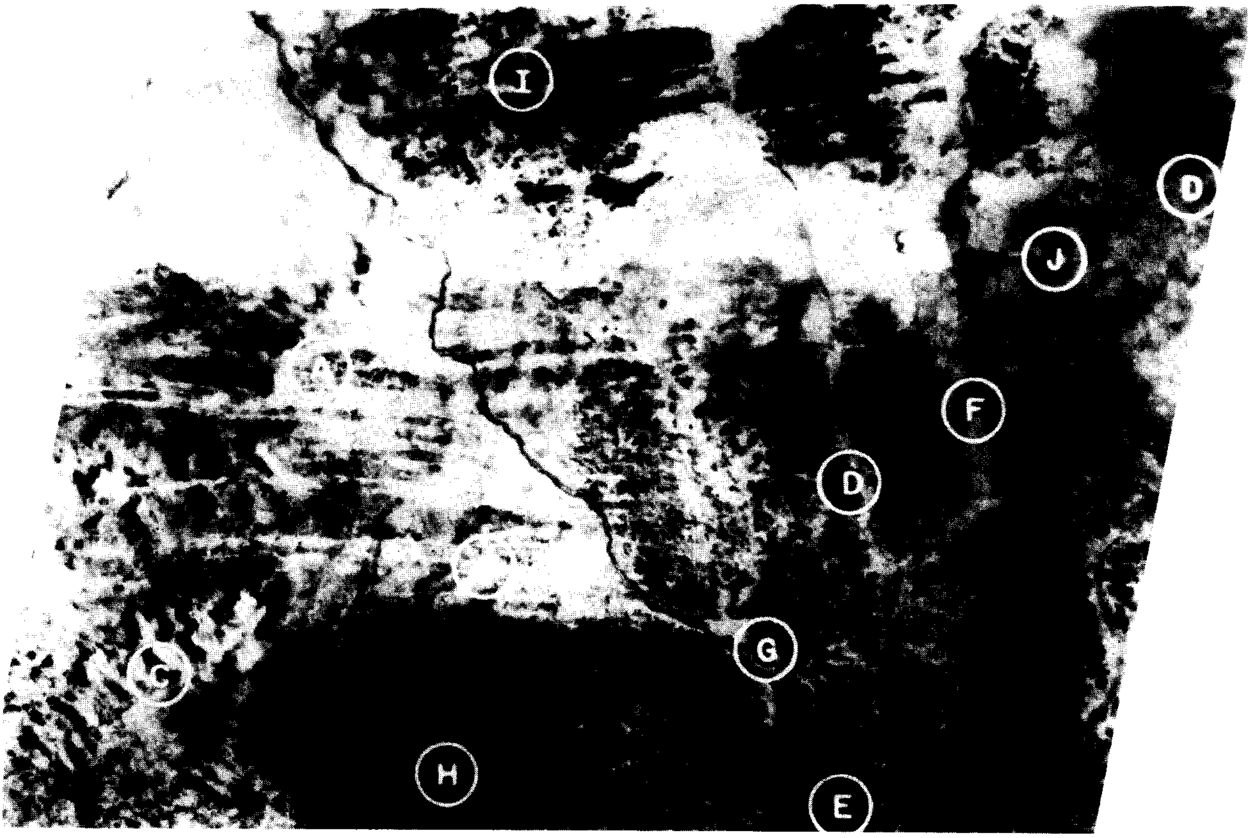


Photo 6: "Fossil" sand dunes, Upper Volta, Niger and Mali (Landsat mosaic; from Fig. 337, SHORT et al. 1976). Scale: Distance between E (Ansongo, Mali) and G (Niamey, Niger) is 290 km.

tremely arid climate that prevailed during the Würm (Wisconsin) glaciation. Since then, soils have developed over the eolian sands which now support distinctive vegetation communities. The difference in soil types and vegetation cover that have formed over sand as compared with bedrock appear on the Landsat imagery as narrow, linear reflectivity boundaries. Land use patterns, including agricultural practices, are to a large extent a function of the underlying soil types. The orientation of the fossil saltation sheets or streaks parallel to the prevailing desert winds, and the disturbance of the vegetation cover by human activities make these fragile areas a potentially prime source of deflatable material. This example illustrates the utility of Landsat imagery together with ground-based data in identifying critical areas, subject to desertification processes.

2.5. OBSERVATION OF "FOSSIL" SALTATION FORMATIONS

Another example of partially stabilized, "fossil" saltation formations occurs at the border between Upper Volta, Niger, and Mali (Photo 6; [Fig. 337, in SHORT et al. 1976]). This mosaic of 12 Landsat images covers the transition between the Sahel (north) and Savannah (south). The prevailing wind direction in this region is from east to west (Fig. 4).

Long, narrow, bright subparallel east-west trending streaks are observed. According to SHORT et al. (1976), the streaks represent stabilized and currently cultivated dunes, which reveal the former southward extent of the Sahara. In the north, the streaks cross dissected plateaus capped by dark lateritic soils, while in the center of the area, they cover grass and shrubland.

The streaks are estimated to be only several centuries old, since they are superimposed over the Dallol Bosso River (intermittent), and its tributaries, but are cut by the Niger River (permanent stream). Furthermore, they must have been deposited under a wind regime not unlike the present one. The false-color composite mosaic, compiled between April 17 and 21, 1973, during the early 1970's drought, shows only traces of vegetation in the south (faint red). The rest of the image reveals the darker tones of plateaus or exposed bedrock. Although reportedly cultivated, the dunes bear no signs of vegetation. The absence of pronounced vegetation cover and the alignment with the prevailing wind direction make these dunes especially vulnerable to wind erosion.

3. REFLECTIVITY MEASUREMENTS

The saltation formations can be easily distinguished in satellite imagery from the stable regions, based on the pronounced differences in reflectivity. The sharp reflectivity boundaries mark a sudden change in surface characteristics. Surface crusting, accumulation of plant debris on the surface and shadowing effects of shrubs both living and dead all contribute to the reduced reflectivity of stable zones (OTTERMAN 1981). In some cases, the dark surfaces consist of locally derived gravel pavement with manganese and iron oxide patina on exposed rock surfaces. In this section, quantitative measurements from space of the reflectivity contrasts are presented.

Portions of Landsat Multispectral Scanner (MSS) digital tapes for three areas (1. Plateau du Mangueni, Niger; 2. Jebel Uweinat, Egypt-Libya; 3. Thies-Diourbel, Senegal) were sampled in order to obtain quantitative measurements of spectral reflectivities across the brightness boundaries. Adjacent pairs of relatively homogeneous light and dark terrain were selected, and checked for uniformity by examining the grayscale printout for each site. The average spectral radiance (mW/cm^2sr) for each sample area, the histograms and the standard deviations were obtained. Sample areas vary between 121 and 870 pixels. The smaller sample size stems from the narrow widths of some sand streaks or shadow zones.

The radiance values were then used to calculate spectral reflectivities. The space reflectivity $a_{S\lambda}$ is defined as follows (OTTERMAN & FRASER 1976):

$$a_{S\lambda} = \frac{\pi L_\lambda}{S_\lambda \cos\theta_0}$$

where L_λ is the spectral radiance measured by the satellite-borne radiometer (calculated from the digital data for each of the four MSS bands), S_λ is the solar spectral irradiance perpendicular to the solar beam at the top of the atmosphere (the values of S_λ for each MSS band are given by OTTERMAN & FRASER 1976), and θ_0 is the zenith angle of the sun. The ground is assumed to be a Lambertian reflector, that is, radiance measured near the ground is independent of both the direction of incident radiation and the direction of observation.

Tab. 1: SPECTRAL REFLECTIVITIES

Location, Landsat scene	sample	MSS Band 4 0.5-0.6	MSS Band 5 0.6-0.7	MSS Band 6 0.7-0.8	MSS Band 7 0.8-1.1μm
Niger, 1194-09061 (Fig. 3)					
Sand stringer	1451	0.341	0.472	0.488	0.543
Shadow zone	1451	0.265	0.323	0.327	0.353
Sand stringer	1452	0.345	0.482	0.499	0.554
Bedrock and soil	1453	0.211	0.216	0.208	0.236
Shadow zone	1453	0.263	0.317	0.322	0.351
Sand stringer	1454	0.363	0.470	0.485	0.518
Bedrock and soil	1455	0.213	0.222	0.215	0.238
Shadow zone	1455	0.290	0.349	0.355	0.378
Sand stringer	1456	0.365	0.485	0.499	0.539
Sand stringer	1459	0.355	0.529	0.560	0.612
Shadow zone	1459	0.304	0.404	0.418	0.466
Jebel Uweinat, Egypt–Libya 1114-08200 (Fig. 5)					
Sand east of Hagher el Garda	1447	0.412	0.581	0.594	0.663
Hagher el Garda volcano	1445	0.224	0.241	0.233	0.244
Sand west of Jebel Arkenu	1444	0.416	0.581	0.591	0.655
Shadow zone, W of Jebel Arkenu	1446	0.290	0.325	0.323	0.345
Sand, SW of Jebel Babein	1442	0.372	0.565	0.588	0.663
Shadow zone, SW of Jebel Babein	1443	0.349	0.456	0.468	0.516
Thies–Diourbel, Senegal, 1213-10573 (Fig. 6c)					
Bright ground	1464	0.242	0.272	0.286	0.352
Dark ground	1463	0.197	0.196	0.221	0.282
Bright ground	1465	0.275	0.310	0.325	0.392
Dark ground	1466	0.215	0.224	0.239	0.301
Bright ground	1467	0.236	0.253	0.272	0.342
Dark ground	1468	0.198	0.197	0.220	0.277

OTTERMAN & FRASER (1976) assessed analytically the atmospheric effects on the space reflectivity $a_{s\lambda}$. The conclusion was that the space reflectivity differs usually by only a few percent from the surface reflectivity as measured close to the ground, if the surface reflectivity is higher than 0.15. Based on this conclusion we do not correct for the atmospheric effects, that is, the surface reflectivity is assumed equal to the measured space reflectivity. The reflectivities are tabulated in Table 1.

Contrast ratios for pairs of adjacent sites representing the two surface types are given in Table 2. The contrast ratio is simply the reflectivity ratio of the bright to the adjacent dark surface. These ratios range from 1.17 to 2.33 in Niger, 1.07 to 2.72 in Egypt-Libya and 1.19 to 1.39 in Senegal. The contrast ratios are significantly greater than 1.00, and it is therefore fairly easy to distinguish the two surface types. The standard deviation of reflectivities of picture elements in the sampled sites ranges from 2.5 to 7.0%, both for the bright areas and for the ad-

Tab. 2: CONTRAST RATIOS OF BRIGHT TO DARK SURFACES

		MSS Band 4	MSS Band 5	MSS Band 6	MSS Band 7
Niger					
Sand stringer/shadow zone	1451	1.29	1.46	1.50	1.54
Sand stringer 1454/soil + bedrock	1453	1.72	2.17	2.33	2.20
Sand stringer 1454/shadow zone	1453	1.38	1.49	1.51	1.48
Sand stringer 1456/soil + bedrock	1455	1.71	2.18	2.32	2.27
Sand stringer 1456/shadow zone	1455	1.26	1.39	1.41	1.42
Sand stringer 1459/shadow zone	1459	1.17	1.31	1.34	1.37
Jebel Uweinat, Libya–Egypt					
Sand 1447/volcano	1445	1.84	2.41	2.55	2.72
Sand 1444/shadow zone	1446	1.44	1.79	1.83	1.90
Sand 1442/shadow zone	1443	1.07	1.24	1.26	1.29
Thies–Diourbel, Senegal					
Bright ground 1464/dark ground	1463	1.23	1.39	1.29	1.25
Bright ground 1465/dark ground	1466	1.28	1.39	1.36	1.30
Bright ground 1467/dark ground	1468	1.19	1.29	1.24	1.24

jacent shadow zones, but it is considerably higher (to 20%) for exposed bedrock. The relatively low scatter in the reflectivities for both the bright saltation formations and the dark shadow zones indicates a homogeneous surface in both cases. Thus, the reflectivities, calculated from the radiance values, provide a good index of the nature of the surface.

4. POSITIVE FEEDBACK MECHANISMS CONTRIBUTING TO LOCALLY SELF–PERPETUATING CONDITIONS

From the reflectivities analysis in the previous section it can be seen that the saltation formations and the stable areas are each quite uniform, but sharply contrasting from each other. This contrast, that is the transition across the "banks" of the saltation formations (parallel to the dominant wind direction) occurs within one or two pixels (picture elements) in most cases. The contrast in surface characteristics occurs therefore over a distance of about 100 m or less (MSS pixels are 60 × 80 m). Shifts in wind direction in different seasons and under different meteorological conditions, would be expected to have produced diffuse boundaries. Although prevailing wind directions are west-southwesterly throughout much of the Sahara (Fig. 4), annual sand rose diagrams indicate considerable directional variability of wind during the year (BREED et al. 1979). Thus the seasonally shifting winds span a much wider angle than shown by the spread of the sand streaks. Wind blowing across the boundary from a saltation formation into a stable region should occur with high probability in any season, even if allowance is made for the topographic control of the surface winds. Such a wind component can be expected to continue the saltation, introducing at least locally and temporarily loose sand into the stable region. These incursions of the bright sand should create an irregular and gradual boundary, contrary to the actual observations. Therefore the observed sharpness in the boundary is somewhat puzzling. It suggests that an occasional wind accompanied by an incursion of saltating particles will produce little or no change over a stable surface, which tends to be "immune" to eolian influences. On the other hand, a saltation formation (that is, an area with loose soil) a short distance away is prone to be disturbed repeatedly by a comparable wind and a comparable concentration of saltating particles. Such an explanation points out that surface characteristics (stability vs. instability) are locally self-perpetuating.

This either/or principle of soil characteristics (Thesis 2) can be explained in terms of positive feedback mechanisms. Those factors which promote soil stabilization (in other words, which tend to prevent or minimize disruption of a soil surface) delevop under conditions of relative stability. Thus any increase in soil stability reinforces the factors that preserve the stability – thereby constituting a positive feedback mechanism. We discuss first factors that produce higher energy thresholds for disturbing the surface, and thus lower the effective eolian forces at the surface. Subsequently we discuss how each of those factors depends on the soil stability.

A very important factor in determining soil stability appears to be the cohesion of the soil surface. Breaking a crusted surface and dislodging a grain of sand, whether by aerodynamic forces (aerodynamic entrainment threshold velocity) or by impact (threshold velocity for continuation of saltation) requires a higher energy than merely dislodging a grain out of the loose sand.

The hard surface crusts (or duricrusts) include calcretes (predominantly calcium carbonate), silcretes (silica-rich), laterites (iron-oxides) and gypsum.

Surfaces highly resistant to wind erosion are characterized by crusts having a high salt, clay or silt content. Vegetation and algae play an important role in stabilizing the surface (bio-crusting). Aside from the soil-anchoring effects of root systems, the fixation of loose sand is enhanced by salts released by plant residues (see PETROV 1973, 227). Many desert plants accumulate N, K, and Ca, and halophytes concentrate salts. Some plants and bacteria may accumulate sulfur, which has been linked to gypsum formation. Furthermore certain algae form resistant crusts, while sulfate-reducing bacteria cause precipitation of Na_2CO_3 (COOKE & WARREN 1973).

The formation of algal and lichen crusts is closely related to the clay content of desert soils, since clays retain more moisture and nutrients, and hold soil particles together. Once formed, the bio-crusts counteract erosion by binding soil particles with secreted mucilaginous material, which inhibits deflation by wind and also enhances water infiltration and soil fertility. For example, on the North American continent, the northern Great Basin, with up to 80% of the surface covered by bio-crusts, shows considerably lower rates of erosional effects than the Sonoran Desert, where only 4% of the surface is covered by algal crusts (WEST & SKUJINS 1978).

A second important factor in producing a higher energy threshold is the sorting of particle sizes, associated to some extent with the absence of a crust in the saltation formations.

Fine dust-sized particles may become airborne, and be deposited later, spread over very large areas. The remaining larger particles are characterized by a low threshold velocity for entrainment (BAGNOLD 1941, GILLETTE et al. 1980). The threshold velocity for maintaining saltation (impact or dynamic thresold) can be expected to be significantly lower in the well-sorted saltation formation than in an unsorted soil, since energy is saved by not having to dislodge dust-sized particles that do not contribute to maintaining saltation.

A third factor that reduces the effectiveness of wind erosion is an increase in surface roughness. Plants increase the surface roughness sharply, especially in the growth pattern of isolated shrubs or tussocks characteristic of arid climates. The stems and leaves, even of solitary shrubs, act as mechanical obstacles that reduce the velocity and alter the direction of the wind. As a result, sand grains near these obstacles drop out from the saltating flow and accumulate near the plants (PETROV 1973, 183). The increase in surface roughness reduces the effective wind speed significantly. (The theoretical derivation of surface roughness for brushes and shrubs is quite difficult. That is, measurements of wind vertical profiles need to be conducted to assess the surface roughness of a given ecosystem). A similar increase in surface roughness is produced by the rocky cover over a desert pavement. A high proportion of rocks or pebbles covering a soil protects the underlying material and renders the surface virtually non-erodible (MABBUTT 1977).

The development of the above-cited factors – crusting, particle sorting and surface roughness is enhanced under conditions of soil stability (immobility) and is impeded by conditions in saltation formations. Mineral or algal crusting cannot readily proceed in the saltation formations, in the absence of fine-grained material. Most species of algae and plants cannot grow on such often-moving sands, deficient in fines and mineral nutrients. On the other hand, plants grow in cracks on crusted surfaces. The presence of surface crusts increases the runoff, but produces a **high** concentration of moisture over **small** areas within cracks. Such a moisture-concentrating mechanism is necessary for plant growth in very arid climates, because the available moisture equally-averaged would be insufficient to sustain plant life.

The above-mentioned factors that protect the stable surface against disruption explain the sharpness of the transition across the "banks", inasmuch as they effectively prevent saltation on the stable areas by sand encroaching from the adjacent saltation formations. Because saltation is impeded on such surfaces, the sand flowing in from the adjacent saltation formation in occasional wind shifts, tapers off and stops within less than 100 m, that is, within a few hundred particle "jumps". The stable surface therefore maintains its stable character, preventing the flow of saltating particles on it. Thus, sand tends to flow within the existing saltation formations, disturbing the surface repeatedly. Local perpetuation of surface characteristics results and the boundaries between stable and unstable regions remain sharp and essentially unchanging.

It should be added that this inference about the either/or situation and a need to postulate positive feedbacks can be arrived at by examining the narrow and long shadow zones. A stable shadow zone 2 km wide and 80 km long precludes existence of **effective** wind direction shifts of greater than 1.5°. Such a control by topography must be dismissed as entirely unlikely over any terrain, and especially over the quite flat sandy desert regions at the Egypt-Libya border.

5. DISCUSSION AND CONCLUSIONS

From space imagery, bright streaks or ribbons can be seen stretching over long distances (up to hundreds of kilometers) along the prevalent wind directions in contrast to approximately parallel darker areas. These bright formations are interpreted as sheets or stringers of unstable soil, usually sand, in which saltation repeatedly disturbs the surface. There is no direct information how often in any given year each square meter of a saltation formation is disrupted by the saltating particles. The notable uniformity of the reflectivity along the wind direction suggests to us that every part of a given formation undergoes this disturbance probably several times a year. When sequences of particle "jumps" necessary to cover the length of saltation formation are added, they are calculated to total up to 10^6 or 10^7 "jumps". This calculation points out to the inherent continuity of the processes. The darker areas are interpreted as zones of relatively undisturbed, stable and partially crusted soil.

We observe that when the flow of grains in such saltation formation encounters an apparent obstacle (which is not necessarily a wind-reducing barrier), the bright formation terminates abruptly and a dark zone begins. (Occasionally, the saltation formations terminate without an apparent obstacle; then the termination is gradual). In the lee of an isolated obstacle to the particle flow (an outcrop or a steep hill) we observe a shadow zone, with a uniform low reflectivity and without patterns of deposition/erosion. Where the shadow zone tapers off gradually the saltation formation links up from both sides. Some shadow zones are very long (up to 100 km) and quite narrow (only 2-3 km wide).

We conclude that saltation is the dominant process of surface disturbance in arid regions, and that continuity of the particle flow is the key to understanding this large-scale phenomenon.

The sharp transitions which are observed in satellite imagery across the "banks" between the saltation formations and the stable areas are surprising, in view of the vagaries of wind directions. We postulate positive feedback mechanisms that tend to perpetuate local conditions. An either/or situation results, because a stable area tends to be immune from an incursion of windblown particles, while a comparable incident disturbs anew the surface in a saltation formation.

We also conclude that creation of soil stability can be regarded as a linear rather than an areal protection problem (at least in a basic sense, which might not be practical). By creating a barrier in a line perpendicular to the flow direction (by planting a row of prickly pear cactus or erecting a low, solid fence) one can interrupt the particle flow, permitting the soil to stabilize in the lee of such a barrier. In this context, the either/or situation can be regarded as a see-saw effect: preventing the arrival of the saltating particles should tip the balance from a disturbed surface to a quiescent zone. Such low barriers obviously need maintenance to prevent their burial by the moving sand.

The space imagery which combines a synoptic view with a radiometric accuracy, is a useful tool to study the surface processes. However, such studies suggest ground observations, measurements and experiments, to gain in-depth and quantitative knowledge of these important processes.

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