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REMOTE SENSING OF SAND TRANSPORT IN THE WESTERN DESERT OF EGYPT

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ABSTRACT

Wind erosion and deposition operating in the open desert of Western Egypt have produced a variety of dunes and other sand accumulations, some of which have been tracked by traditional surveying methods, and which can now be used with remote sensing methods to determine net sand transport. In addition to longitudinal dunes and barchans, a vast storehouse of aeolian sand occurs in the surficial deposits of the sand sheet, broad flat regions occupying thousands of square kilometers that are protected by a veneer of granule-size sediments. Using Landsat images from the early 1970's, and SPOT images from 15 years later, migration rates for dunes have been remarkably constant over the past decade. An even longer time period of observations represented by an isolated dune at the border of Sudan and Egypt has confirmed a migration rate of 7.5 m/yr, with no more than 0.5 m/yr variation in rate. Within the sand sheet, paleosols and fine gravel deposits are reworked into ripples of varying sizes, ranging from 500 m wavelength "giant ripples" to 3.5 km wavelength low relief "chevron ripples" detected only from remote sensing data. Changes in the chevron-shaped ripples over the 15 year time period observed indicate that they migrate southward (downwind) at 500 m/yr. Field surveying in the region indicates that the chevrons are controlled by several scales of long-wavelength ripples (130 m to 1200 m wavelength) with amplitudes of 15 to 30 cm. Net transport volumes within the sand sheet are much greater than those of dune fields because of the extent of sediment exposed to the wind. Utilizing time-series remote sensing data, sand transport can now be assessed over broad regions of the desert rather than by extrapolations from measurements of isolated dunes.

INTRODUCTION

Erosion and deposition in a desert environment are typically closely associated with the movement of dunes. Dunes have been used as wind direction indicators (Breed and others, 1979; Gifford and others, 1979; Mainguet, 1984), as evidence of desertification, and as "storehouses" of sand that can be used to estimate sand transport volume. Typically past studies of dune migration relied on either repeated surveying of individual dunes (Ashri, 1973; Embabi, 1982) or detailed measurements of the airflow over dunes as a function of wind speed, which, when coupled with equations of sand movement, can be used to estimate transport (Lancaster, 1985).

Using early generation Earth remote sensing data, the size range of individual barchans was generally too small to be monitored with the 80 m

Figure 1. Index map of the Egypt showing location of the Western Desert Oases of Bahariya and Kharga, and the Selima Sand sheet. Shaded box in the northern part of the Selima Sand Sheet is the location of Chevron-patterned wind streaks shown in Figure 9.

resolution of Landsat satellites. In western Egypt, dunes detectable at that resolution move at rates that would require 10's of years to be measurable. However, with the advent of the Thematic Mapper capabilities of LANDSAT (30 m resolution), and the Panchromatic camera of SPOT (10 m resolution), dune migration can be studied on shorter time intervals (Maxwell and Strain, 1987). In this paper, we summarize the results of sand transport studies that have been done in two of the depressions and in the open desert of southwestern Egypt using a combination of field surveying and remote sensing measurements (Figure 1).

SATELLITE OBSERVATIONS OF DUNE MOVEMENT

Because of the coarse resolution of early remote sensing satellites only a few studies have used this methodology to monitor dune movement. Instead, LANDSAT data have been used primarily to determine the regional setting and wind direction in several terrestrial desert regions (e.g. Breed and others, 1979). Ground-based studies of desertification and dune movement have primarily been based on a few select inhabited regions, where human influences on sand movement are greatest. In order to study sand transport and

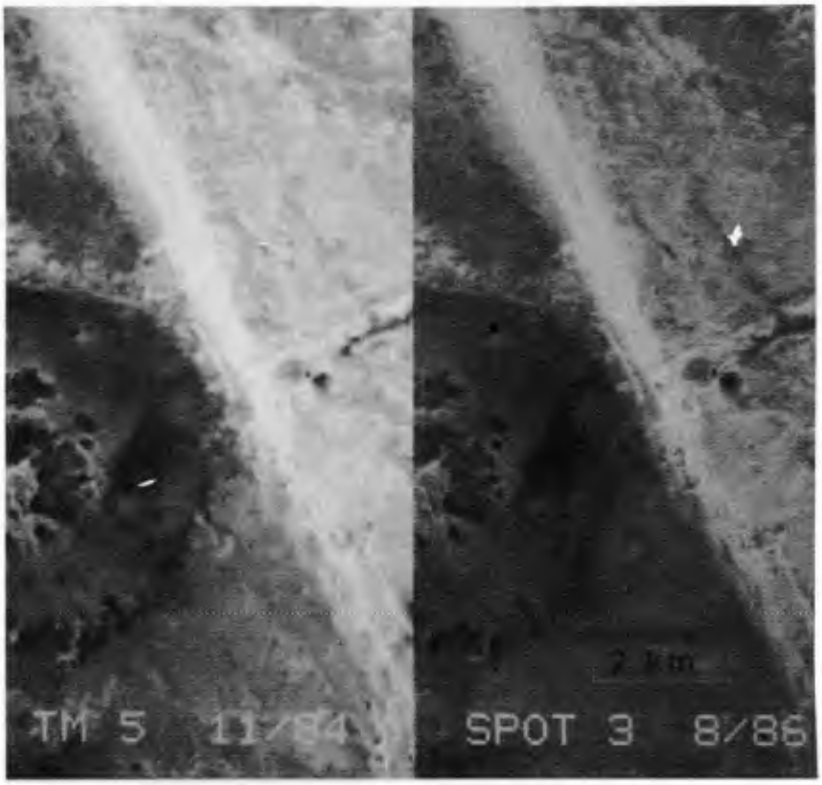


Figure 2. Comparison of Landsat Thematic Mapper image taken in November, 1984 and Spot image from August, 1986. Sand deposits on the southern margin of the dunes are more extensive in the November scene, resulting from the dominant northerly winds during the late fall and winter months.

surface characteristics in environments unaffected by human intervention, as well as inhabited areas within the same transport zone, we have investigated two regions in western Egypt utilizing data from the SPOT satellite, and retrospective data from LANDSAT and other sources (Maxwell and Strain 1987). SPOT image data were compared with lower resolution LANDSAT data taken 14 years earlier in order to determine changes both in the shape and morphology of dunes. In addition, the 57-year record provided by a solitary barchan at the Egypt/Sudan border extends these results back in time to investigate long-term migration rates.

For the two areas investigated using remotely sensed data, geometric correction and registration with retrospective scenes was performed with a combination of field control points and control points derived from the SPOT scene. The LANDSAT data originally obtained at 80 m resolution were resampled to 20 m resolution to match the SPOT data using bilinear interpolation. The accuracy of the geometric correction varies from 20 to 200 m among different scenes, and in addition to the inherent error of locating definable control points on the lower resolution scenes, the geometric correction is subject to the problems of locating specific points that do not change in this active aeolian environment.

Dune Migration in Western Desert Oases

Two major Oases in the Western Desert, Bahariya and Kharga (New Valley) are both affected by the Ghard Abu Muharik, a complex

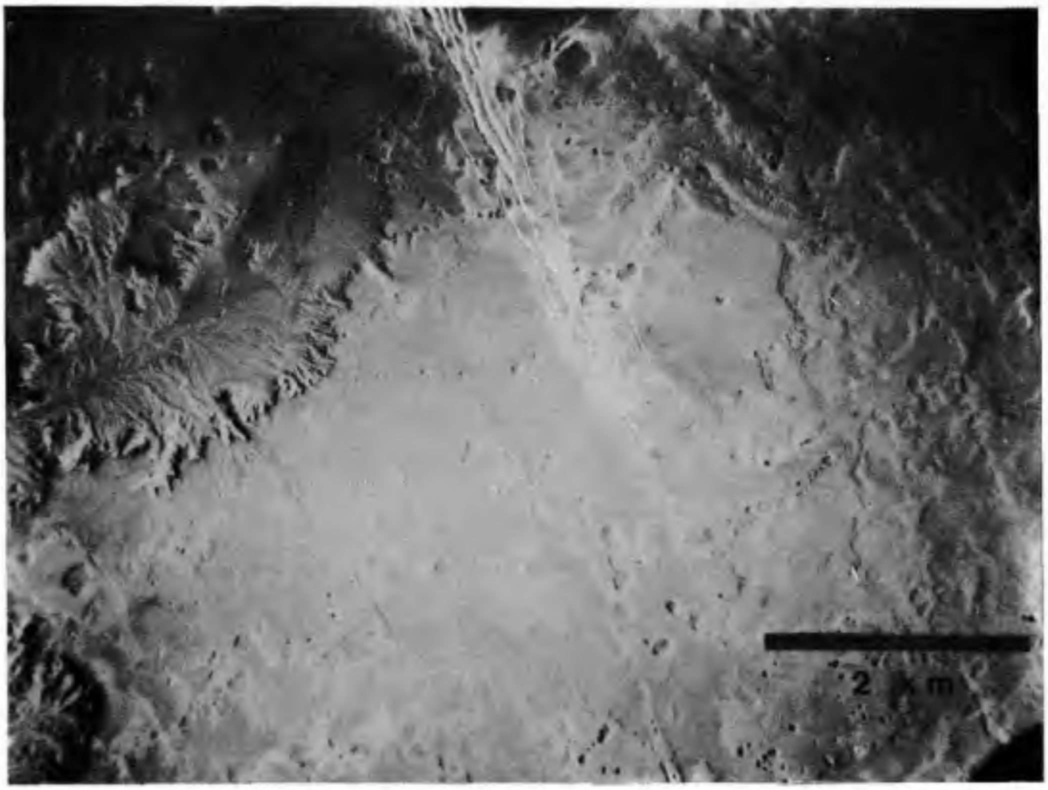


Figure 3. Air photo of the El-Ghorabi dunes at the eastern edge of the Bahariya depression. Photograph was taken in May, 1944.

longitudinal dune system that originates north of the northern edge of the Bahariya depression and continues 400 km south to the northern escarpment bounding the Kharga depression. In the Kharga region, the dune breaks up into individual barchans, which continue migrating southward across roads and through villages.

The Bahariya depression provides an ideal location for observing sand transport in a hyperarid environment because of the availability of remote observations dating from 1944, and the relative ease of accessibility for field work. At the northeastern edge of the depression, the El-Ghorabi dunes are not influenced by human activity. In this area, comparison of a single SPOT image with a single LANDSAT Thematic Mapper image acquired two years earlier (Figure 2) suggests that eastward transport of the longitudinal dune has dominated. However, using air photos taken in 1944 (Figure 3) as well as additional LANDSAT images taken in 1972 and 1984, it is apparent that seasonal effects dominate the growth and movement of the dunes (Maxwell,

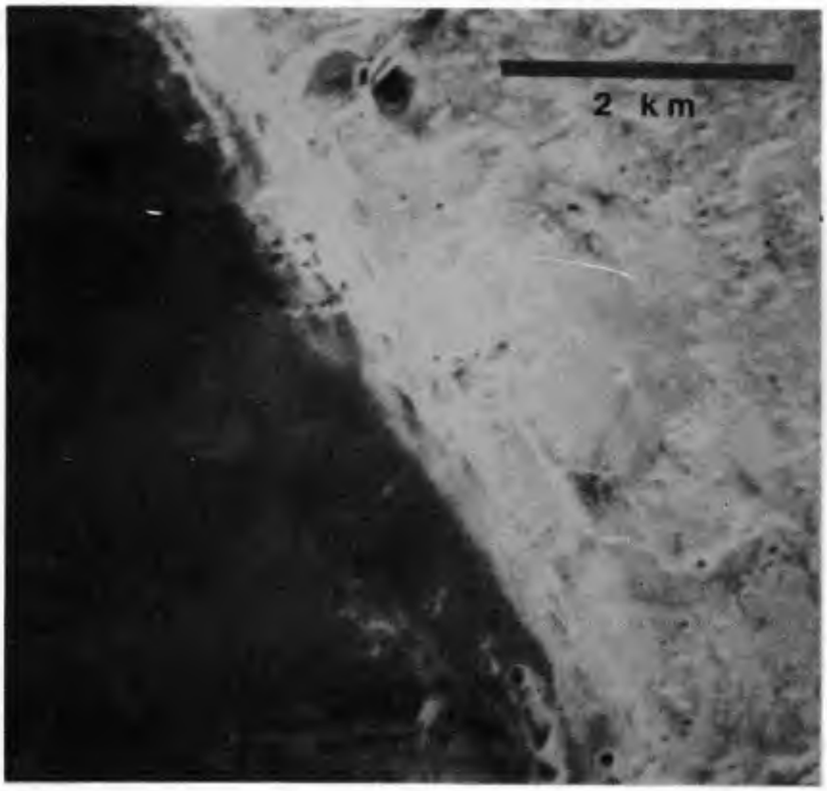


Figure 4. Portion of Spot XS image taken in August, 1986 (20 m spatial resolution). No net elongation of the dunes are evident over the 42-year record (compare isolated hills at southern tip of dunes with same area shown in Fig. 3).

1989). The dominant N-NE wind during the winter months (October-March) reverses during the summer, and creates a zone of sand cover extending several hundred meters on the downwind side of the dune. A broader zone of sand cover is evident on the SPOT image at the eastern edge of the depression as a distinct zone of brightening in the interdune areas (Figure 4). Elongation of the dune is not apparent, even over the 42-year period of observation.

In the Kharga region at the southern tip of the Abu Muharik, previous studies of dune movement based on field and airphoto analysis suggested movement ranging from 10 to 100 m/yr depending on dune size (Ashri, 1973; Embabi, 1982). For this study, a Landsat scene acquired in 1972 was registered to a 1986 SPOT scene, and by comparison of immobile features, no greater than a 2-pixel (40 m) error was noted.

The movement of 34 individual barchans was measured on the composite image (Figure 5). Dunes selected were those for which the outlines in both years could be clearly delineated and distinguished from surrounding dunes. The dunes range in size from 80-380 m along the longitudinal axis (N-S) and from 100-400 m wide. Over the 14 year time span, dune motion ranged from 60 to 220 m, resulting in annual rates of 4 to 16 m/yr. Contrary to some previous findings, measurements based on the remote sensing data alone did not indicate any variation of movement rate with dune size. This finding is being investigated further, but may be due to the fact that the smallest barchans are not measurable on either sources of satellite images.

"Bagnold's Barchan"

An even longer record of dune movement is

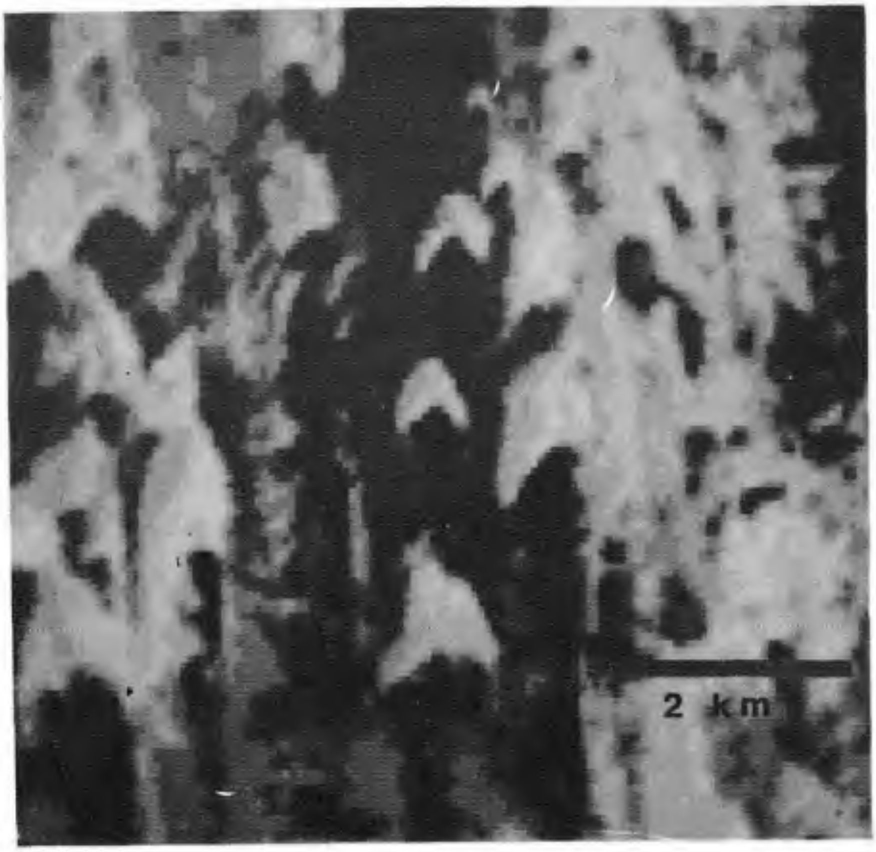


Figure 5. Multiplexed composite image of barchan dunes west of the Kharga depression. Light grey areas are the position of barchans in 1972 (Landsat MSS image), and dark gray indicates dune position in 1986 (courtesy P.E. Strain).

provided by an isolated barchan at the Egypt-Sudan border, termed "Bagnold's Barchan" by Haynes (1989). This dune, the location of the campsite of R. A. Bagnold on November 2, 1930, was re-discovered in 1980, and found to have migrated 165 m to the southwest. Subsequent field surveying resulted in a precise record of dune migration and morphologic changes. Between 1981 and 1987, the dune migrated 46 m downwind, at an average rate of 7.0 to 7.5 m/yr (Haynes, 1989). For a 275 m wide barchan, this rate is somewhat less than those of the Kharga depression, where the funneling of wind by the walls of the depression may increase the rate of dune motion.

In 1988, we installed a marker at the location of Bagnold's 1930 camp (Figure 6), to be used in monitoring this barchan and the associated dunefield to the north. An October 1988 SPOT multispectral scene was acquired to fix the location of the marker relative to the dune, but the marker, an 8 by 8 m square array of rusted benzine tins (Figure 7) was not visible in that scene. We are presently obtaining a panchromatic image to see if the increased spatial resolution will allow recognition of the tins. (The multispectral scene was originally acquired in the hopes that the dark, iron patina of the tins would be significantly different spectrally from the surrounding sand sheet. Although this was the case visually, it was apparently not the case in the SPOT image.)

Both the successful and unsuccessful efforts at monitoring dune movement reported above indicate the importance of ground control points for

Figure 6. SPOT panchromatic image of the downwind edge of a barchan field in northern Sudan. The isolated barchan at the southern end of the field has migrated at a consistent rate of 7.5 m/yr over the last 57 years. Arrow denotes location of R.A. Bagnold's camp in the lee of the same dune on November 2, 1930.

accurate scene registration, and prior knowledge of the local wind regime to properly interpret time series remote sensing data. For the Bahariya region, had not seasonal variations in wind and remotely sensed data been utilized, the interpretation of dune movement would have been much different (and incorrect). The problem of locating stable, recognizable control points in an active desert is illustrated by both the Kharga and Bagnold's barchan work. In particular, the area surrounding Bagnold's barchan has only two distinct rock outcrops that can be used to register

Figure 7. Array of benzine tins used to construct target to monitor Bagnold's barchan movement. First attempts at locating this marker in SPOT images have proved unsuccessful, although a combination of 10-m panchromatic and multispectral data should aid in its identification.

satellite data, and these are located on an east-west line perpendicular to the direction of dune movement. Because of rapid changes in the surrounding sand sheet (described below), it is not possible to use the dunes themselves as markers and look for mismatch in the surrounding surface.

SAND TRANSPORT IN THE SELIMA SAND SHEET

The Selima Sand sheet is located at the southern edge of the Western Desert, and occupies more than 100,000 km^2 of the open desert. As the name implies, the surface is a monotonous, flat, vegetation-free expanse of sand and granules, broken only by the nearly imperceptible giant ripples (Breed and others, 1987) and by sporadic deposits of Sudan Defense Force camp remains (Haynes, 1984). Although evidence of sand movement is obvious during times of high winds, the documentation of erosion and deposition is much more difficult because of the absence of large bedforms or stratigraphic marker horizons. Sand transport has only been noted by observations of the infilling of historical remains, and by remote sensing studies of surficial changes.

Historical Evidence of Sand Transport

During the early days of World War II, recapture of Kufra in southern Libya resulted in the establishment of a convoy of food and supplies between Wadi Halfa and Kufra (Wright, 1945). Named the Sudan Defense Force, this series of life-saving missions consisted of lorries that ferried material across the central part of the Selima Sand Sheet. Several camps have been found dur-

Figure 8. Sudan Defense Force food tins in the Selima Sand Sheet (ca: 1942). Tins are inset into Stage 2 sand sheet sediments, and are infilled by active sand and fine granules.

ing traverses by Haynes from 1975 to the present, and partially buried remains provide clues to Holocene redistribution of sand sheet sediments (Haynes, 1983, 1984).

Typically empty cans that once contained beans and bully beef are now buried up to several centimeters in the sand sheet by the youngest stage of the sand sheet soils (essentially loose sand). A demarcation between unrusted and rusted tin marks the original resting orientation of these cans, providing a marker for net deposition (Figure 8). Deposition of fresh sand may have occurred in days or weeks following the original encampments; no doubt the surrounding surface was greatly disturbed by the lorry and human traffic, but the stratified sequence exposed in a few instances suggests a longer-term re-equilibration with the sand sheet. Deposition of 2-3 cm is evident surrounding cans and bottles, which indicates very little net erosion or deposition over the past 50 years. Disturbance of the uppermost surface of the sand sheet can have a great effect on orbital views of such areas.

Remote Sensing of Sand Transport

Changes in the surface of the sand sheet were not evident until we noted that light- and dark-toned areas on a 1970's vintage LANDSAT image we were using for navigation greatly differed from the surface observations of the distribution of coarse granule lag and horizontally truncated ripples. Following field work, we obtained another image acquired while we were in the field, which showed apparent movement of dark and light toned patterns. It is now evident that these changes are due to the migration of low-

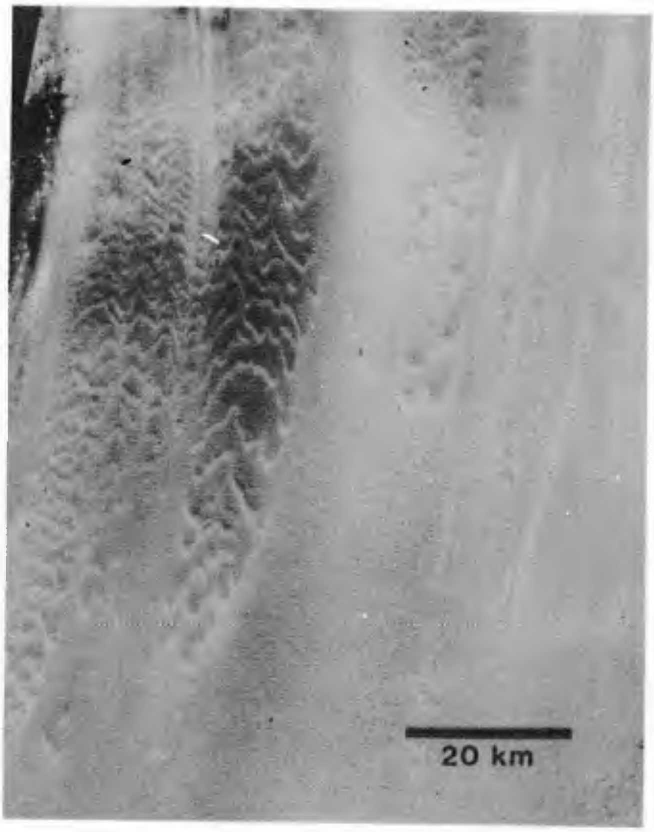


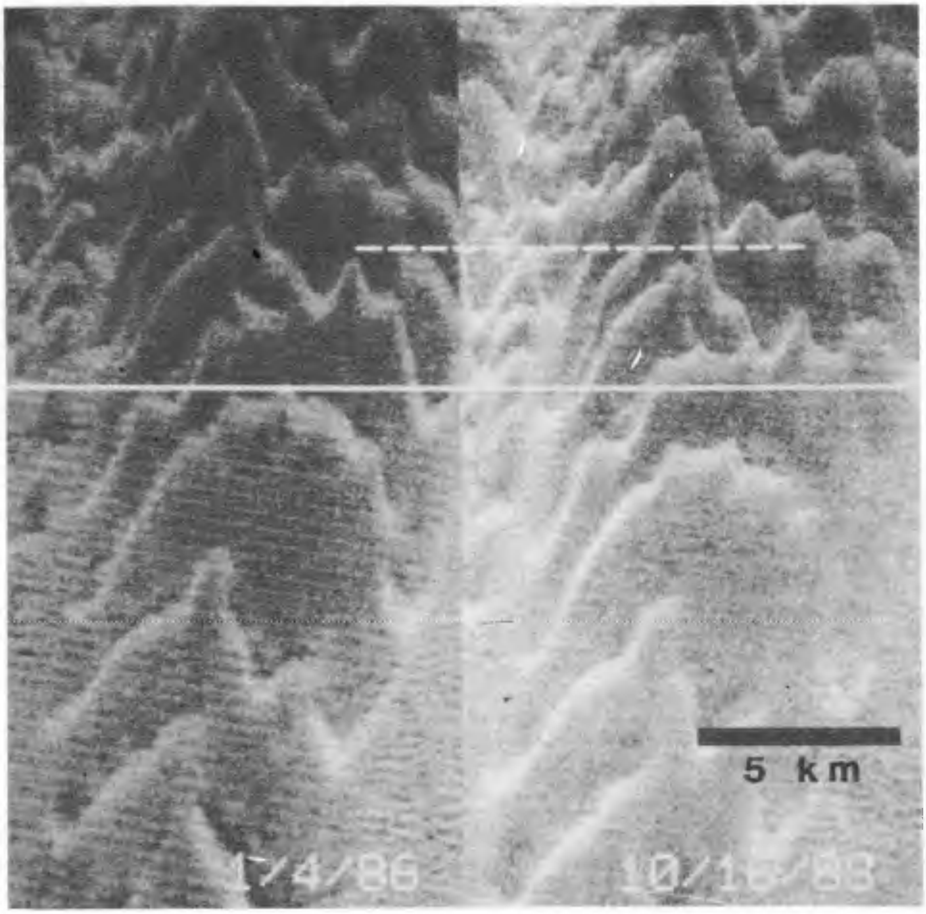
Figure 9. Chevron-shaped patterns at the northern edge of the Selima Sand Sheet. This near-infrared Landsat MSS image has been geometrically corrected and stretched to emphasize the patterns. Transverse high-frequency pattern in the lower part of this image are giant ripples reported by Breed *et al.*, 1987.

amplitude, extremely large aeolian ripples that migrate at rates up to 500 m/yr (Maxwell and Haynes, 1989).

These light and dark chevron patterns consist of irregularly spaced 500 to 2000 m wide streaks that are oriented generally transverse to the dominant northerly wind direction (Figure 9). The patterns contain acute angles point in both up-and downwind, and exhibit an average spacing of 3 km. Monitoring of these chevrons using orbital data between 1972 and 1988, and with field measurements between 1987 and 1989 (Figure 10) has allowed us to determine the migration rate and cause of these features.

Several scales of extremely long wavelength ripples, ranging from 130 m wavelength to over 1200 m are present in parts of the sand sheet, typically 10's of kilometers downwind from topographic breaks such as bedrock scarps or barchan dune fields. No obvious cross stratification is present in the sediments, instead, planar horizontal stratification caused by interlayered fine sand and granules is typical. In the lee of the most prominent, 20 cm high crest of such ripples, the youngest sediments are thickest, and consist of 10-20 cm of loose sand sheet deposits.

Based on correlation between the field location of light chevrons and their appearance on orbital images, we have interpreted the light chevrons to be areas of active sand sheet deposits that cover the coarse, ferruginous granule component present in darker areas (Maxwell and Haynes, 1989).



Figures 10. 1986/1988 comparison of chevron ripples. Horizontal lines indicate the amount of movement over this 2 1/2 year period (1.4 km; see Maxwell and Haynes, 1989).

Dark discrete chevrons are most likely the stoss sides of long wavelength ripples, and owe their lower reflectance to an admixture of coarse grains.

The extremely high rate of movement of these features results in a sand transport rate that is greater than most dune fields in the region. Tens of thousands of cubic meters of sediment per year migrate southward in these specific areas. Because of the source of sand to the north, and the evidence of only minor net erosion of historic sites, it is apparent that the sand sheet is being continually replaced, and although the transport rate is very high, the net change to the landscape is small over time periods in the 10's of years. Nonetheless, both orbital and field investigations of these features provide the data necessary to study long term sand transport and denudation rates, and allow comparison with dune motion to monitor erosion and deposition over large areas.

CONCLUSIONS

Comparison of orbital images for selected desert regions provides rates of dune movement that are consistent with those of previous studies, but that are not limited to small field sites. The use of satellite images for the 20 years period now available has allowed these relatively slow, but continual changes to be monitored. This process, however, is subject to certain limitations, such as localized errors in image registration, the inability to recognize and monitor small dunes, and the limited resolution of the earliest satellite data available. Specific examples of sand transport in Western Egypt show that:

1) At the upwind end of the Abu Muharik dune comlpex, seasonal effects dominate the appearance and disappearance of a thin sand deposit that occurs on the margins of a longitudinal dune. No net elongation of these dunes is apparent.

2) Measurements of barchan migration in the Kharga depression indicate an average migration rate of 10 m/yr to the south. In contrast to prior studies, no correlation of migration rate with dune size was noted, probably because of the resolution constraints on early image data.

3) In the Selima Sand Sheet, historic evidence suggests that the net erosion and deposition is very minor. Only a few centimeters of net deposition can be supported by field observations.

4) Comparison of LANDSAT images from 1972 through 1988 show low amplitude bedforms of extremely long wavelength that migrate up to 500 m/yr. The high sand transport rate interpreted for these features is not compatible with historic evidence for only minor net deposition or erosion in the sand sheet, suggesting a continual replenishment of source material.

Time comparison remote sensing data offer an opportunity to gather detailed transport rates for large areas of desert terrain. However, care must be used in the interpretation of these data, and attention must be given to local and seasonal variations in wind regime as well as the capability to recognize control points. Simple comparisons of two scenes may result in spurious conclusions.

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