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A SYNTHESIS OF SAND SEAS THROUGHOUT THE WORLD

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ABSTRACT

This report covers an investigation of sand seas studied on a global scale, largely by the use of ERTS imagery but supported by Skylab and aerial photography, and by ground-truth data in many areas. The project involved the study of 17 major sand seas in the eastern hemisphere and of 5 smaller ones in the western hemisphere. The procedure consisted of the development of mosaics from ERTS false-color imagery for each desert area, the classification of basic patterns of dune types within these areas, and the preparation of thematic maps, depicting with appropriate symbols the distribution of the basic sand patterns.

The objective classification of dune patterns as recognized in this study of ERTS imagery recognizes five main types and numerous varieties of each. All patterns appear at the same scale on these images. Some patterns are repeated in many parts of the world; others seem to be much restricted. The main types recognized are (1) parallel straight (linear), (2) parallel wavy (crescentic), (3) radial or star megadunes, (4) parabolic dunes, and (5) sand sheets and streaks.

Another phase of the investigation consisted of supplementary studies designed to analyze factors controlling dune forms and to interpret their genesis and manner of growth.

For purposes of comparison of the areas studied, quantitative analyses of dune distribution were prepared from the mosaics and are presented on maps in the form of dune-spacing density indicators. For the recording of wind data, including both direction and velocity, wind roses have been overprinted on mosaics. Precipitation is recorded in similar manner.

Because of limitations in time and funds, completion of maps and texts at this time has been restricted to the five major sand seas or dune areas for which image coverage and supporting data are sufficient for detailed analysis. Studies of other test sites are in various stages of completion. Those illustrated and described in this report are the Namib and the Kalahari Deserts of southern Africa, the Rajasthan-Thar Desert of India and Pakistan, the Algodones Desert of California and Mexico, and the Gran Desierto sand sea of Sonora, Mexico.

From this synthesis of data on sand seas at least four basic concepts seem to be evolving, though further support from air photography and ground-truth studies in other areas is necessary to establish their validity: (1) there is a good correlation between type of dune and wind circulation within large areas of sand seas; (2) the relations of dunes to interdune areas reflect the amount of horizontal migration as compared to vertical build-up of sand masses to be expected within a given sand area; (3) potential barriers or stabilizers such as bedrock, vegetation, and water bodies locally affect and control the movement of sand bodies in predictable manner, and (4) the color (degree of red in natural color, or degree of yellow in false-color imagery) may reflect the degree of activity or of stabilization in a sand body.

The above and other provocative concepts stimulated by observations of ERTS imagery and tested, for some areas, by ground truth have an obvious relationship to the control of sand movement as related to many desert development programs of man. Furthermore, a better understanding of dune structures that affect the movements of water, oil, and gas, especially in ancient rocks, should result.

Type III Final Report

ERTS-A

I. SUMMARY (PREFACE)

I. Objective

Vast areas of the earth are covered by eolian sand seas which, for lack of reliable base maps and air photos, have not been systematically studied and compared on a worldwide basis. The objective of this study is to use ERTS-1 imagery to delineate, describe, and compare the surface morphology and geographic relationships of these sand seas, and to combine the information from ERTS with ground-truth data, especially wind data, to determine the genetic controls on origin, distribution and movement of sand seas. Field studies to determine the internal structures of the sand-sea forms seen on ERTS-1 are a necessary part of the investigation, but for lack of time and money have not yet been completed. Success in interpreting sand-sea characteristics should have geologic application in at least 5 ways:

a. Interpretation of the environments of deposition of eolian sandstones, in which primary structures control migrating fluids such as oil or water, as in the Navajo and Coconino Sandstones of Northern Arizona.

b. Better understanding of dune movement and its control for application in agricultural and other land use areas subject to sand inundation.

c. Prediction of future environments of sand deposition in areas of drought as in parts of India, North Africa, and Australia.

d. Interpretation of exotic environments of wind deposition, such as are believed to exist on Mars, by analogy with sand seas on Earth.

e. Aid in exploration for wind-concentrated mineral deposits.

2. Scope of Work

This project has attempted to define the morphology and geographic extent of sand seas within a broad belt of the northern hemisphere extending from North Africa through Arabia, India, and U.S.S.R. to China, in a few areas of the southern hemisphere including parts of Australia and southern Africa, and in a number of small sites in the United States and Mexico (fig. 1). In most of the large deserts, major areas of sand seas previously have been mapped only sketchily and studies that have been made were limited either by a lack of regional data or by general inaccessibility.

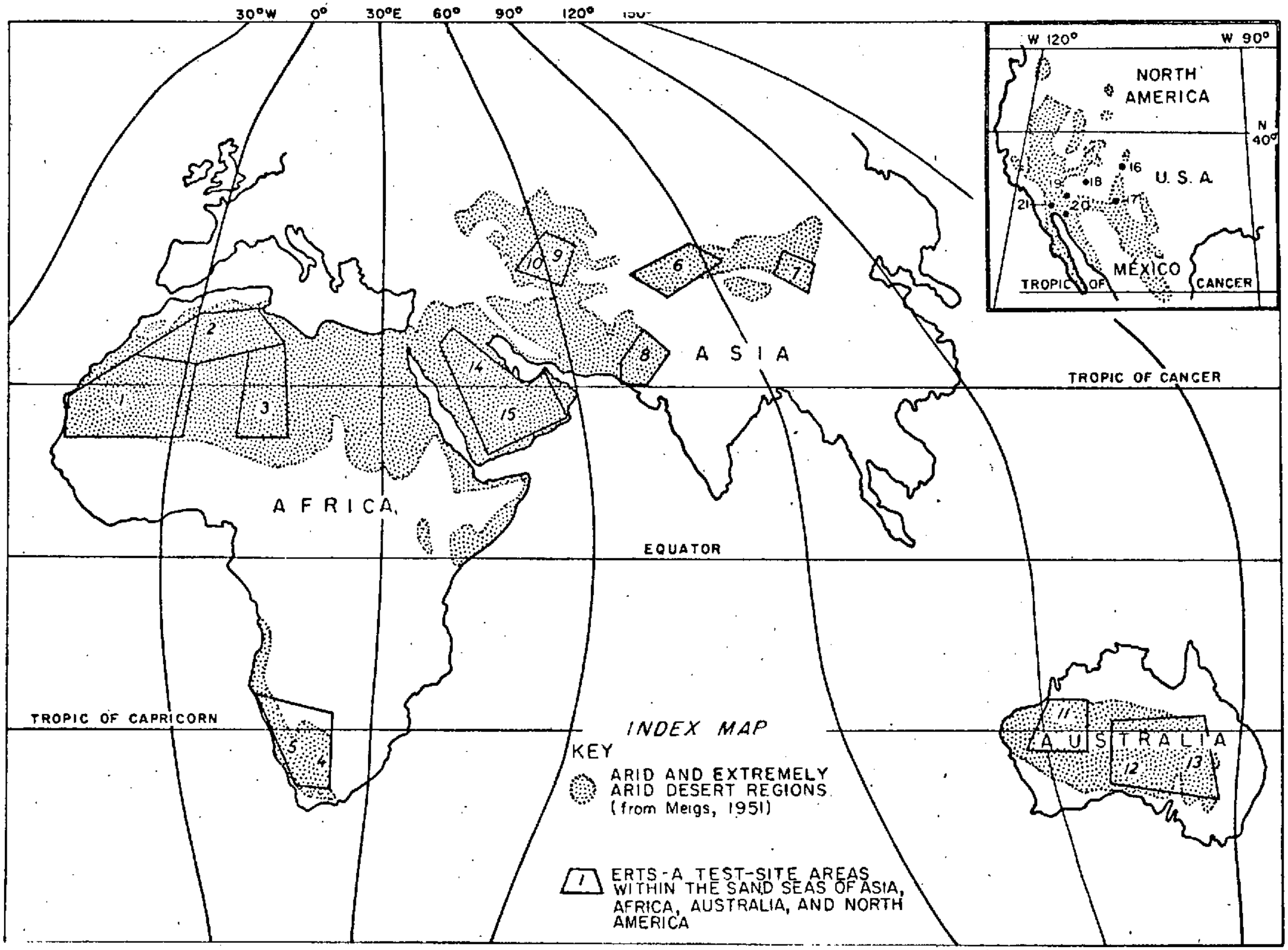

Figure 1. Index map of principal desert and semidesert regions and selected test areas. (1) Mauritania, Mali; (2) West Erg and East Erg, Algeria; (3) Libya, Niger, Chad; (4) Kalahari Desert, southern Africa; (5) Namib Desert, South West Africa; (6) Taklamakan Desert, China; (7) Gobi Desert, China; (8) Rajasthan-Thar Desert, India and Pakistan; (9) Kyzylkum Desert, U.S.S.R.; (10) Karakum Desert, U.S.S.R.; (11) Great Sandy Desert, Australia; (12) Great Victoria Desert, Australia; (13) Simpson Desert, Australia; (14) An Nafud, Saudi Arabia; (15) Empty Quarter, Saudi Arabia; (16) Sand Hills, Nebraska; (17) White Sands, N. Mex.; (18) Great Sand Dunes, Colo.; (19) Navajo Country, Ariz., (20) Gran Desierto, Mexico; (21) Algodones Desert, Calif.

On this project ERTS bulk color composite prints for each test site have been assembled into mosaics. These mosaics have been completed, at this date, only for the Rajasthan-Thar Desert of India and Pakistan, the Namib and Kalahari Deserts of South West Africa, the Simpson Desert of Australia, and the Algodones-Gran Desierto dunefields of the southwestern United States and northwestern Mexico.

Areas for which mosaics are near completion are: the Takla Maklan and Gobi Deserts of China, the Kyzlkum and Karakum Deserts of the U.S.S.R., the Great Victoria and Great Sandy Deserts of Australia, and the An Nafud and Rub al Khali (Empty Quarter) Deserts of Saudi Arabia. Areas for which mosaics are largely incomplete at this date are: the deserts of Mauritania, Algeria, and Libya.

From the completed mosaics, thematic maps have been prepared showing the regional relations between various sand-sea types and indicating their distribution with respect to topographic, vegetative, and precipitation barriers. Wind data from widely scattered sources have been gathered and wind roses are overprinted on the mosaics. The wind roses show the influence of sand-moving winds on the source, distribution, and movement of desert sand seas. Principal sources of wind data were the National Climatic Center, North Carolina, the National Center for Atmospheric Research at Boulder, Colo., and the Weather Services of several foreign countries.

Many of the supporting data on geologic setting and other background information were obtained through a systematic search of the voluminous literature on previous studies of each area.

3. **Staff**

The current project entitled "The Morphology, Provenance and Movement of Desert Sand Seas," based primarily on ERTS-1 images, has been directed by Edwin D. McKee, Principal Investigator, and Carol S. Breed, Co-investigator. In the early stages, Lawrence Harris also participated. Later, as the program advanced, a staff was recruited, including professional geologists and also volunteer workers enlisted largely from students of Northern Arizona University.

Principal job classifications and personnel assignments are as follows:

a. Organization of ERTS imagery, including cataloging, classifying, recording measurements and compilations: Dana Gebel.

b. Climatic research (especially wind and precipitation) and overlay preparation: Steven Fryberger, assisted by Gary Dean.

c. Bibliographic research, involving preparation of background summaries, glossary and reference catalogs: Camilla McCauley.

d. Photography; cataloging and copying of supporting aerial and ground photos: Marion Blancett.

e. Mosaicking ERTS imagery: Katherine Nation.

f. Analysis of bedrock geology, barriers and vegetation influences: Iris Sanchez, Kandy Kisser, Eric Curaton, and Chuck Wahler.

g. Secretarial duties, filing, typing: Marjorie Cater and Deloris Douglas.

4. Conclusions

Analysis of ERTS-1 imagery has resulted in an objective classification of sand-sea landforms that is believed to have worldwide application (table 1). Topographic patterns of sand seas have been identified according to their regional morphology as seen on ERTS-1 images, and these patterns have been assigned to subcategories within the U.S. Geological Survey system of land-use classification prepared for use with ERTS imagery (Place, 1973).

Mosaics of bulk color composite prints, on which eolian sand mostly is a bright yellow, have provided the basis for thematic maps of the Namib, Kalahari, Rajasthan-Thar, Algodones, and Gran Desierto sand seas. These maps show the distribution and areal relationships of the various sand patterns and their relation to topographic, vegetative, and moisture barriers.

The relation of each sand assemblage to climatic controls is illustrated by combining ERTS imagery of a sand sea with wind roses and with precipitation data. Preliminary field work indicates that these relationships will be reflected by the internal structures that are believed to be characteristic of key types of sand-sea patterns (McKee, 1966, p. 58-68).

5. Recommendations

A number of tests to substantiate the theoretical results of ERTS-A studies probably will be done during the ERTS-B phase of this investigation, as follows:

a. The classification system of sand seas based on areas studied in ERTS-A should be tested against sand seas in other parts of the world, especially in the deserts of South America, north-eastern China, Iran, Mexico, Egypt, and the Sudan.

b. The basic premise that surface form will be reflected in internal geometry must be tested by field work in accessible dunefields in the U.S., Mexico, India, Peru, and Africa (studies have been carried out previously by McKee in New Mexico, Libya, Saudi Arabia, and Brazil). Until further field work is done, results of this study cannot be definitely applied to geological analysis of eolian sandstones.

Table 1. Objective classification of eolian sand deposits seen on ERTS-1 imagery:

Type of eolian sand deposits observed on ERTS-1 imagery	ERTS-A Classific. Number	Major areas of occurrence
1. Parallel straight (linear) dune complexes; basic type has dune/interdune width ratio of 1:1, length many times greater than width.	07021A	Australia, southern Africa, North Africa, Saudi Arabia, Ariz.
a) Variation: wide interdune type, with dune/interdune width ratio <1.	07021B	North Africa, Saudi Arabia.
b) Variation: feathered self type.	07021C	North Africa, Saudi Arabia.
2. Parallel wavy (crescentic) dune complexes; basic type composed of crescentic segments, each with its wide dimension equal or nearly equal to its length, forming wavy ridges that have all major slipfaces on one side.	07022A	All deserts observed have this type; large-scale occurrences in Neb., U.S.S.R.; small-scale type area: White Sands, N. Mex.
a) Variation: fishscale type, with enclosed interdune spaces.	07022B	North Africa, Saudi Arabia.
b) Variation: giant crescent or megabarchan type.	07022C	Saudi Arabia, Calif., Mexico, India-Pakistan.
c) Variation: basketweave or chevron type	07022D	China.
3. Radial (star) dune complexes; basic type a solitary megadune with segments radiating from the center of the complex in pinwheel fashion.	07023	North Africa, Saudi Arabia, southern Africa, China.
a) Variation: star dunes aligned on subparallel ridges to form "chains".	07023A	North Africa, Saudi Arabia, Mexico.
4. Parabolic (U-shaped) megadunes; basic type has elongate arms extending upwind and is at least partially fixed by vegetation.	07024	India-Pakistan, U.S.S.R., Ariz., N. Mex.
5. Sheets and streaks of sand, without slipfaces but with distinct geographic boundaries.	07025	All deserts observed have this type; large-scale occurrences in North Africa southern Africa, Saudi Arabia.

c. Further refinement of surface wind data is necessary. Wind and other ground-truth data in some of the more remote deserts of the world must still be acquired through methods that are far behind the level of technology represented by ERTS. Wind data, once acquired, must be converted to forms expressing sand-moving potential. As a result, acquisition of supporting data is slow and considerable time is required to get satisfactory results.

d. An atlas should be published showing the range of desert landform types discernible on ERTS imagery, their classification and relation to wind regimes, regional setting, past and present climates, human habitation, grazing, and agricultural practices.

e. The principles of sand-sea deposition and movement derived from this study should be applied to the immediate problems of sand control and to long-range problems of land use in drought-prone countries, especially those of North Africa, India, and Australia.

6. Acknowledgments

Many individuals and organizations have assisted in the work of this project, contributing information, time, and materials; it is a pleasure to acknowledge the following:

Data on wind records, other climatic factors, and general references: Mr. Wayne Hensley, Mr. Horst Beckerwerth, and Staff of the National Climatic Center, Ashville, N. C.; Ms. Mary Haymes and Ms. Pam Noaecker of the National Center for Atmospheric Research, Boulder, Colo.; Ms. Katharine Bartlett and Staff of the library, Museum of Northern Arizona, Flagstaff; Ms. Patricia Paylore of the Office of Arid Lands Studies, Tucson, Ariz.; and Mr. James Nation of the Center for Astrogeology, Flagstaff, Ariz.

Assistance in preparing meteorological data and in planning weather research: Dr. Harry Van Loon, Dr. Roy Jenne, and Dr. Halka Chronic, National Center for Atmospheric Research, Boulder, Colo.

Foreign sources of wind and climate information: Dr. M. K. Seeley of the Desert Ecological Research Unit, South Africa; Dr. H. S. Mann of the Central Arid Zone Research Institute, India; K. Krishnamurthy of the India Meteorological Department; M. M. Sasy of the Meteorological Department, Ministry of Communications, Libyan Arab Republic; and Mr. James P. Mandaville of the Arabian American Oil Co.

High-altitude aerial photographs of dune areas in the western United States: furnished by Dr. Stanley Freden of NASA through the Ames Research Center.

Other photographs of eolian sand and sandstone: contributed by E. Tad Nichols, Tucson, Ariz.; the late H.T.U. Smith of the Univ. of Massachusetts; George Morrison of White Sands National Monument, N. Mex.; Joseph F. Schreiber, Univ. of Arizona, Tucson; J. Philip Schafer, Flagstaff, Ariz.; and the Museum of Northern Arizona, Flagstaff.

Assistance in interpreting local features of sand seas: Donald Holm, Tucson, Ariz.; Dr. Shunil E. Roy, Head, Agricultural Engineering Div., Indian Agricultural Research Institute, New Delhi; Dr. I. H. Hamrabaev of the Institute of Geology and Geophysics, U.S.S.R.; Mr. Brad Musick of the Office of Arid Lands Studies, Tucson, and Dr. Len Berlin and Dr. Errol Montgomery of Northern Arizona University.

NOTE:

Illustrations originally in color are identified in their caption by an EDC-01000_. Copies of the original color are available for purchase from the EROS Data Center, Sioux Falls, South Dakota, 57198, using the EDC number. Prices are available on request.

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V. LIST OF ABBREVIATIONS AND SYMBOLS

cm = centimeters

ERTS = Earth Resources Technology Satellite

I.C.Z. = Intertropical Convergence Zone

K1, K2, K3, K4 = keys to sand-moving winds

km = kilometers

kph = kilometers per hour

KTS = knots

Lat. = latitude

Long. = longitude

mb = millibar

mm = millimeters

5 YR/4/8; 5G/3/2; et al. = numerical designation of particular colors as determined on Rock-Color Chart distributed by Geological Society of America.

VI. HISTORY OF OVERALL PROJECT

This project has been set up on the basis of three assumptions: (1) synoptic satellite coverage at a constant scale will reveal measurable and comparable patterns of sand seas; (2) patterns of sand seas reflect environments of deposition, and these patterns are recorded in the internal structures (stratification) of the sand dunes; and (3) information about the environment of deposition of modern sand seas can be applied to (a) geologic studies of eolian sandstones, (b) sand control in areas of human occupation and development, and (c) interpretation of supposed eolian deposits on Mars.

The Earth Resources Technology Satellite-1 has provided the first comprehensive and directly comparable summary views of sand seas on a worldwide scale, making this project feasible. Earlier work in this field has mostly been limited to local studies in the major desert regions because of their remoteness and difficulty of access. The great number of these studies has resulted in a multiplicity of names for dune types. Much dune terminology cannot readily be transposed from region to region because many of the older local classifications carried genetic implications (i.e., "transverse," "longitudinal"). For this reason, the first goal of the present study has been to develop an objective classification of sand-sea patterns as recognized on ERTS-1 imagery (table 1).

The basic classification of dune complexes derived from ERTS-1 imagery is five fold with numerous subtypes in each category (table 1; figs. 2-6). The five basic types represent development of dune forms in the central parts of desert basins where the wind is free to sweep sand without deflection from barriers. At the scale of ERTS-1 imagery individual dunes mostly cannot be discerned, but patterns formed by groups of dune complexes are prominent. These complexes are composed of numbers of individual dunes and, depending upon the type, commonly are 2 or 3 kilometers in diameter, from front to back at the base, or from horn to horn. In many regions, also, they are separated from each other by flat, windswept interdune corridors or hollows which form an integral part of the overall pattern.

Each sand sea displays several characteristic and distinctive dune patterns, yet sufficient similarities between regional sand patterns have been seen on ERTS images to date to justify a worldwide classification into five major categories: (1) parallel straight, (2) parallel wavy, (3) radial, (4) parabolic, and (5) streaks or sheets.

1. Parallel straight dunes, whether simple or complex (fig. 2), have long dimensions that are many times greater than their wide dimensions. Commonly the resultant linear ridge has slipfaces along both sides. Assemblages of this type have been called longitudinal dunes (Aufrere, 1928; Hack, 1941; McKee, 1957; Folk, 1971); sand ridges (Madigan, 1936; Warren, 1970); draa (Capot-Rey, 1945; Lelubre, 1948); and seif chains or seifs (Bagnold, 1941; McKee, 1966; Glennie, 1970). The typical appearance in air photos of this sand type is shown in figure 7b of the Namib Desert in South West Africa, and in figure 9c near Sebha Oasis, Libya. Variations of this type include linear ridges with wide interdune spaces (fig. 2e) and "feathered" linear ridges (fig. 2f).

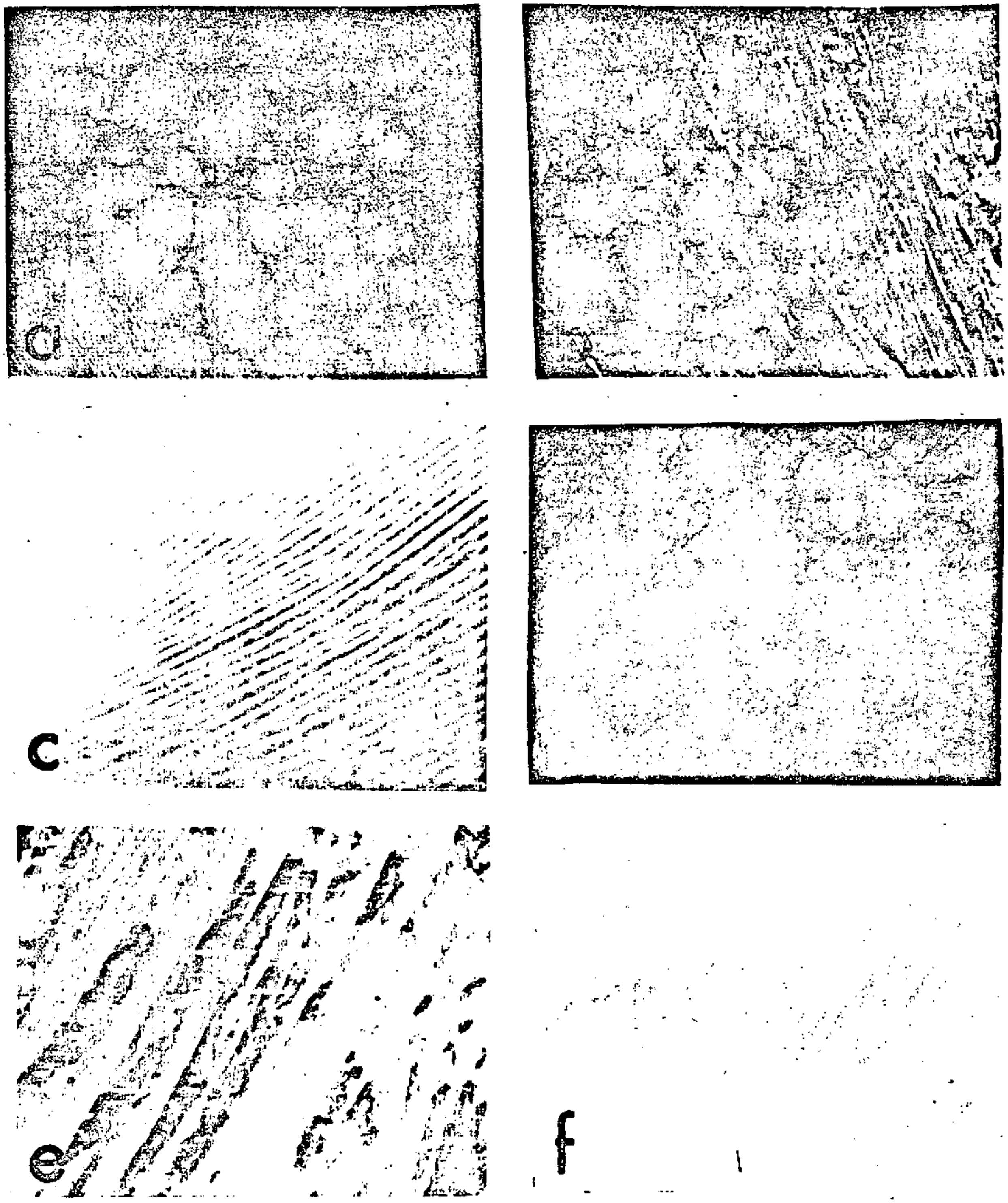


Figure 2. Parallel straight (linear) dune types: (a) Simpson Desert, Australia; (b) Kalahari Desert, southern Africa; (c) Empty Quarter, Saudi Arabia; (d) Sahara, Mauritania; (e) wide interdune areas, Mauritania; (f) feathered seifs, Saudi Arabia. Area of each section is approximately 4,500 square kilometers.

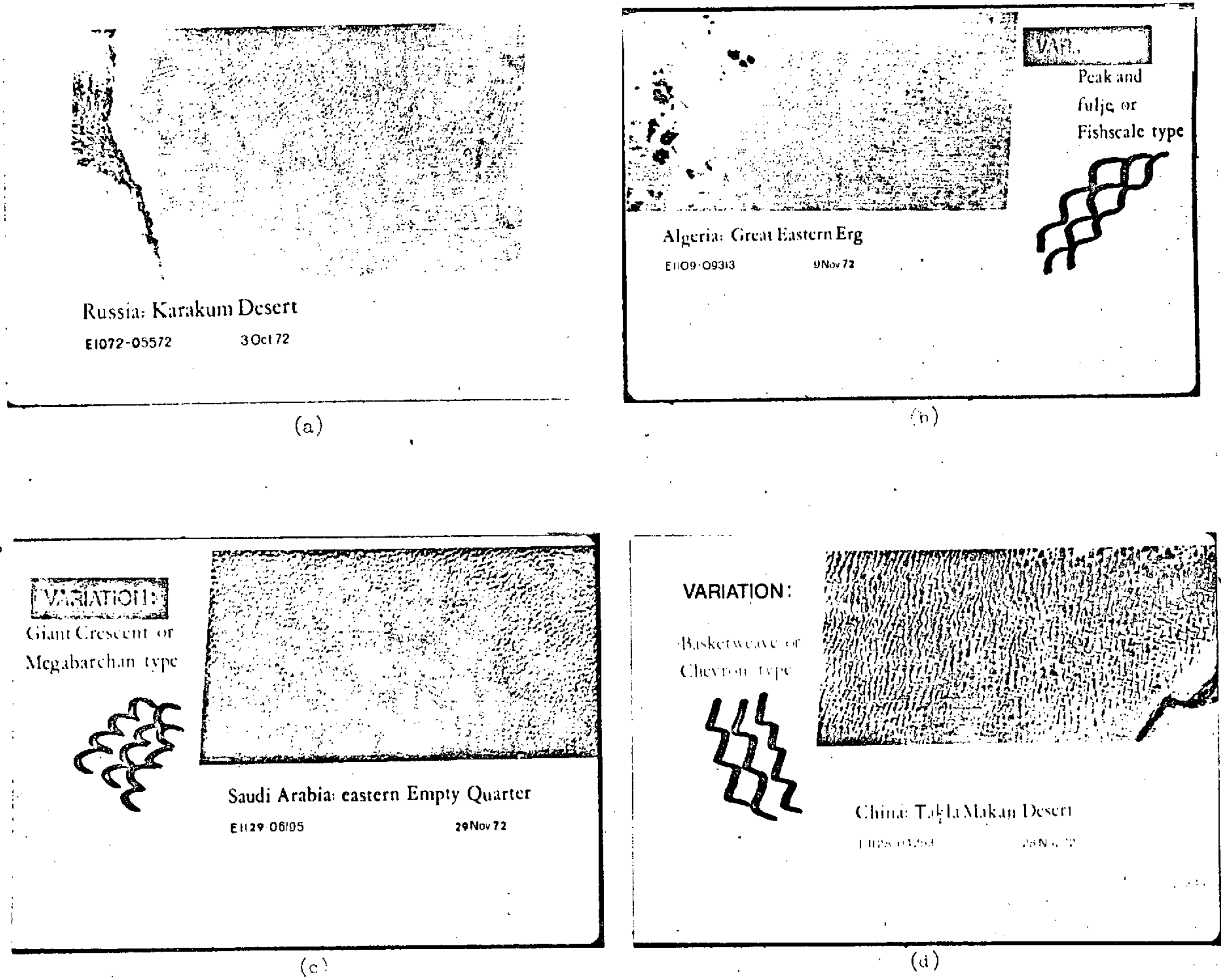


Figure 3. Parallel wavy (crescentic) dune types.

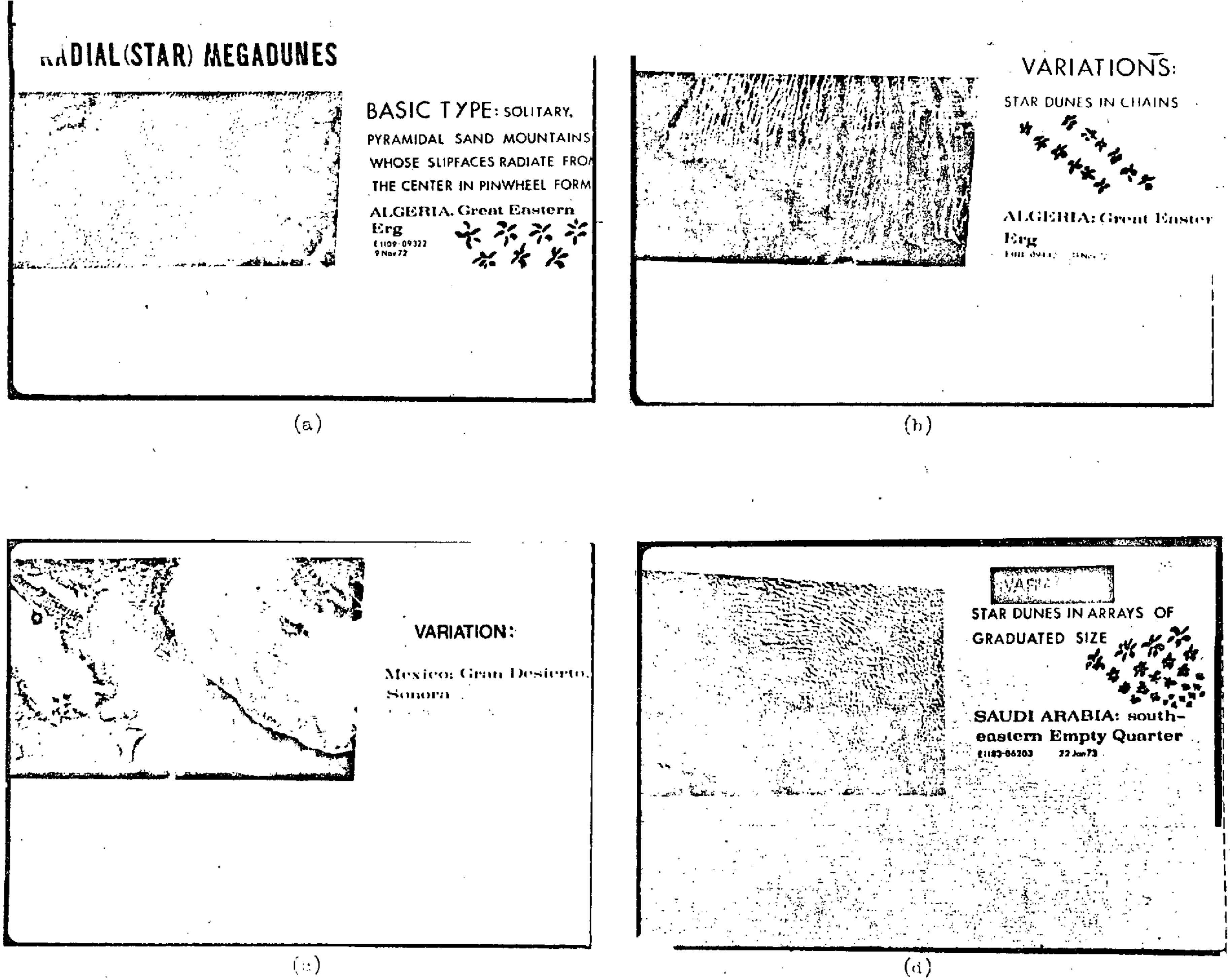
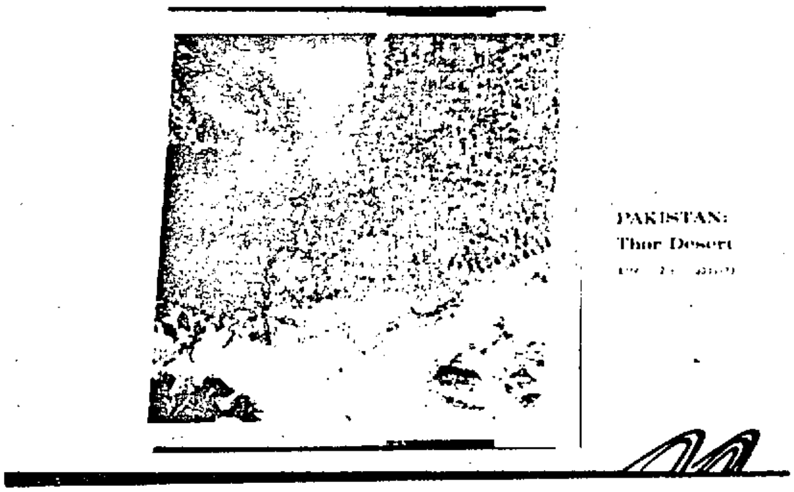


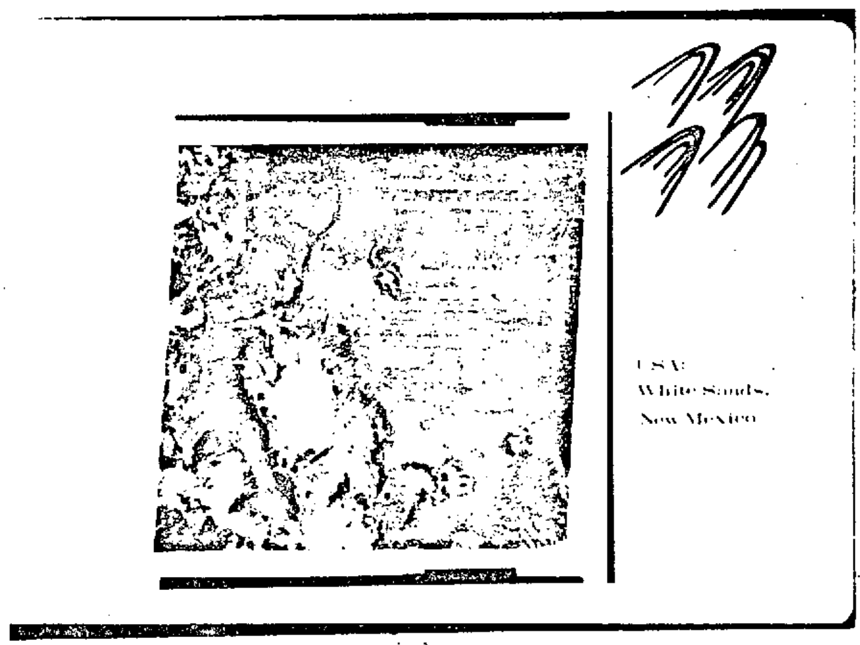
Figure 4. Radial or star megadunes: (a) random distribution; (b) chain type; (c) chain type; (d) graduated size.

PARABOLIC (U-SHAPED) DUNE ARRAYS

BASIC TYPE: BLOWOUTS WITH VEGETATED ARMS POINTING UPWIND.



(a)



(b)

Figure 5. Parabolic (U-shaped) dune arrays.

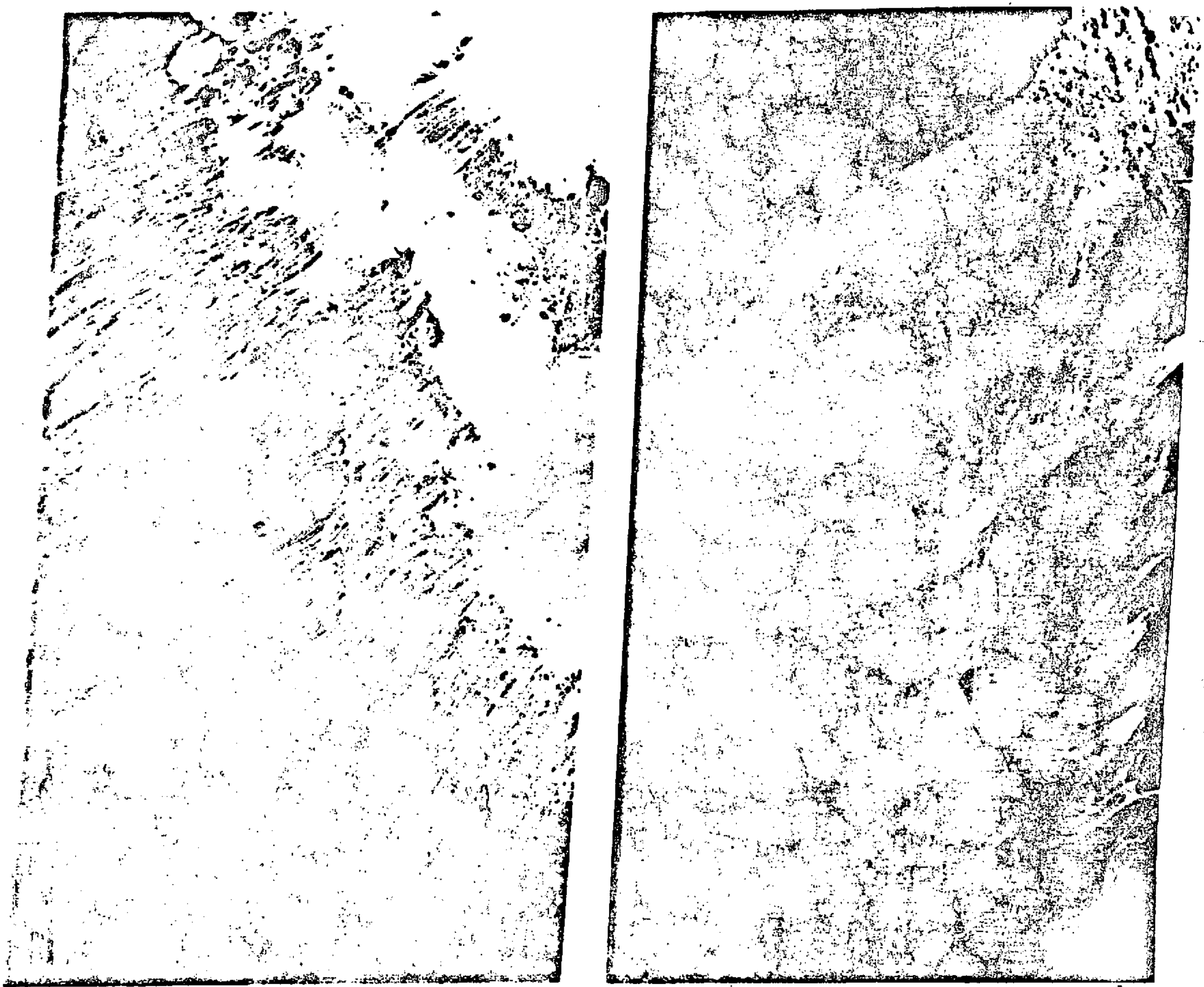


Figure 6. Sheets and streaks of eolian sand: (a) associated with yardangs, Libya and Chad; (b) associated with linear dunes, Mauritania. Area of each section is approximately 17,000 square kilometers.

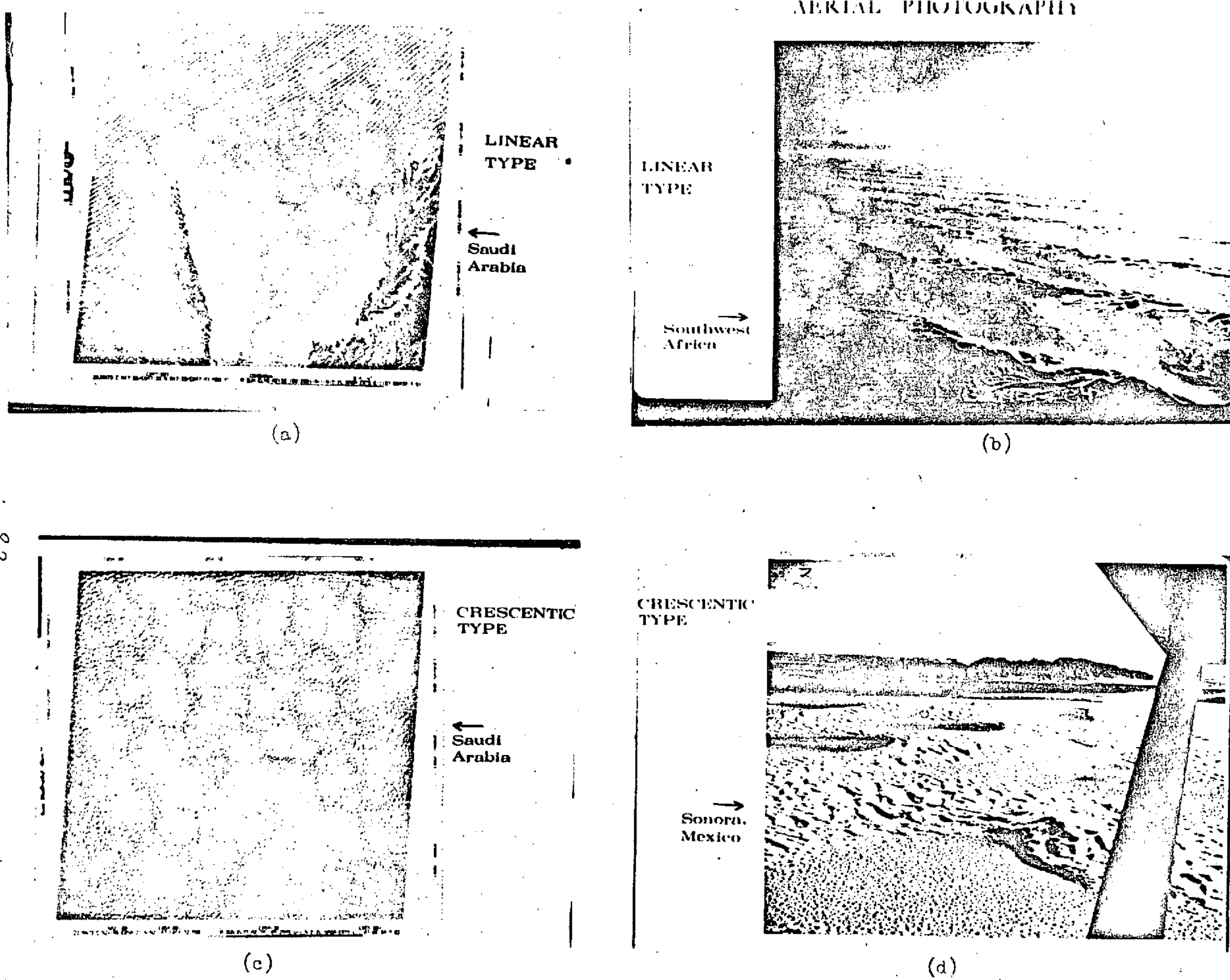


Figure 7. Comparison of ERTS imagery (a and c) and air photographs (b and d) for two basic types of dunes.

2. Parallel wavy dunes (fig. 3) are composed of segments, each of which is crescentic and has a width equal to or nearly equal to its length. The segments in most areas are aligned in wavy ridges that are asymmetrical in plan, and have all of the major slipfaces on one side. The commonest development of this type is the transverse or barchanoid ridge with open interdune corridors, described by McKee (1966) at White Sands, N. Mex., and shown in the left sections of figures 9a and 15b. This type appears to be ubiquitous throughout the deserts of the world.

Barchanoid dunes that furnish full enclosure of the interdune spaces give rise to compound transverse dunes as described by Smith (1964). This type forms the "peak-and-fulje" topography of Melton (1940) that is termed "akle" by Cooke and Warren (1973), after Monod (1958). The term "fishscale" is used in this report to describe this type of parallel wavy dune (fig. 3b).

A third type of parallel wavy dune in this general category is the dune complex named "giant crescents" by Holm (1960) and termed "megabarchans" by Norris (1966) (fig. 3c). Examples of this type are shown on ERTS-1 imagery (fig. 7c) and on an aerial photo (fig. 7d).

A fourth type of dune complex that probably falls within the parallel wavy category is the basketweave or chevron type. Insofar as we have observed, this form is unique to the Taklamakan Desert of China (fig. 3d).

3. Radial dune complexes (fig. 4) have segments or arms that radiate from the high center part of the dune complex in pinwheel or starlike fashion and constitute mountains of sand. These huge features, which may be hundreds of meters high and a kilometer or more in diameter, have been called rhourds or polypyramids (Aufrere, 1932); mastodons (Price, 1950); oghurds (Gautier and Mayhew, 1935; Folk, 1971); khurds (Capot-Rey, 1945); pyramidal dunes (Holm, 1960); star dunes (McKee, 1966); and draa peaks or stellate roses (Wilson, 1972). Figure 4b shows a series of these dunes in Algeria as seen on ERTS-1 imagery; figure 8 shows similar forms of radial dunes in a photograph from Skylab (8b) and in an aerial photograph from Saudi Arabia (8a), and Mexico (8c).

4. Parabolic dune complexes (fig. 5) are U-shaped dunes (called upsiloidal by Smith, 1964) which are greatly elongated in plan and have arms, partially fixed by vegetation, which extend upwind. Parabolic dunes at White Sands, N. Mex. (fig. 5b), and in the Rajasthan-Thar Desert of India and Pakistan (fig. 5a), are shown in figure 5; aerial photographs of this type are shown in figure 9a and b.

5. Sheets and streaks of sand (fig. 6) are relatively flat-appearing deposits lacking discernible slipfaces, but with well-defined geographic boundaries.

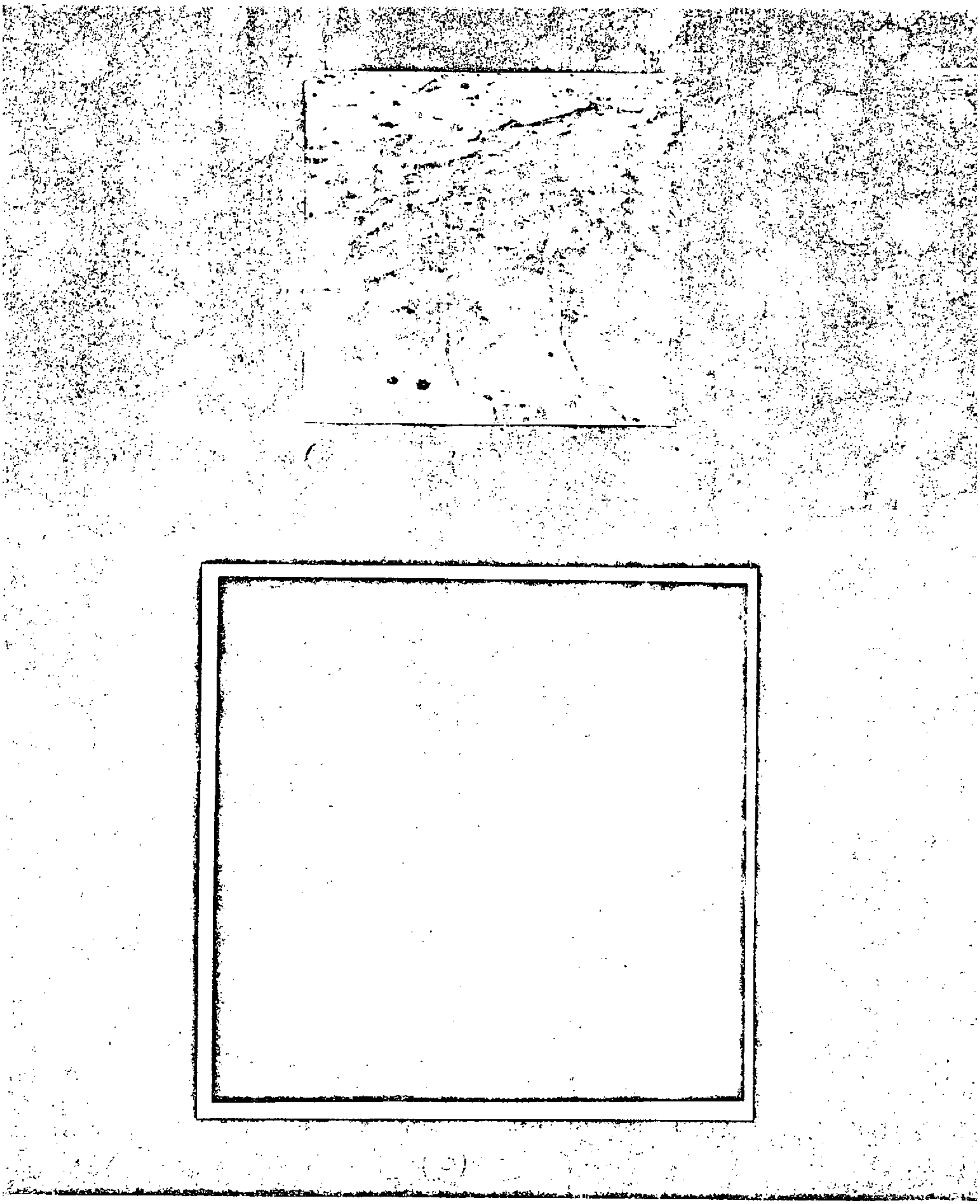


Figure 8. Comparison of ERTS imagery and air photographs of star dunes: (a) star dunes near Zalim, Saudi Arabia (photograph by E. Tad Nichols); (b) Skylab exterior color photograph of chains of star dunes, Grand Erg Orientale, Algeria. (EDC-010001)

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Figure 8 (c). Star dunes on linear ridges, Gran Desierto, Mexico (photograph by E. Tad Nichols).

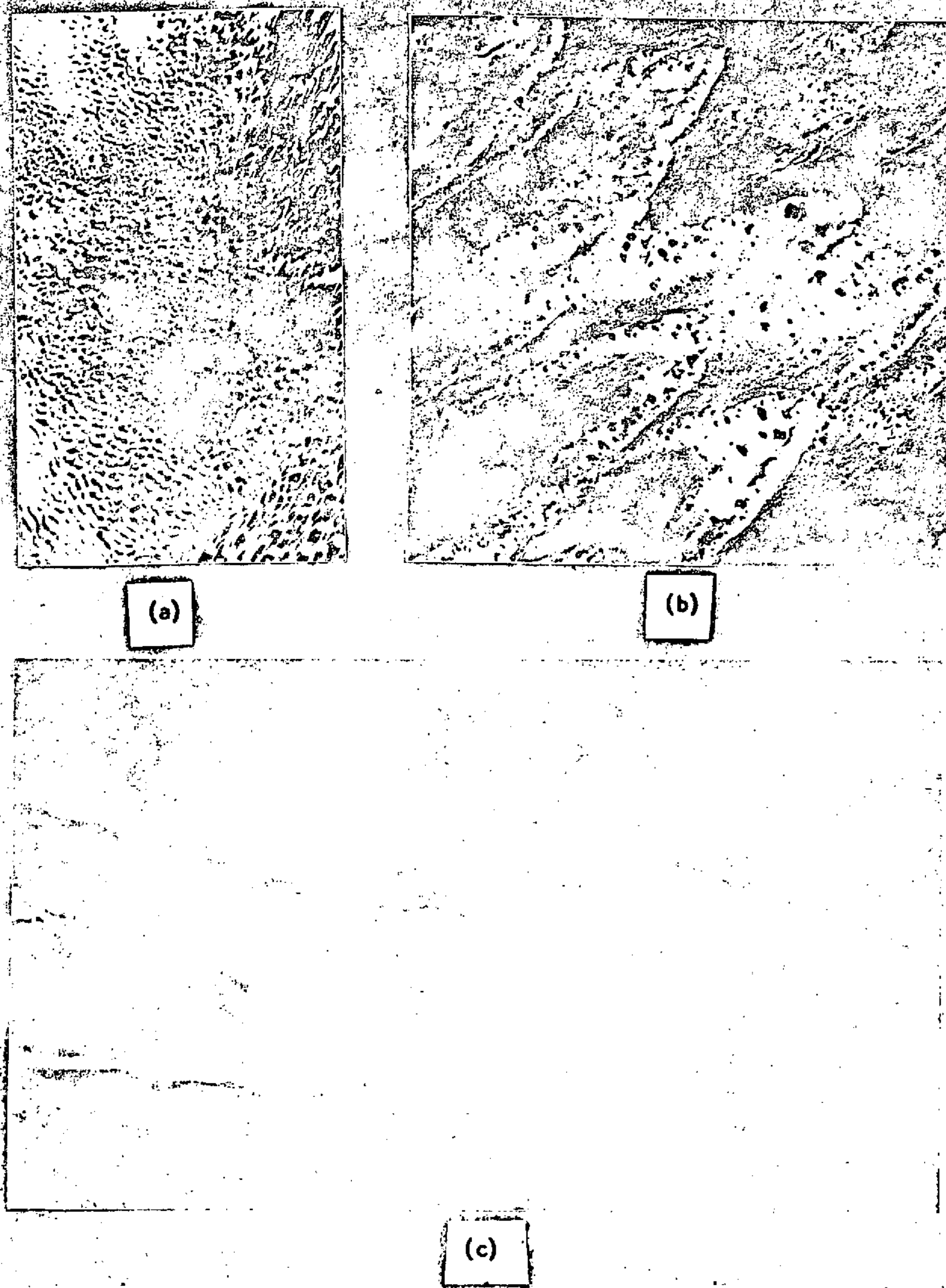


Figure 9. Details of dune forms shown in air photographs: (a) barchanoid complex, parabolic dunes along east (right) margin, White Sands, New Mexico; (b) parabolic dunes, White Sands, New Mexico; (c) seif dunes north of Sebha Oasis, Libya.

This classification is for very large-scale, complex dune systems as seen from a high orbital satellite. It is developed from images furnished by Earth Resources Technology Satellite-1 from an altitude of 567 miles. Nearly all the resolvable features on this imagery fall into the category of dune complexes, i.e., eolian features having a wavelength of 0.5 to 5 kilometers, referred to as "draa" by Wilson (1972). The many more familiar, small, individual dune types such as the barchan, hook, dome, teardrop, finger, tail, lunette, and others cannot be recognized on the ERTS-1 imagery and are not included in this classification, except as they join in forming the larger features (fig. 10).

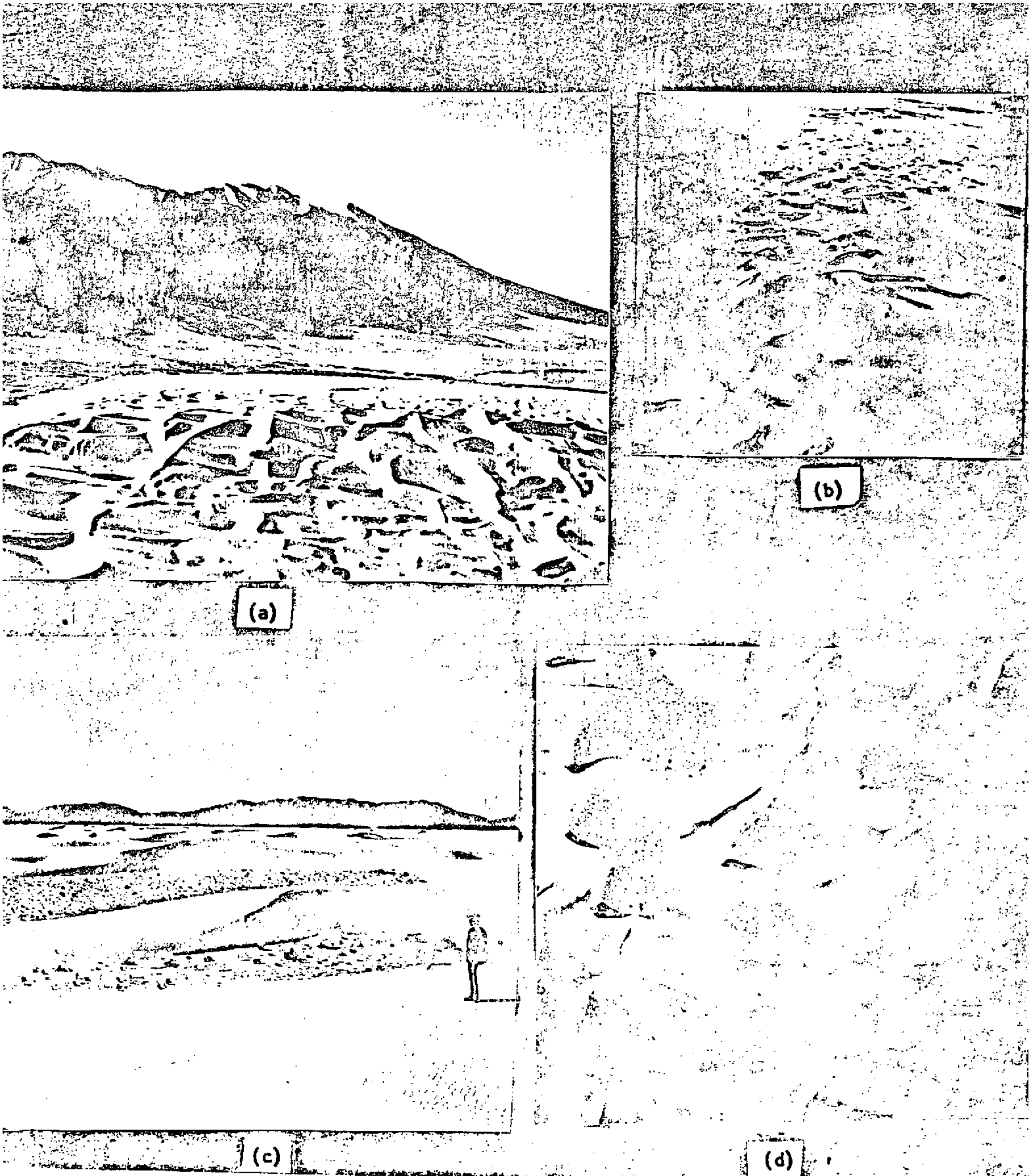


Figure 10. Distinctive patterns of dune types determined from air photographs and ground views: (a) reversing dunes, Great Sand Dunes, Colorado (photograph by John Shelton); (b) star dunes near Zalim, Saudi Arabia; (c) barchanoid dunes and wide interdunes, White Sands, New Mexico; (d) barchanoid complex, White Sands, New Mexico.

VII. NEW TECHNOLOGY

1. Use of Multispectral Imagery

ERTS-1 black-and-white band 7, 9 x 9 in. positive transparencies and composite false-color bulk prints were selected as the basis for observing eolian sands, for several reasons. Especially important is the high reflectivity of silica and gypsum sand in the near-infrared part of the spectrum, which was described by Hovis (1965), and which causes these bodies of loose sand to be best observed on band 7 transparencies. The brightness of dune sand contrasts most strongly with generally dark tones of the bedrock and/or interdune surfaces in these transparencies.

In middle-latitude deserts, where eolian sand generally is very red, a good contrast between sand and barren surfaces commonly is provided by band 4 transparencies. The red color of the eolian sand in many of these deserts corresponds with the bright golden yellow hue of desert sands on the ERTS-1 bulk color composite images (compare colors of fig. 4b: ERTS-1; and fig. 8b: Skylab). This characteristic yellow of sand as seen on false-color imagery has been of great usefulness, especially in delineating small bodies of loose sand, and has been very helpful in distinguishing sand from salt beds, snow, and clouds, all of which may resemble it in black-and-white ERTS-1 imagery.

An investigation is planned to test the relationship between surface color, composition, particle size, and texture of various dune sands and the general appearance (color) of these dunes as seen in ERTS-1 imagery. Selected samples of dune sands collected from the deserts of North Africa, Saudi Arabia, South America, and the southwestern United States, with samples of their appearances on ERTS-1 bulk color and bands 4 and 7 imagery, have been assembled for this purpose.

2. Quantitative Analysis of Data

Comparative studies of dune morphologies in various deserts of the world as made by analysis of ERTS-1 imagery are important to this investigation. Several sophisticated methods for quantitative analysis of the dune patterns have been suggested and are being tested.

One method of analysis is optical diffraction by laser analysis, suggested by Mr. Larry Lepley of the Office of Arid Land Studies, Tucson, Ariz. No results have as yet been reported on this method.

A second method considered is densitometer analysis. This method is being tried currently by personnel of the Center for Astrogeology at Flagstaff. The method appears to be expensive and time-consuming, however, for a study of many differently oriented patterns on large numbers of images.

The conclusion reached at this time is that the best method for rapid quantitative analysis probably is density slicing. The capability of the density slicer to discriminate among many elements of a sand pattern, and to provide instant planimeter readings of the relative percentage of area of an image occupied by each element of the pattern, seems to offer an excellent means of rapid processing of imagery and the best way to compare, with the least amount of observer bias, the elements of various deserts.

Pending results of experiments with sophisticated methods of image analysis, both manual and visual methods have been employed on relatively simple dune patterns, to provide a crude example of the kinds of quantitative analyses envisioned. The distribution of spacing of linear dunes in the Simpson Desert of Australia is shown on a map (fig. 11). It illustrates a measure of dune spacing called the dune spacing index. It was developed by counting visually all the dunes crossing several 50-km-long lines perpendicular to the trend of the dunes and obtaining an average number of dunes per kilometer for each area. Several counts were made on imagery giving total coverage of the Simpson Desert; lines were then drawn on the map to connect points of equal dune spacing or dune density.

Types of measurements other than those illustrated in figure 11 in this and in other deserts, and particularly in areas of more complex patterns, will include ratios of dune to interdune areas, and will require the use of a density slicer or some other computerized method, as discussed above. Quantitative analyses of the measurable characteristics of dune patterns on ERTS-1 imagery may reveal relations between these patterns and sources of sand, depth of sand, variations in wind regimes, the position of barriers, sand movement, and other features. This research will be given top priority for the ERTS-B phase of this project.

Some of the factors believed to affect the distribution and size of eolian sand deposits in various deserts of the world are illustrated in figure 12. The influence of these factors can best be studied on the regional scale provided by ERTS imagery.

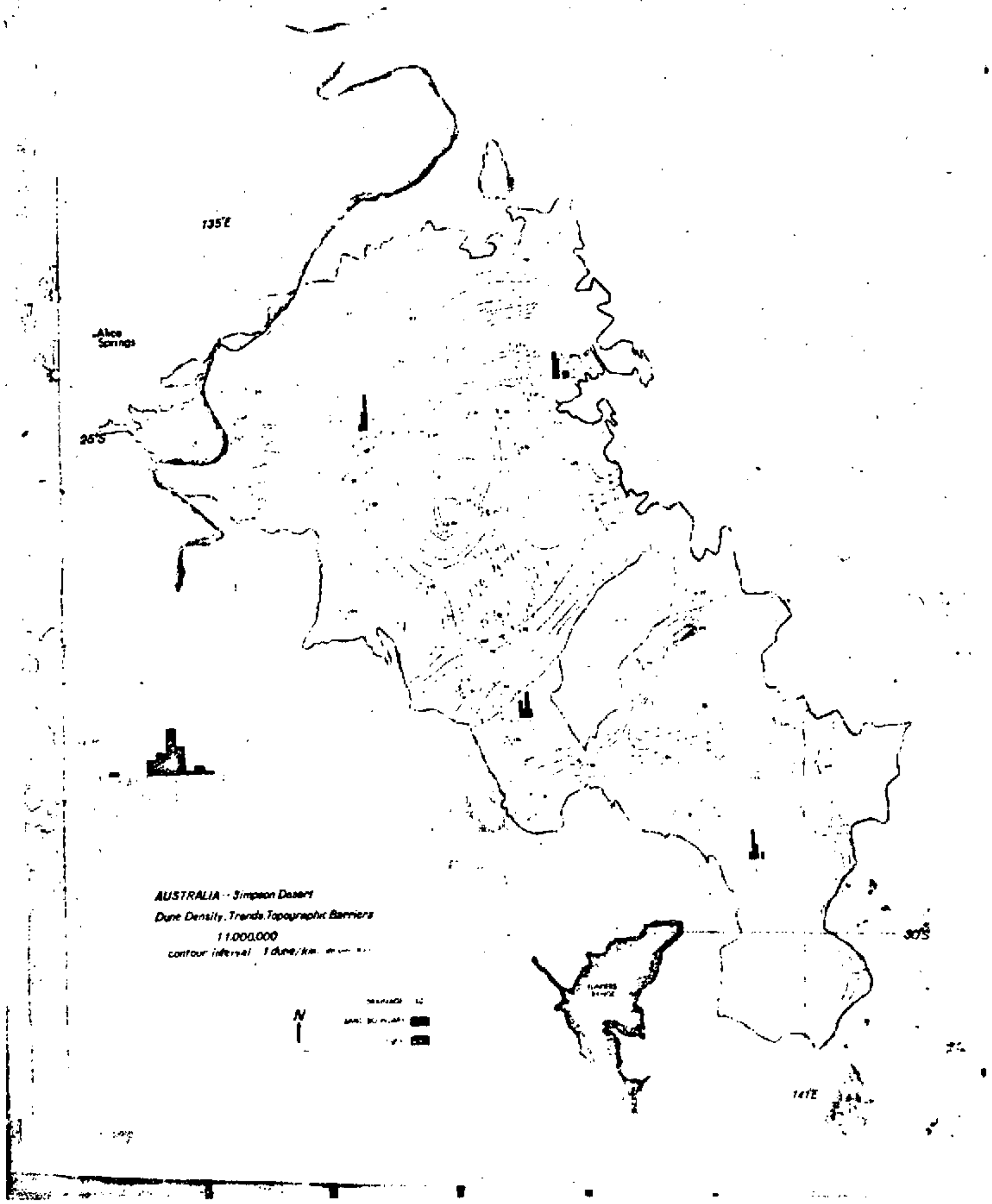


Figure 11. Distribution of dune spacing densities in the Simpson Desert of Australia. (Prepared by Dana Gebel)

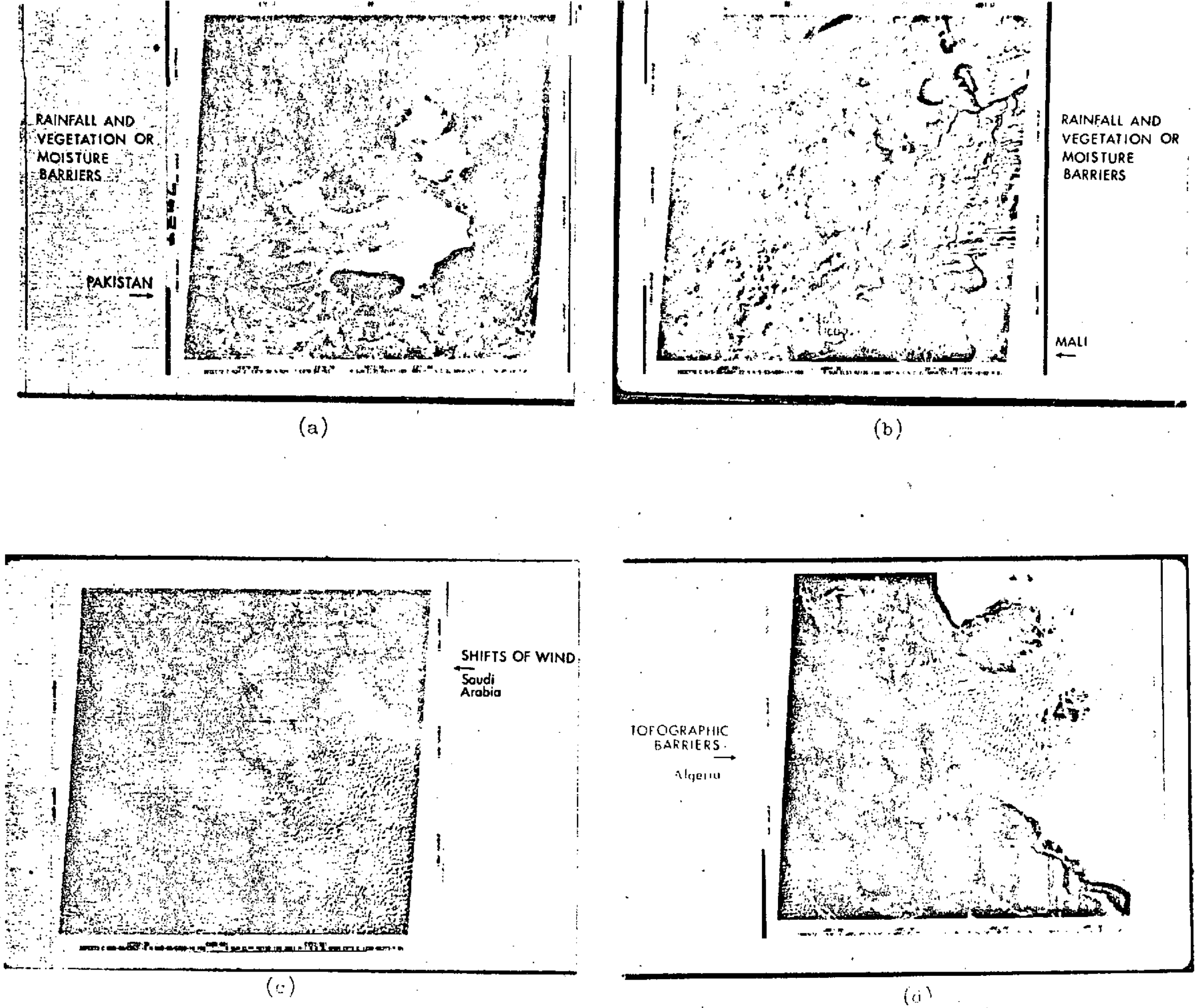


Figure 12. Physical features affecting size and shape of dunes and megadunes in sand seas: (a) Pakistan (water and vegetation); (b) Mali (water and vegetation); (c) Saudi Arabia (shifts of wind); (d) Algeria (topographic barriers).

VIII. SCIENTIFIC PROCEDURES AND RESULTS

1. The relation of wind data to sand seas

Threshold velocity.--Not all winds are strong enough to move sand. Sand of a particular grain size begins to move or saltate when the wind attains a certain minimum speed, as established by Bagnold (1941), Chepil (1945), and others. Although dune sands differ considerably in grain size, they commonly are about 0.25 mm in diameter; the threshold, or wind speed at which grains of this size begin to saltate, is about 16 km per hour (9 knots). For this reason, wind roses (figs. 13, 14, 15a and b) depict only wind groups with average velocities in excess of this figure.

The sand-moving potential of wind.--The power of wind to move sand increases as the cube of its velocity. Although winds of high speed may not occur as frequently as moderate winds, they may be equally important in the moving of sand masses. A plot of the annual sand-moving potential of winds at Walvis Bay, in South West Africa, based on the formula of Skidmore and Woodruff (1968, p. 2), is presented in figure 16b. A comparison of this plot with the standard wind rose (fig. 13) on the overlay reveals that the percentage occurrence of sand-moving winds is not directly indicative of their potential effects.

Seasonal and other variations in wind speed and direction.--Seasonal and diurnal fluctuations in wind flow must be identified in making wind transport studies because dune morphology depends not only on immediate resultant sand movement, but also on net sand movement through time. A seasonal variation in both wind speed and direction is illustrated for the vicinity of Gobabeb in the Namib Desert test site (fig. 13). During January (summer), wind speed and direction vary from time to time throughout the day. The strongest winds come from the southwest at about 16 km per hour (9 knots), in the late afternoon. During July (winter), maximum speed occurs at noon and comes from the east at a somewhat lesser speed of 12 km per hour. A southwest wind at this season is still represented by a secondary maximum in the evening, but it has little potential for moving sand. Because seasonal, diurnal and other factors combine in complex ways to produce local wind regimes, individual areas must be studied carefully to ascertain exactly when sand is in motion, and what its direction of movement is.

Modification of wind regimes by large dunes.--Both the sizes of many of the Old World dunefields, and of individual dunes within them, are much larger than the largest sand features in the United States. Dune complexes in the interior Namib Desert of South West Africa, for example, approach 270 meters in height and extend hundreds of kilometers. The extent to which dunes themselves modify the winds which pass over them is not certain; and therefore caution is required in extrapolating wind measurements from stations at the edges of deserts into interior regions.

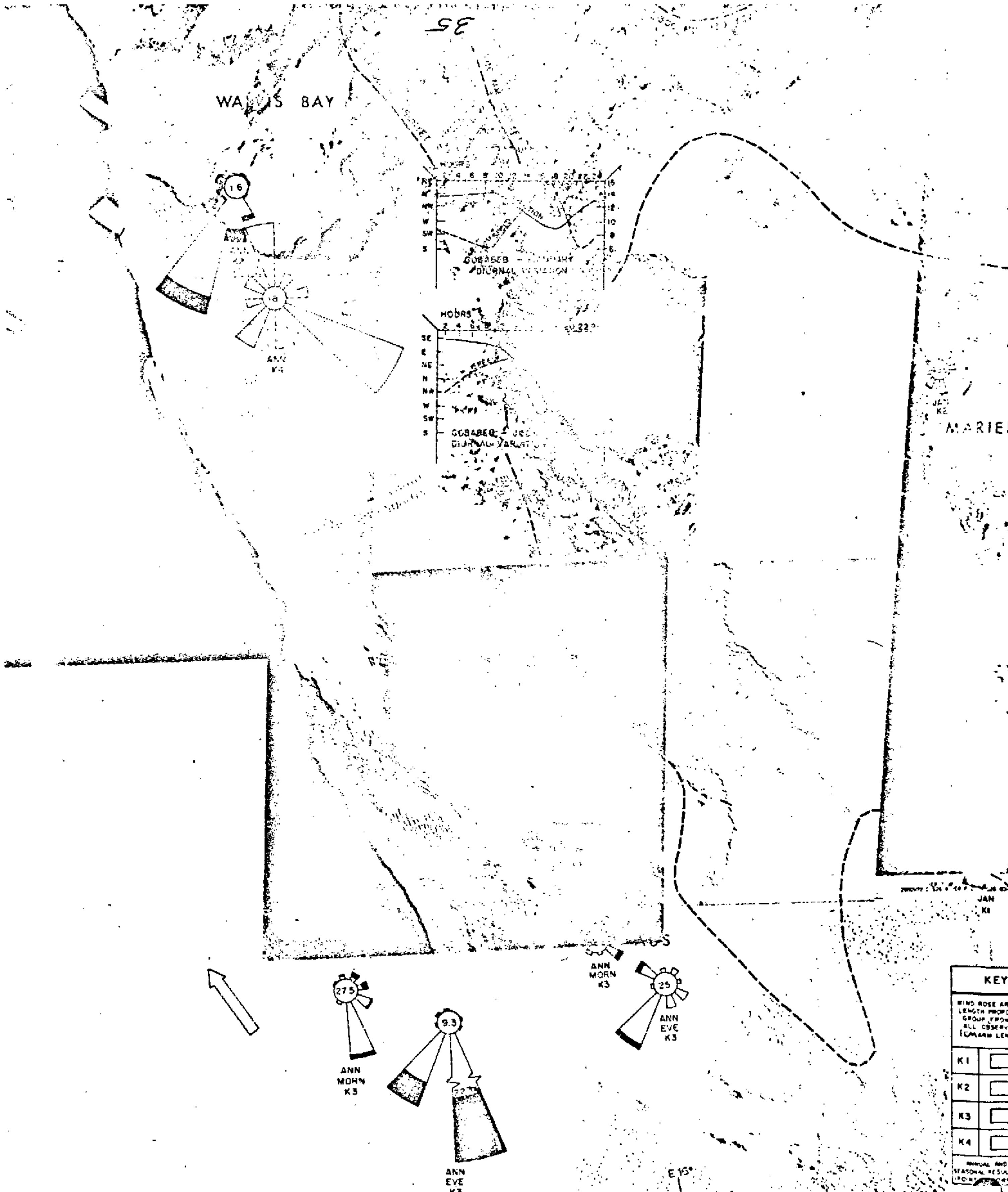
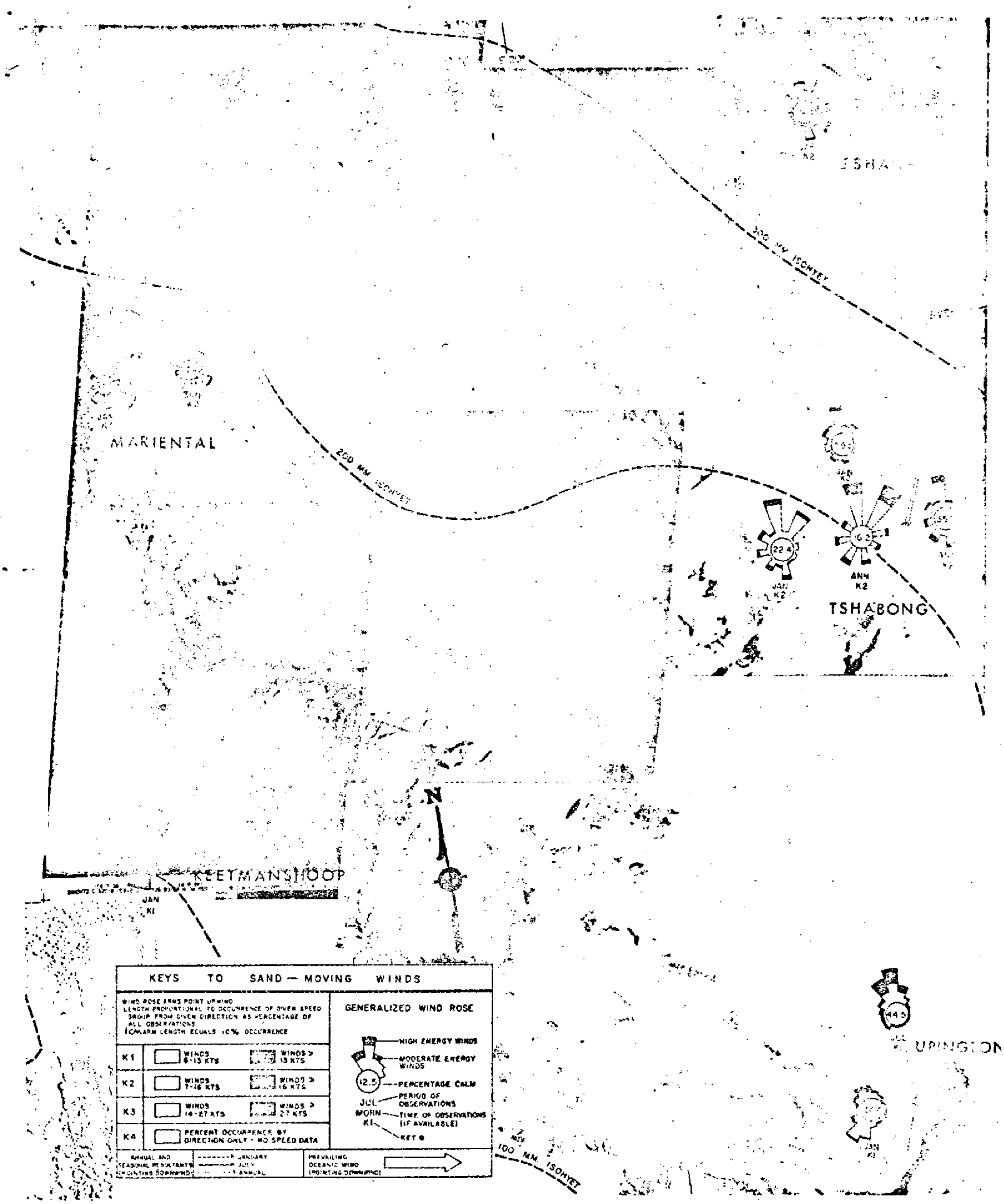
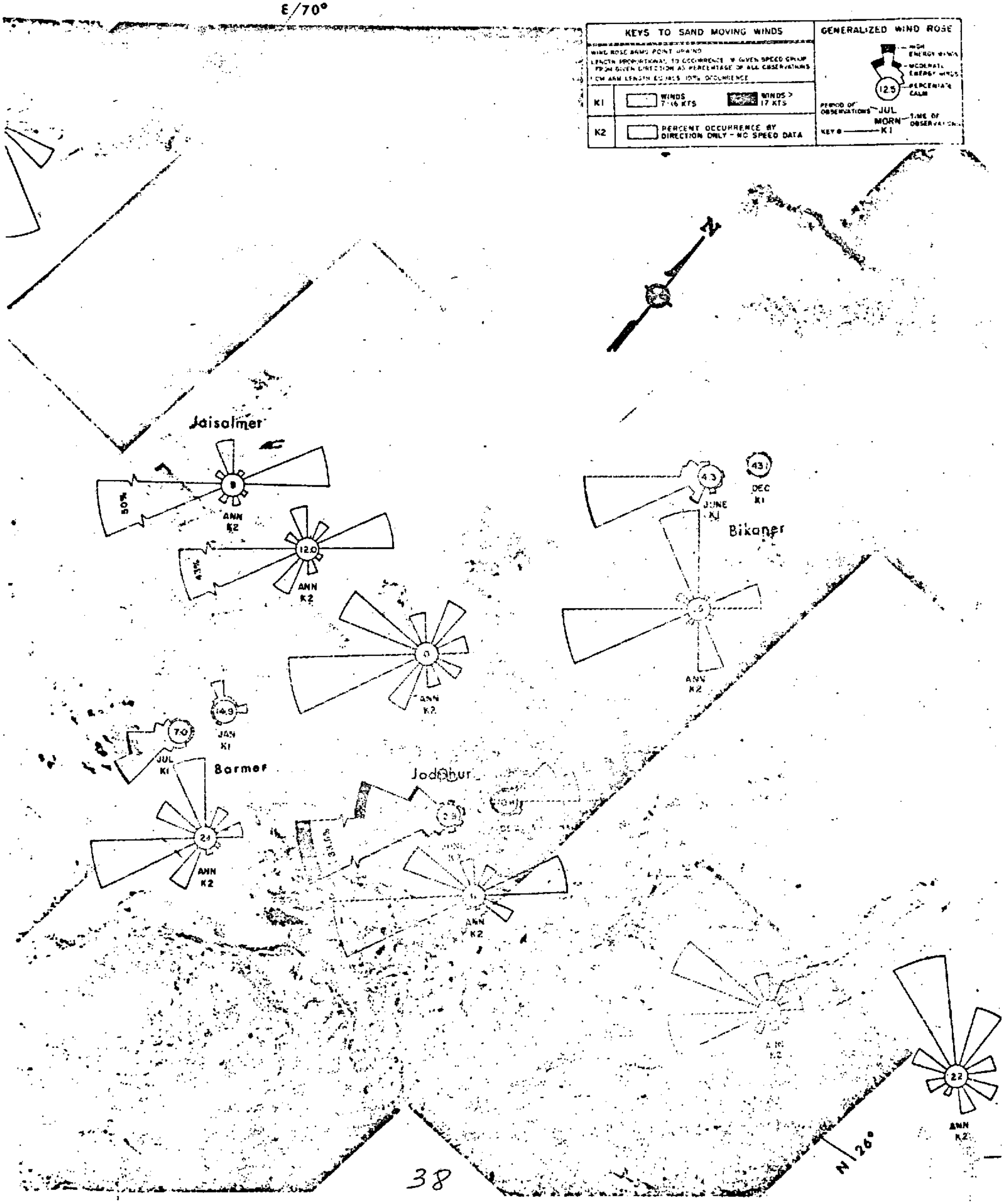


Figure 13. ERTS mosaic of the Namib and Kalahari Deserts of southern Africa with wind rose data and precipitation data.



200 MM. ISOHYET
MARIENTAL
200 MM. ISOHYET
22.4
JAN
K2
16.2
ANN
K2
TSHABONG
N
KEETMANSHOOP
JAN
K1
44.5
UPINGTON
JAN
K1
100 MM. ISOHYET
KEYS TO SAND — MOVING WINDS
WIND ROSE ARMS POINT UPWIND
LENGTH PROPORTIONAL TO OCCURRENCE OF GIVEN SPEED GROUP FROM GIVEN DIRECTION AS PERCENTAGE OF ALL OBSERVATIONS
1CM ARM LENGTH EQUALS 10% OCCURRENCE
K1
WINDS 6-13 KTS
WINDS > 13 KTS
K2
WINDS 7-16 KTS
WINDS > 16 KTS
K3
WINDS 14-27 KTS
WINDS > 27 KTS
K4
PERCENT OCCURRENCE BY DIRECTION ONLY - NO SPEED DATA
GENERALIZED WIND ROSE
HIGH ENERGY WINDS
MODERATE ENERGY WINDS
12.5
PERCENTAGE CALM
JUL
PERIOD OF OBSERVATIONS
MORN
TIME OF OBSERVATIONS (IF AVAILABLE)
K1
KEY #
ANNUAL AND SEASONAL RESULTANTS (POINTING DOWNWIND)
JANUARY
JULY
ANNUAL
PREVAILING OCEANIC WIND (POINTING DOWNWIND)

Figure 14. ERTS mosaic of the Rajasthan-Thar Desert of India and Pakistan with wind rose data.


E/70°
KEYS TO SAND MOVING WINDS
WIND ROSE ARMS POINT UPWIND
LENGTH PROPORTIONAL TO OCCURRENCE OF GIVEN SPEED GROUP FROM GIVEN DIRECTION AS PERCENTAGE OF ALL OBSERVATIONS
1 CM ARM LENGTH EQUALS 10% OCCURRENCE
K1
WINDS 7-16 KTS
WINDS > 17 KTS
K2
PERCENT OCCURRENCE BY DIRECTION ONLY - NO SPEED DATA
GENERALIZED WIND ROSE
HIGH ENERGY WINDS
MODERATE ENERGY WINDS
PERCENTAGE CALM
12.5
PERIOD OF OBSERVATIONS
JUL
MORN
TIME OF OBSERVATION
KEY #
K1
N
Jaisalmer
50%
ANN
K2
12.0
43%
ANN
K2
ANN
K2
4.3
JUNE
K1
43.1
DEC
K1
Bikaner
ANN
K2
14.9
JAN
K1
7.0
JUL
K1
Barmer
Jodhpur
2.9
ANN
K2
ANN
K2
ANN
K2
22
ANN
K2
N 26°

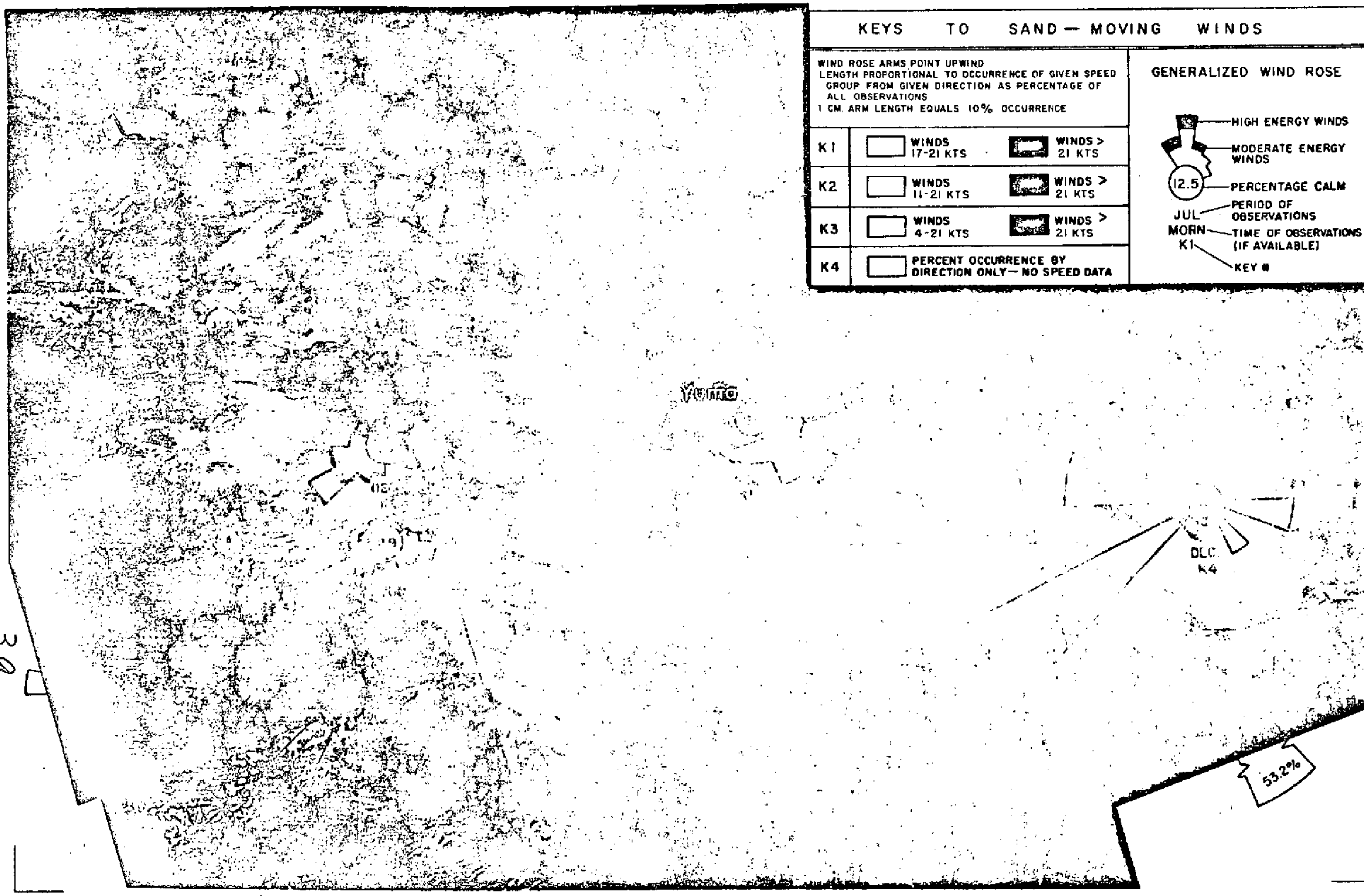


Figure 15 (a). ERTS mosaic of the Algodones and Gran Desierto sand seas of California and Mexico, with wind rose data.

Figure 15 (b). Parabolic and barchanoid-type dunes, White Sands, New Mexico, with wind overlay.

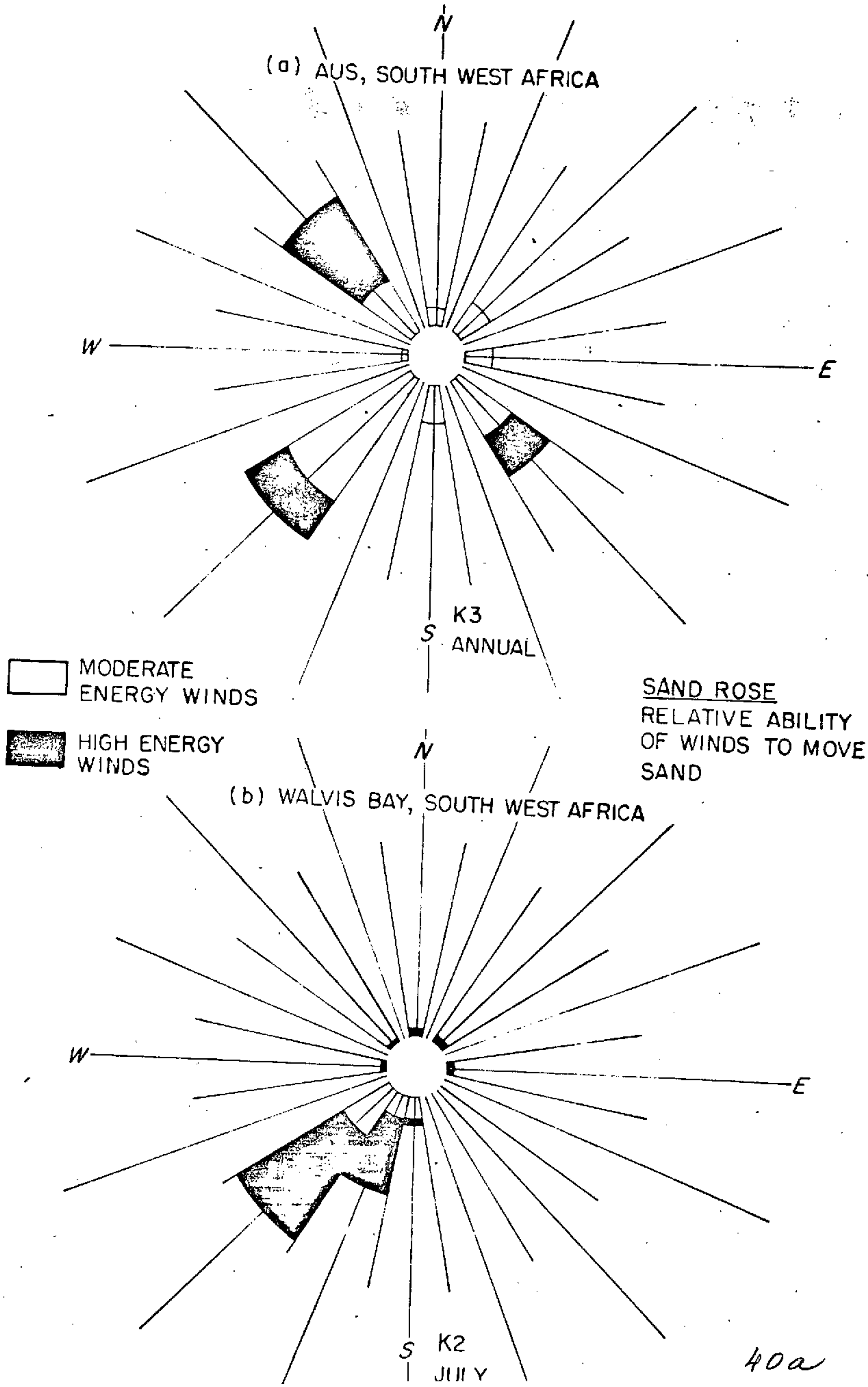


Figure 16. Sand roses prepared by plotting the cubes of the velocities of sand-moving winds.

Nature of wind data available.--No worldwide standardized system for the recording of wind speed and direction data is currently in use. Even countries such as South Africa, with highly developed weather networks, list their data in a variety of forms. For example, depending on the reference work consulted, one may find wind speeds recorded in knots, meters per second, statute miles per hour, or Beaufort scale. Moreover, observations are classified in differing speed ranges and differing subdivisions of compass direction. Differences also occur because governments change procedures through the years.

Because of the general scarcity of observations for some of the remote regions encompassed by the test sites, the current study has used any and all information available, regardless of the date of its publication, the recording system used, or its quality. To accommodate the existing diversity of systems used in measuring wind velocity, all our data have been converted into knots. In our study, each key (K1, K2, etc.) designates all data that were originally recorded in the same system. The legend used on each illustration (figs. 13, 14, 15) is independent; no progression is implied in the key for figure 13.

Procedural and observer bias influence the published form of wind data to different degrees, depending on the quality of observations, type of equipment used, and methods of reducing data into a summarized form. Elimination of bias from observations is a complicated process that requires the use of computer processing (Wallington, 1968) and is considered too expensive for this project at present. However, characteristic patterns of bias can be recognized and taken into account in qualitative interpretations. Both observer bias and procedural bias are minimal for the three areas described in detail in this report.

A common form of bias is illustrated by the wind rose for Tshane, Kalahari Desert, South Africa (fig. 13), which favors the cardinal directions at the expense of intermediate directions; wind direction distributions are known to have, in general, an elliptical pattern (Wallington, 1968).

2. The relation of rainfall data to sand seas

Studies by a number of authors, including Warren (1970), and experience gained from the present project indicate that the isohyet line representing 100 mm annual average rainfall marks the boundary between areas which have free drifting sand and those in which sand is partially anchored by vegetation. Generally, the presence of vegetation is indicated by a characteristic stabilized dune morphology, which is quite different from the morphology of loose sand in active sand seas. The two differ in color, texture, and sharpness of pattern elements.

Rainfall variability.--Total annual rainfall commonly shows considerable variation in arid areas. This variability places much stress upon plant life of the region, and also limits the number of species that can live in a harsh, marginal environment. Moreover, the distribution of rainfall throughout the year usually is uneven, and may result in distinct wet and dry seasons. If germination and vegetation growth are controlled by such a cycle, much more sand will be moved during a dry season than during a wet season, if winds of equal strength are assumed. Where rainfall and strong winds are associated, the effectiveness of strong winds in moving sand dunes is greatly decreased by the rainfall. Thus, in evaluating wind data for sand movement in areas such as the Rajasthan Desert in India, the times when wind is associated with precipitation should be ascertained.

IX. RESULTS OF ERTS IMAGE ANALYSES FROM TEST SITE AREAS

Three test sites for which bulk color composite mosaics are complete, or nearly so, have thus far been studied in detail by analyzing the imagery in combination with available ground-truth data. This ground truth consists both of climatic information, especially wind data, acquired from various sources, and of material gleaned from the literature. The three areas that have been studied with reference to climate and for which mosaics, wind charts, and thematic maps have been prepared are: (1) southern Africa, including both the Namib and the Kalahari Deserts (figs. 13, 17); (2) India and Pakistan, including the Rajasthan-Thar Desert (figs. 14, 18); and (3) Arizona-California-Mexico, including the Algodones dunes and the Gran Desierto sand seas (figs. 15, 19).

A thematic map of southern Africa (fig. 17) showing the distribution and patterns of eolian sand deposits in the Namib and Kalahari Deserts of South West Africa and South Africa was prepared from a mosaic of ERTS imagery (fig. 14) with wind and precipitation data superimposed on it. Summaries of the sand seas in these two areas follow:

1. Southern Africa; the Namib Desert

Extent and character.--The great sand sea of the central part of the Namib coastal desert of South West Africa extends from the Kuiseb River on the north to a southern boundary formed by the Luderitz-Keetmanshoop Railway line. The sand sea extends inland a distance ranging from 80 to 160 kilometers, from the Atlantic Ocean to the Great Western Escarpment, shown as bedrock on the map (fig. 17). Beneath the sand lies the Namib Platform, composed mainly of schists, quartzites, and granite intrusives.

Most of the Namib Platform is covered by eolian sand, but rock masses locally protrude through the sand as inselbergs. Other parts of the platform are flat, barren pediment surfaces, or gravel flats that range from grayish white to yellow. Sand is actively encroaching upon these exposed surfaces of the Namib Platform in many places (Logan, 1960). The map derived from ERTS-1 imagery (fig. 17) reveals characteristic sand-free "shadows" on the seaward sides of many of the inselbergs, with sand encroaching upon the edges of the rock masses on their inland sides.

Although the Kuiseb River forms an abrupt barrier to northward movement of the sand sea along most of the river's course, near Walvis Bay the dunes have crossed the mouth of the river and extend northward for some kilometers to the south bank of the Swakop River. The dunes north of the Kuiseb River are 70-100 meters high, extend some kilometers inland, and are accessible for study from Walvis Bay.

Surface relief in the Namib sand sea had not been reliably mapped until ERTS-1 imagery provided a data base; the Operational Navigation Chart of the U.S. Coast and Geodetic Survey shows large blank areas labeled "relief data unavailable."

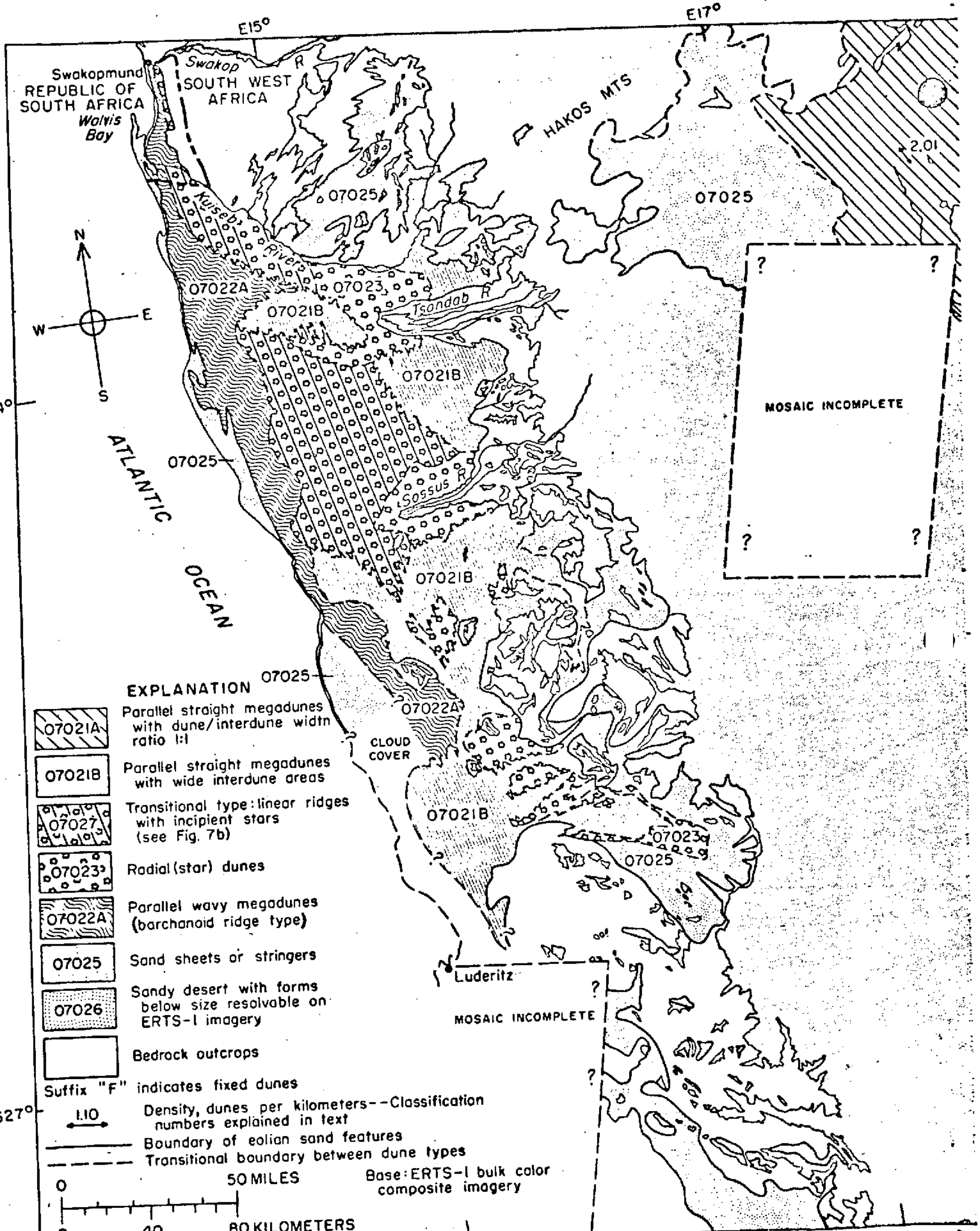
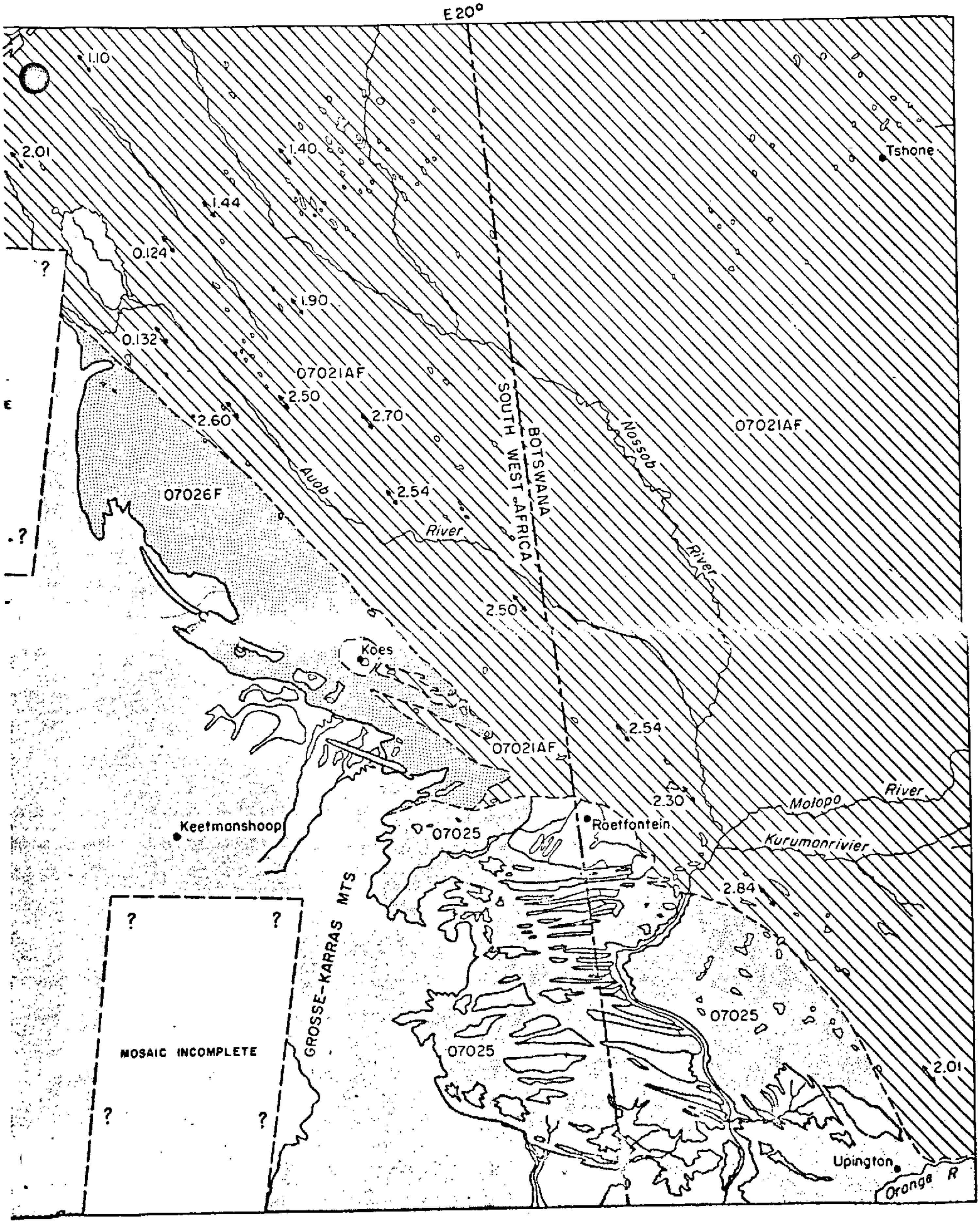


Figure 17. Thematic map showing the patterns and distribution of eolian sand in the Namib and Kalahari Deserts of southern Africa.



E20°
1.10
2.01
1.40
Tshone
1.44
0.124
1.90
0.132
07021AF
2.50
2.60
2.70
BOTSWANA
SOUTH WEST AFRICA
Nossob
River
07021AF
Auob
River
07026F
2.54
2.50
Koes
2.54
07021AF
2.30
Molopo
River
Keetmanshoop
07025
Roetfontein
Kurumanrivier
GROSSE-KARRAS MTS
2.84
MOSAIC INCOMPLETE
07025
07025
2.01
Upington
Orange R

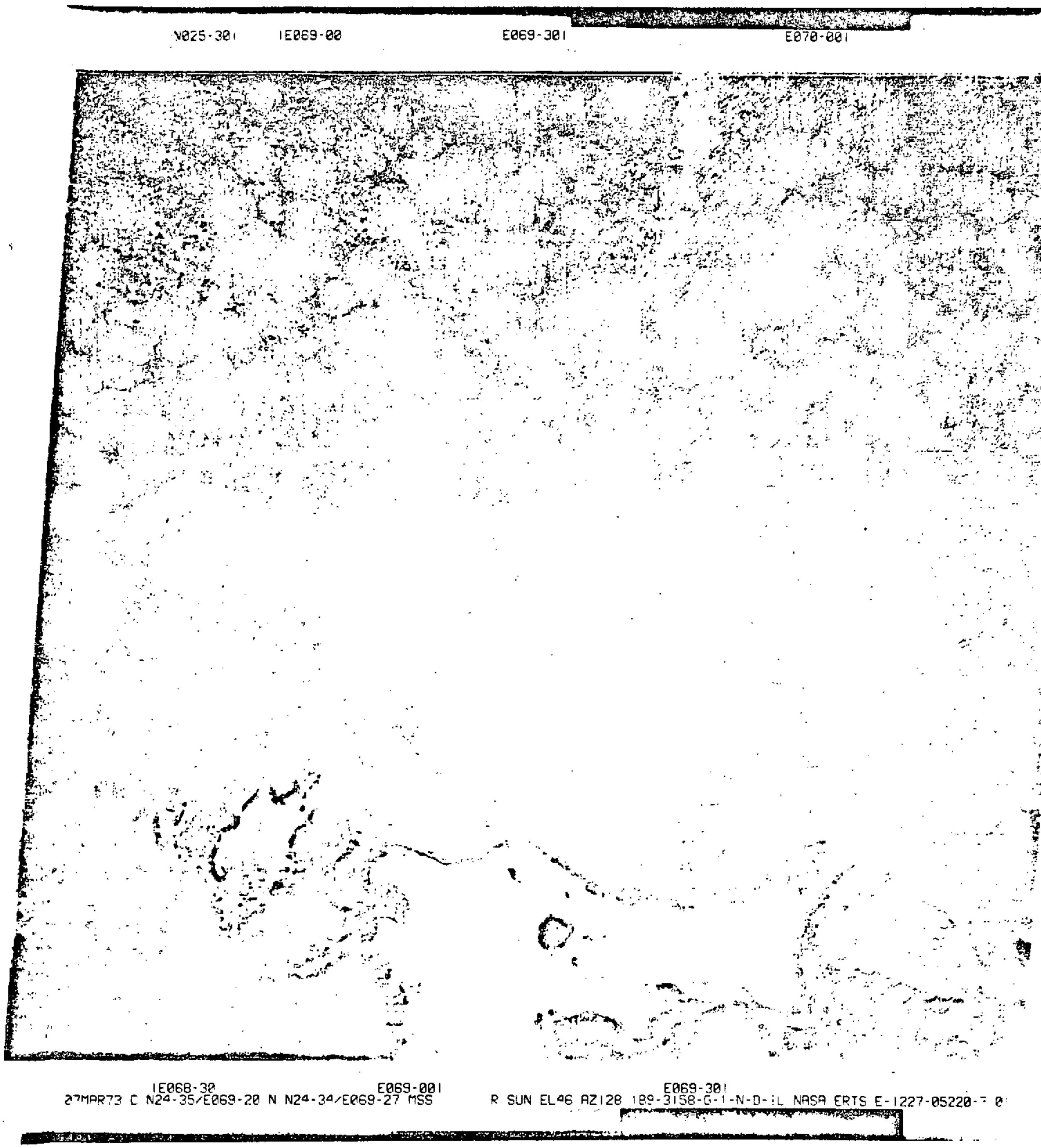


Figure 18 (a). ERTS-1 false-color image of the southern Rajasthan-Thar Desert in India and Pakistan during the dry winter season. (EDC-010002)

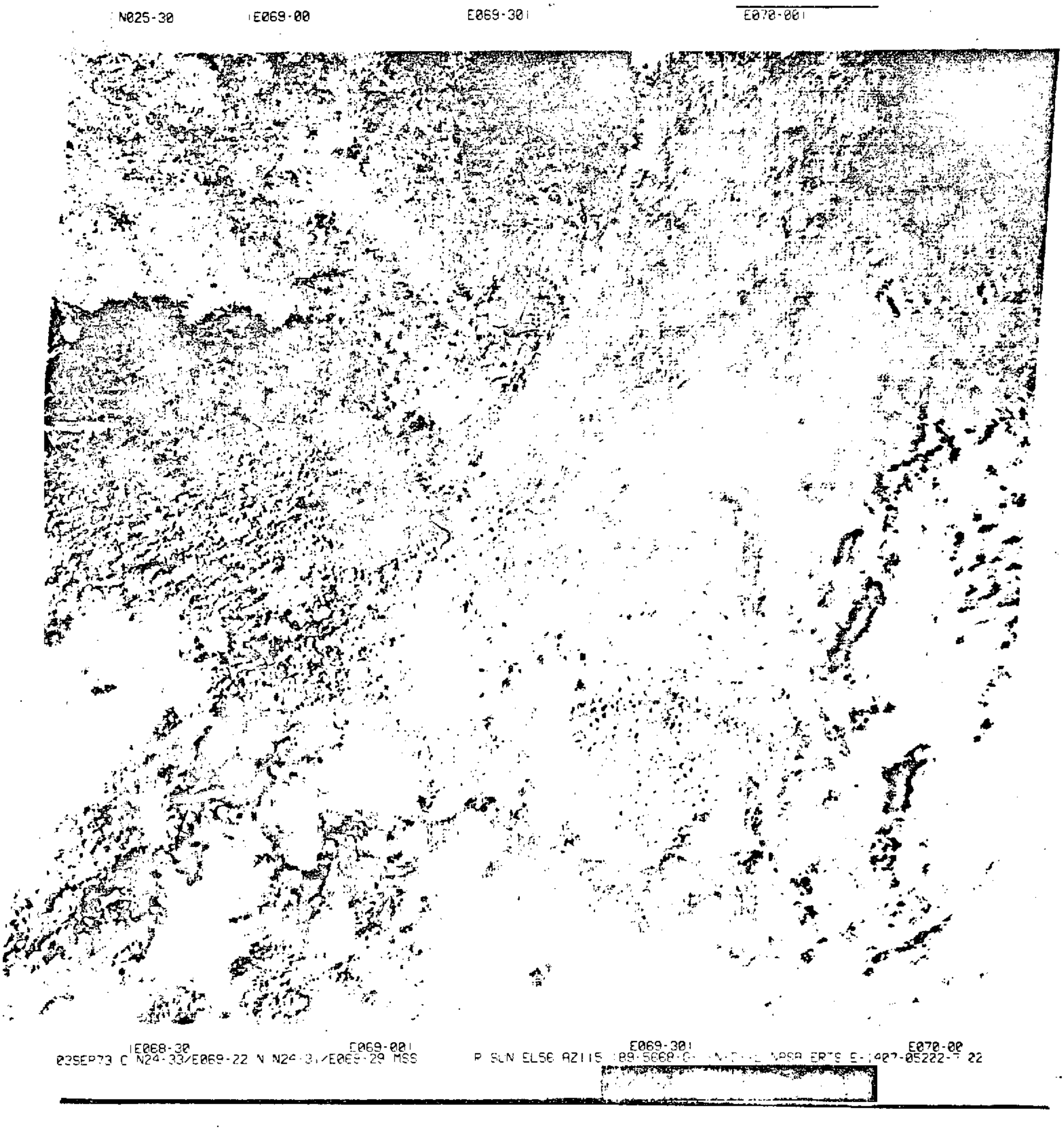


Figure 18 (b). ERTS-1 false-color image of the southern Rajasthan-Thar Desert in India and Pakistan during the summer southwest monsoon, showing vegetation in leaf. (EDC-010003)

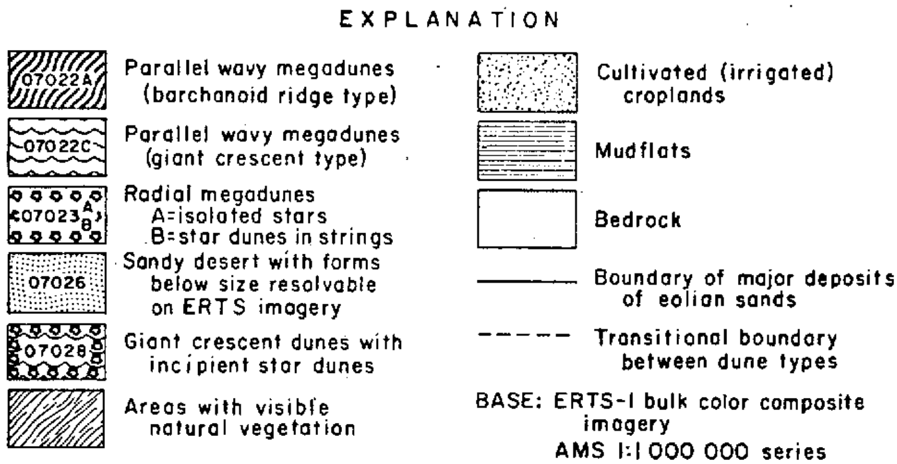
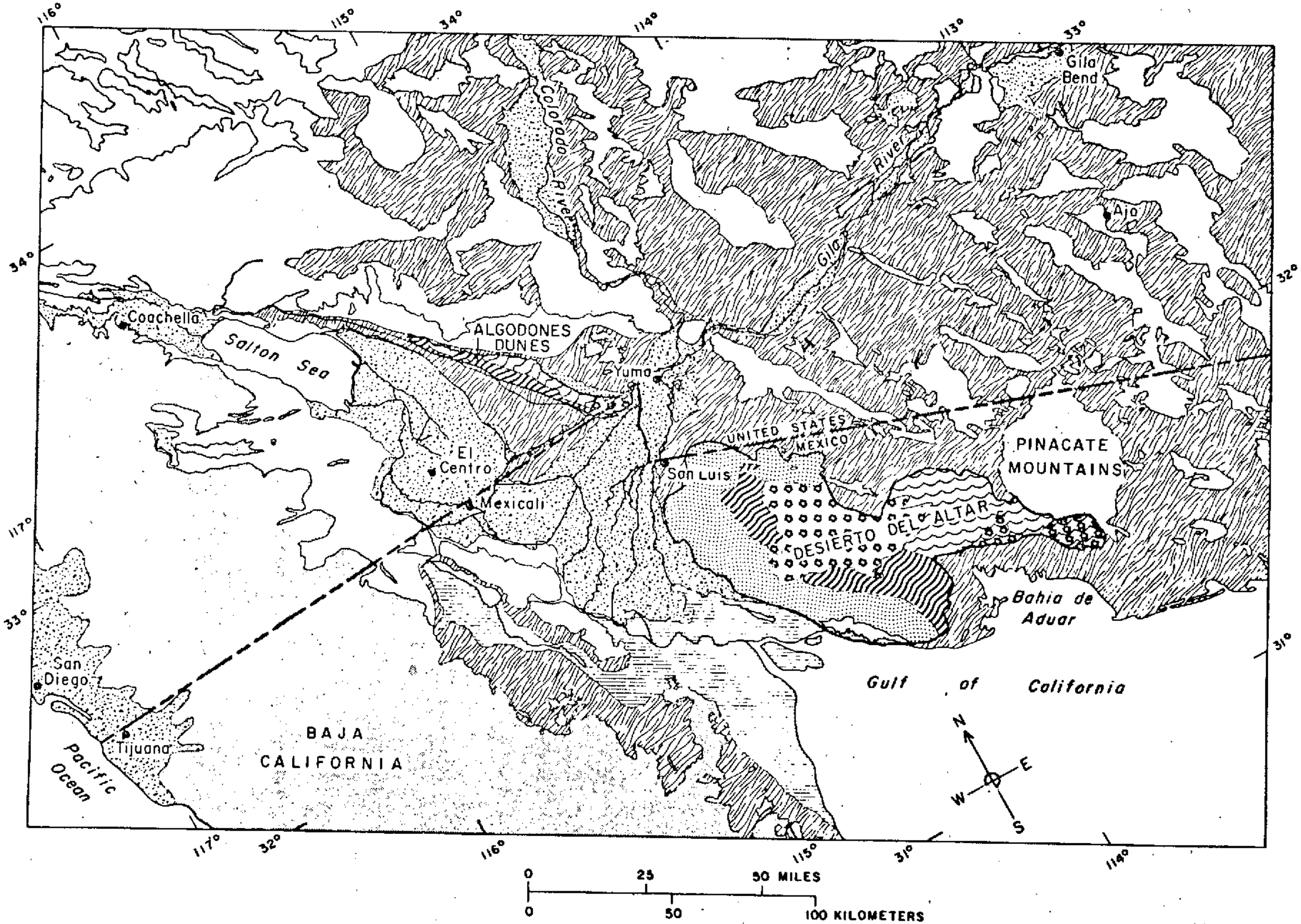


Figure 19. Thematic map showing the distribution of eolian sand in the Algodones and Gran Desierto Deserts of California and México.


Gila Bend
Colorado River
Gila River
Ajo
Coachella
Salton Sea
ALGODONES DUNES
Yuma
UNITED STATES
MEXICO
El Centro
Mexicali
San Luis
PINACATE MOUNTAINS
DESIERTO DEL ALTAR
Bahia de Aduar
Gulf of California
San Diego
Tijuana
Pacific Ocean
BAJA CALIFORNIA
N
E
S
W
0 25 50 MILES
0 50 100 KILOMETERS

Types of dunes.--As seen in ERTS-1 imagery, dunes of the Namib Desert are not all of a single type, although the parallel straight (linear) type is most abundant. This type was described by Logan (1960) as dunes aligned in rows with a northwest-southeast direction, moderately inclined (sloping 10°-15°) on their southwest sides and with slipfaces (inclined at 33°) on their northeast sides. The regularity of the crests of these dunes, interrupted by breakthroughs and blowholes, and the abundance of troughs between the dunes, blocked by cross-drifts of sand up to half the height of the main ridges, were recorded by Logan (1960). These "transverse" elements he attributed to the winter Berg wind, blowing from the east, although he believed that the main ridges resulted from a prevailing southwest wind. These dunes are well illustrated by figure 7b.

Along the coast and extending inland are parallel wavy dunes (fig. 17) of the type described by McKee (1966) at White Sands, N. Mex., as barchanoid ridges. These are a simple and ubiquitous type of dune form which we believe results, along the Namib coast, from the onshore southwesterly winds shown on figure 13. Farther inland are the parallel straight linear ridges with cross ridges described by Logan (1960). Still farther inland the pattern is different again, particularly where rock masses tend to interrupt the wind and therefore the flow of sand.

Around the two most prominent dry riverbeds in the Namib Desert--the Sossus and the Tsondab--interruptions of the linear dune pattern occur, and in these places radial (star) dunes have formed. This type of dune is believed to form only where, as described by Holm (1960) the winds "beat around the compass." A trimodal wind regime near the town of Aus (fig. 13) is approximately 80 kilometers from a large group of star dunes in the southern part of the sand sea. A sand rose near Aus (fig. 16), in which the cube of the velocity of the winds reflects their sand-moving capacity (Skidmore and Woodruff, 1968) and has been used to indicate the amount of sand moved by the winds. This sand rose confirms the trimodal transport pattern. Dunes that occur farthest inland in the Namib reach heights of nearly 270 meters above the adjacent troughs (Logan, 1960); presumably Logan was referring to the dune complexes described here as star dunes.

Color of sand.--Color variation in dunes of the Namib sand sea was described by Logan (1960) as follows: "the farther inland a dune is located the redder is its color." Confirmation of the true red color of the dunes, and of the increasing intensity of redness from the coast inland, is provided by color exterior photographs of the Namib taken by the crews of Skylab (fig. 20a). The false color of the dunes on the ERTS-1 bulk color composite images is bright yellow, ranging from whitish yellow along the coast to deep golden yellow in the interior of the desert.

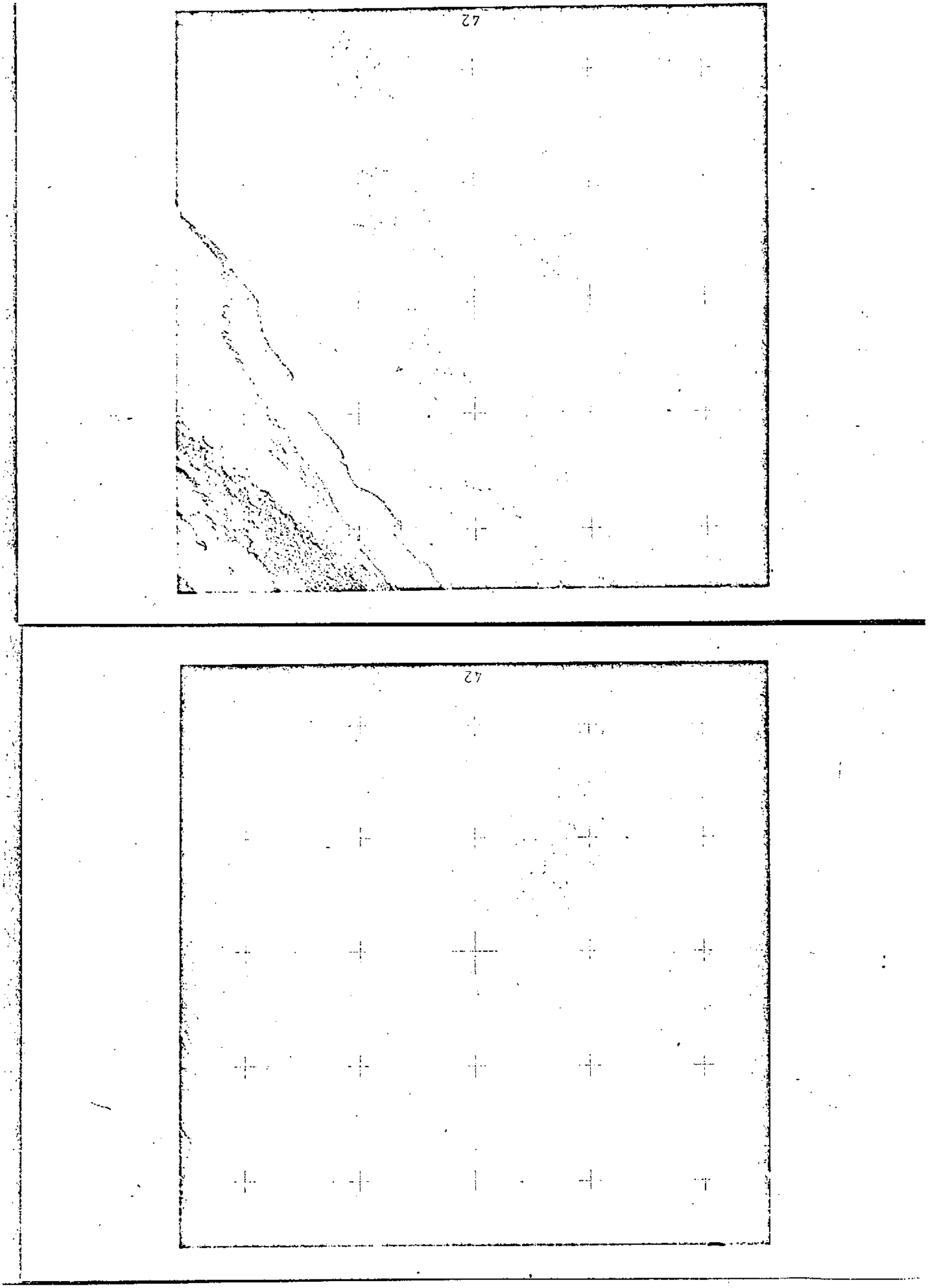


Figure 20. Skylab exterior color photographs of southern Africa: (a) Namib Desert, showing red color of sand and increasing redness from coast inland (EDC-010004); (b) linear dunes, Kalahari Desert, southern Africa (EDC-010005).

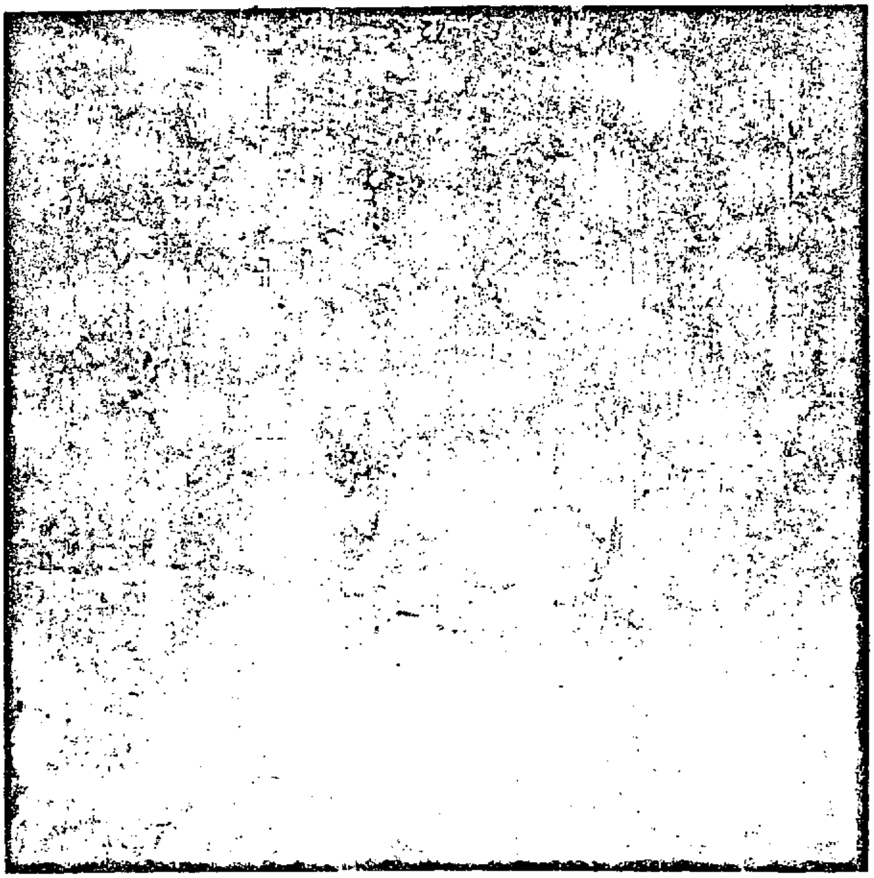


Figure 20 (c). Sand sheets and streaks, Kalahari Desert, southern Africa.
(EDC-010006)

Changes in degree of redness in the sand of various parts of a sand sea may be explained as the result of differences in composition, grain size, sun angle, source, age or other factors. In the Namib Desert, on the assumption that the far inland dunes have an age much greater than that of the coastal dunes, and therefore have had more time to form oxidation of iron components, observed differences in color are explained by Logan (1960) as a function of time. Support for this belief possibly is furnished by the presence of large star dunes in the interior areas and by the growth there of considerable vegetation, including bushes, annual herbaceous plants and grasses, all of which suggest a condition approaching stabilization. Star dunes of similar size and form in the Grand Erg Oriental of northern Africa are calculated by Wilson (1972) to have required 10,000 years to attain their present height; unfortunately, no estimates of age have yet been made for the Namib dunes.

Sand source and character.--The source of the sand of the Namib sand sea is believed by Logan (1960) to be the rivers (particularly the Orange River) that drain the interior highlands of southwestern Africa; river sediments are deposited on the Namib Platform and there reworked by the wind. At least some of the sand may be derived from beaches along the Atlantic Coast, but no supporting evidence for this source has as yet been acquired.

Little if any field work has been done on the composition, texture, and internal structures of any of the dunes of the Namib. The interiors of the dunes (presumably the linear type) are "crudely stratified" according to Logan (1960, p. 136), but no description is given. Obviously, the principal need at present is for supporting ground-truth data to be acquired by whatever means possible.

Precipitation data.--Rainfall is sporadic in the Namib sand sea with the 100-mm isohyet (fig. 13) roughly paralleling the coast about 60 miles (95 km) inland. The maximum rainfall in a single year at Usakos was 23.6 in. (59.9 cm), but at Walvis Bay only 3.9 in. (9.9 cm), and at Luderitz Bay only 1.3 in. (3.3 cm) (Royal Navy and South African Air Force, 1944). The 100-mm isohyet is generally considered the dividing line between areas capable of supporting vegetation and areas that are not. Rainfall in the southern part of the area, near Luderitz, is associated with the passage of winter cyclones; but northward, this type of precipitation, as a percentage of the annual total, diminishes and is replaced by showery summer precipitation.

Drizzle or heavy dew prevail most mornings along the coastal part of the Namib Desert. At Walvis Bay this moisture is often sufficient to prevent sand movement by the wind from about 10 a.m., when the southwest wind picks up, until about 12 noon, when humidity has decreased and the sand has dried. This heavy dew may amount to 1.5 in. (3.8 cm) per year, a figure based on moisture gathered carefully from rooftops at Swakopmund (Royal Navy and South African Air Force, 1944).

Wind data.--All coastal stations along the Namib Desert experience strong daytime onshore winds throughout the year. These breezes, which often acquire the strength of gales (especially during the summer), are believed to result from rapid heating of the desert sands adjacent to the cold Benguela current, creating a thermal low on shore. Onshore winds are strongest in the southern part of the desert, with generally greater percentages of higher speed winds, diminishing in force northward to Walvis Bay but still strong nevertheless. To what extent this sea breeze or southwest wind penetrates the interior is difficult to ascertain. Previous workers (Logan, 1960) credit it with formation of the inland dunes. From available data, its strength seems to diminish inland, especially during winter. The wind rose for Aus, however, shows that as far inland as that southernmost station the southwest wind has considerable sand-moving potential. The paucity of wind stations in the interior of the sand sea constitutes a problem in attempting to evaluate the importance of so-called effective winds.

The Berg or east wind occurs most frequently in winter in the Namib Desert, usually blowing steadily from the east or northeast for several days, and, according to Logan (1960), bringing with it clouds of red dust and introducing high temperatures. Wind roses along the coast and inland reveal that this wind decreases in strength and duration from the Great Western Escarpment toward the coast. At Gobabeb the Berg wind is the principal sand-moving wind during the winter, coincident with the weakening of the southwest sea breeze. By the time the Berg wind reaches the coastal dunes, its effect may be minimal (see the wind rose for Walvis Bay, fig. 13).

The Berg wind is not everywhere effective throughout the Namib Desert; at Aus it is hardly represented, for the most important components of the wind regime in that area come from the southwest, northwest, and southeast. Although the Berg wind is credited (Logan, 1960) with "creating chaos" and "destroying symmetry" among the dunes, ERTS imagery and analysis of the available wind data suggest either that this conclusion may exaggerate the effect of the Berg wind on the major sand patterns, or that it applies only to local, relatively limited situations.

The southeast and northwest winds in the Namib Desert are well represented in the wind roses for Aus, Luderitz, and Walvis Bay, although in the northern part of the desert they do not account for much sand movement. The southeast winds occur mainly at night or early morning (when solar heating is not in force) and are probably the landward correlatives of the southeast trades, the resultant direction of which is indicated by the large arrows offshore on figure 13 (Harry Van Loon, oral commun., 1974). These winds are a much more important component of the total wind regime in the landward stations than in the shore stations.

The northwest wind is less predictable than the southeast and is associated with periods when the South Atlantic High has receded from the coast and small depressions appear, then move northward just off the coast. This wind is most frequent in winter, bringing cooler temperatures and drizzle.

The wind and precipitation data for the Namib Desert indicate that meaningful analysis of the conditions for sand deposition and movement in that area will depend upon acquisition of additional reliable data and upon much more work along the same lines. In general, surface wind flow information is not sufficient to definitively correlate the central Namib Desert with all of the various dune morphologies observed there.

Two examples of wind directions that logically explain resultant dune types are well documented: (1) the southwest sea wind correlates well with barchanoid ridge dunes developed transverse to wind along the coast, and (2) trimodal winds inland, near Aus (fig. 16a) seem to correlate with a nearby development of star dunes. At present, however, it is mere speculation to conclude that the southwest wind and the Berg wind might combine to produce the parallel linear ridges with transverse elements that form the main body of the Namib sand sea. This, however, is the conclusion that has been reached by previous observers of the region.

2. Southern Africa; the Kalahari Desert

Extent and character.--The sand sea of the Kalahari Desert in southern Africa lies east of the neighboring Namib Desert and merges with it on the southwest, but the Kalahari differs greatly from the Namib in characteristics seen on ERTS-1 imagery. These differences probably occur because the Kalahari is largely a relict sand sea, fixed by vegetation and now inhabited by man. The entire region known as the Kalahari extends from lat. 22°S. southward to the Orange River, and from the Great Western Escarpment eastward to approximately long. 22°E.

The Kalahari is essentially a great basin formed in the Karroo System and Precambrian rocks; it is filled with sands that range in depth from 3 to 30 meters and have been redistributed many times since their original accumulation in Pleistocene time (Grove, 1969). The sand forms a topographic plain broken only by groups of grassy dunes.

Types of dunes.--Only the portion of the Kalahari Desert that lies near the junction of the lower Molopo and the Nossob and Auob Rivers has been included in this study, for in that part of the Kalahari the sand appears to be most active today. In that area, on the basis of analysis of the ERTS imagery, vegetation seems to be least developed on the dunes.

Two major types of sand accumulation, as seen on the ERTS-1 imagery, are shown on the eastern part of the thematic map (fig. 17). From the north to the southeast part of the desert, parallel straight linear dunes of the simplest type trend roughly northwest to southeast for more than 500 kilometers. In the southwestern part of the desert, between the Nossob River and the Grosse-Karras Mountains, east-trending sheets and streaks of what seems to be active sand cross the countryside in great arcs with no apparent relation to underlying structures, drainages, or topography.

A third type of sand pattern, not indicated on the map but seen on the imagery under magnification, is formed by an area of parabolic dunes west of the Auob River and east of Koes. Parabolic dunes also occur on the west side of the Nossob River, according to Grove (1969, p. 199).

The typical appearance of the parallel straight (linear) dunes north of the confluence of the Molopo and Nossob Rivers is shown on the aerial photograph (fig. 21) taken near Aranos. The sand ridges here are 5 to 8 meters high and 100 to 500 meters apart. Dune-spacing indices have been obtained from measurements of the imagery and are shown on the thematic map (fig. 17) for several places within the parallel straight dunes.

The southwestern slopes of the parallel straight dunes of the Kalahari are slightly steeper than the northeastern slopes, according to Grove (1969), and the crests are generally bare of vegetation. A strong similarity between the linear dunes of the Kalahari (fig. 2b) and the linear dunes of the Simpson Desert, Australia (figs. 2a, 11), has been noted by numerous geomorphologists. ERTS-1 imagery should provide a common data base from which comparative measurements of dune characteristics in the two widely separated deserts can now be made.

Features other than the dunes which can be identified on the imagery include interdunal clay pans, visible in more detail in the aerial photograph (fig. 21). These pans are commonly 1 kilometer or more in diameter and up to 15 meters deep (Grove, 1969). Many lunette dunes, too small to be seen on the imagery, are developed along the southern margin of the pans. Grazing plots, across which the dunes cross freely, are seen on the imagery. Surprisingly, the political boundary between South West Africa and Botswana shows clearly for more than 300 kilometers on the imagery, probably because it is fenced, and because agricultural and pastoral practices differ on the two sides of the fence. Another example of a political boundary observed on ERTS-1 imagery within the regions included in this project is that between the United States and Mexico, near Yuma, Ariz. (fig. 15).

Color of sand.--The color of the linear sand ridges in the Molopo-Nossob area ranges from red (2.5 YR/4/8) to yellowish red (5 YR/5/6); the quartz grains are coated with films of iron oxide (Grove, 1969). The sand forming sheets and streaks in the southwestern part of the desert is also red, as shown by the color exterior photographs of the Kalahari taken by the crews of Skylab (fig. 20 b, c).

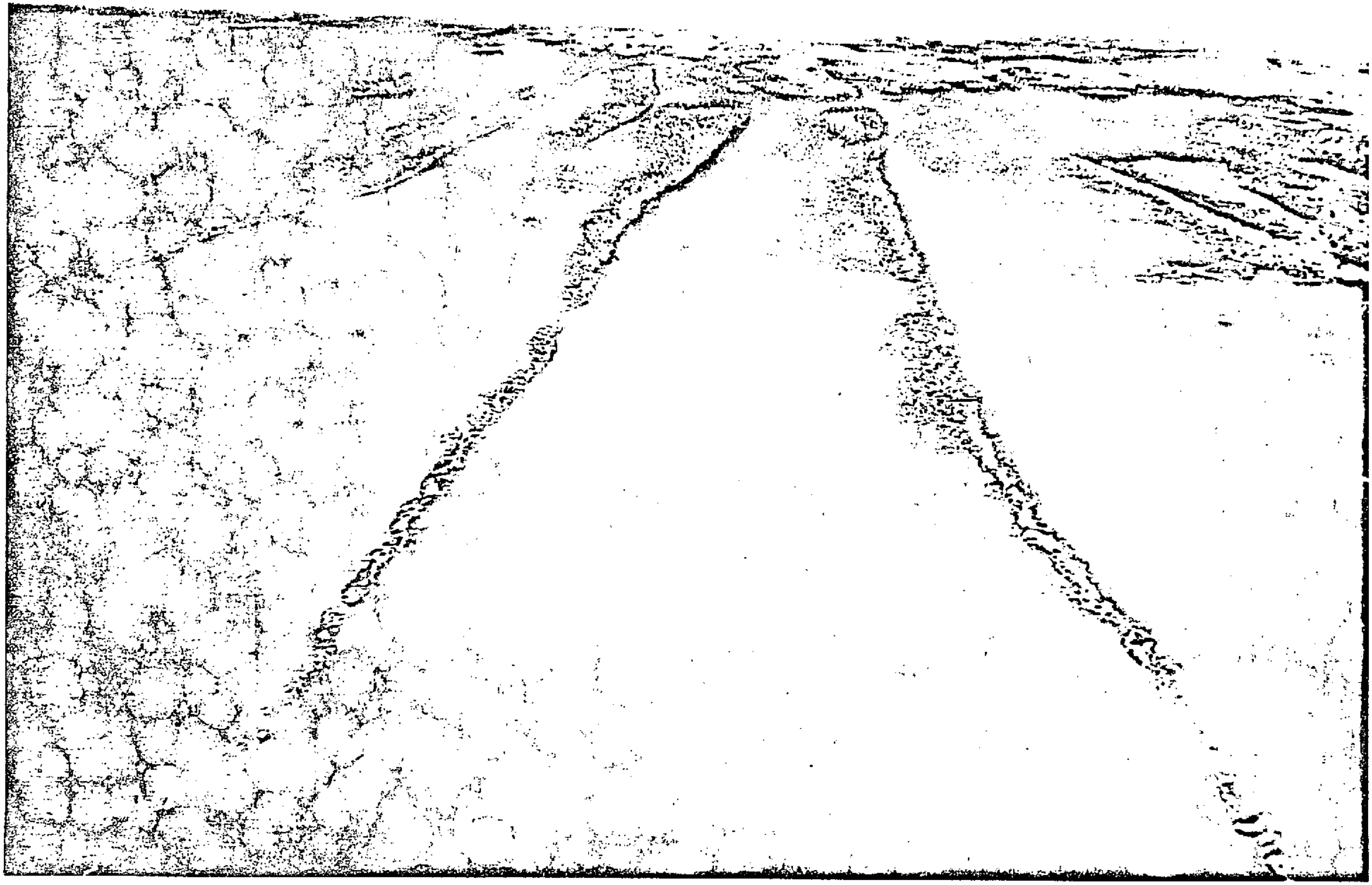


Figure 21. Aerial photograph of the Kalahari Desert, southern Africa, showing typical appearance of parallel straight (linear) dunes (photograph by H.T.U. Smith).

The false color of the Kalahari sand deposits as seen on ERTS-1 color imagery is golden yellow. Within the area occupied by the linear dunes, however, only the narrow crests of the dunes are yellow on ERTS-1 imagery after vegetation has begun to turn green following the seasonal rains. The remainder of the desert takes on a brownish hue (fig. 22). Although tufts of Eragrostis and Aristida sp. occasionally grow on these dune crests, the slopes support clumps of grass, shrubs, and trees up to 3 meters high, whereas trees up to 5 meters high (mainly Acacia giraffae and Acacia haematoxylon) grow in the interdune areas (Grove, 1969). The soils of the Kalahari Desert are weakly developed, brown to reddish-brown sand, sandy loam, gravelly sand loam to clay loam or clay, with calcrete and silcrete layers occurring in some areas (Grove, 1969).

Character of sand.--Between the Molopo River and the Orange River in the southeastern corner of the area shown on figure 13, linear dunes run parallel to the Koranneberg Range (off the map) and form Y junctions with the stems pointing south to southeast. These Y junction dunes are longitudinal features probably formed by northwest winds (Grove, 1969). In the same area, lee dunes (too small to show on ERTS-1 imagery) occur along the southeastern margins of clay pans. The linear dunes in this part of the desert are 10 to 25 meters high and occur about 300 meters apart. Grain size of the sand in these dunes averages 0.21 mm in diameter. The dune ridges are lightly vegetated, mainly along the crests, and small pans occur in the interdune areas. Rainfall in this area is recorded by Goudie (1969) as 17 cm per year.

Geographically distinct, arcuate sheets and streaks of eolian sand, south of the town of Roetfontein and west of the Nossob River, seem not to be vegetated on ERTS-1 imagery, and strike cross-country across bedrock structures and over drainages without being obviously affected by either. No background information has as yet been obtained for this region.

Precipitation data.--Rainfall in the Kalahari Desert occurs mostly in summer and is associated with convective showers and moisture from the Indian Ocean. This seasonality is pronounced and results in shifts of the 50--mm isohyet back and forth across the country, from east to west, as the rainy season waxes and wanes (Schulze, 1965). Rainfall also accounts for a brownish red hue on ERTS-1 color imagery (fig. 22).

Because the parallel straight dunes of the Kalahari Desert are ancient, stabilized types, modern wind regimes may not be related to their patterns and distribution. Also, considerable controversy exists over the kinds of wind regimes that produce parallel straight ("longitudinal") dunes of the type found in the Kalahari, the deserts of Australia, North Africa, Saudi Arabia (fig. 2), and elsewhere (McKee, 1966; Glennie, 1970; Folk, 1971, and others). Until further work is done both with the ERTS imagery and with ground-truth data, especially more structural studies of this type of dune, conclusions concerning the relationship of the parallel straight Kalahari dunes to present wind regimes are premature.

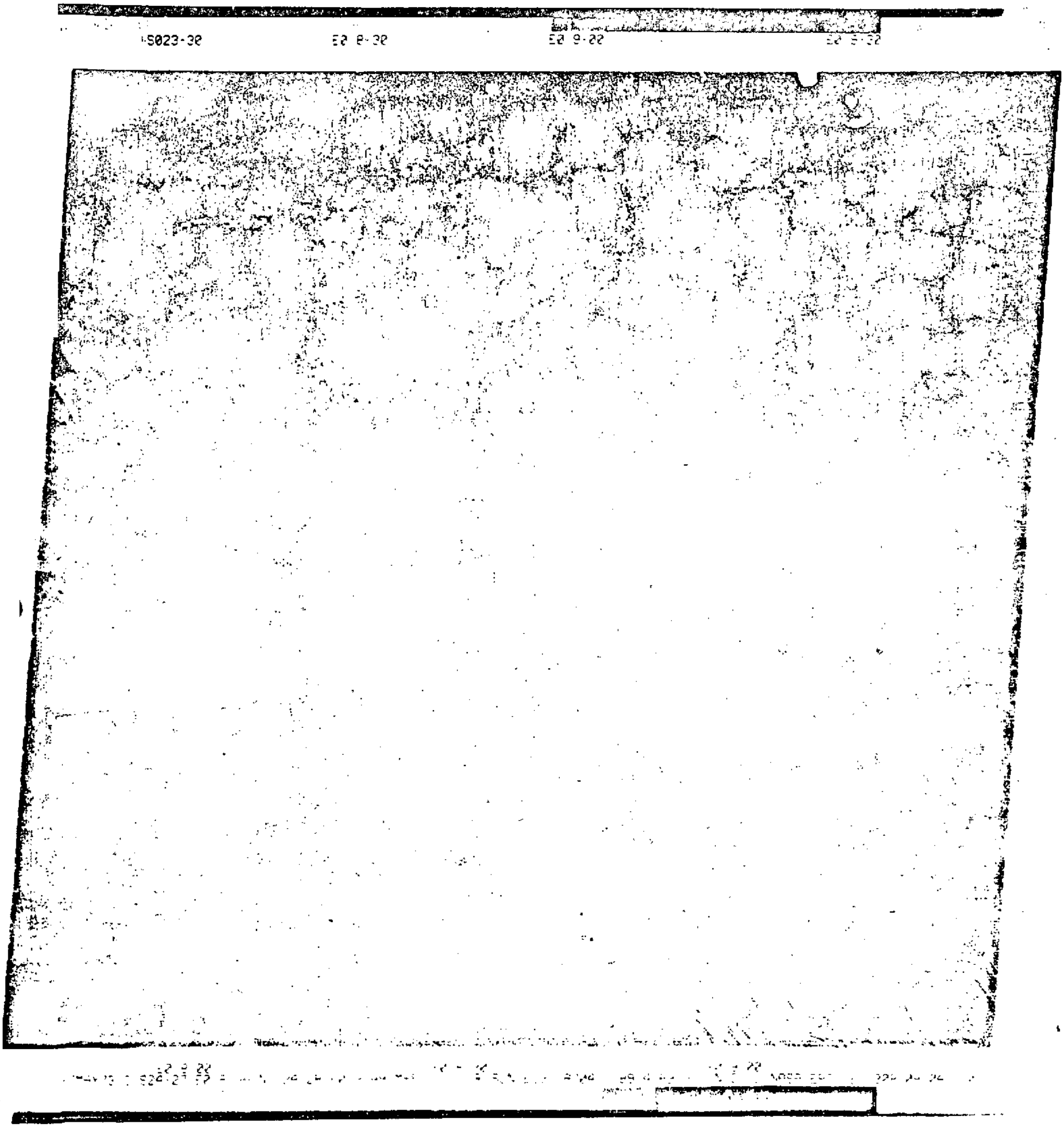


Figure 22. ERTS-1 imagery of Kalahari linear dunes showing changes in color as a result of vegetation in leaf following seasonal rain.
(EDC-010007)

Wind data.--Records of wind for the entire Kalahari Desert have been studied and reveal a pattern of counterclockwise (anticyclonic) circulation of potentially sand-moving winds. Wind roses for the area as shown on figure 13 illustrate the back part of this circulation, influenced mainly by the Indian subtropical high, or the extension of this high into the interior plateau (figs. 23, 24).

In the southern part of the Kalahari, which encompasses the test-site area of this study, the wind regime develops a pronounced bimodality. The Keetmanshoop wind rose (fig. 13) depicts an environment with considerable sand-moving potential expressed in near-perfect reversing modes. To the southeast, at Upington, bimodality is equally pronounced in winter and in summer, but energy is weaker in summer and the bimodality is angular. Summer winds come mostly from the southwest and winter winds mostly from the north.

The wind regime at Tsabong is bimodal, with the greatest amount of energy coming from the north. This situation favors the movement of sand southward into the drainage of the Molopo River, which is dry along most of its course. A similar situation exists at Mariental, where also the wind regime is bimodal but favors a net movement of sand to the south or south-southwest.

3. India-Pakistan; the Rajasthan-Thar Desert

Extent and character.--The Rajasthan-Thar Desert extends westward from the Aravalli Range of northwestern India to the vegetated flood plain of the Indus River in Pakistan, and from the Rann of Kutch, which borders the Arabian Sea on the south, northward into the Punjab (fig. 25). Physiographically, the desert is a vast area of low hills and sand dunes, lying upon sandy alluvium which, in turn, is underlain by limy concretionary beds.

Sand sources and movement.--The sands of Rajasthan-Thar Desert are believed to have been derived in part from weathered materials from the Aravalli Range, in part from deflated flood-plain deposits, especially along the Indus River Valley, and in part from sands deposited along former shorelines (Seth, 1963).

Overgrazing by animals and poor agricultural practices by man have accentuated already existing desert conditions in the Thar Desert. Overgrazing has stripped the protective cover of vegetation from once-stabilized dunes. Farming is attempted on the slopes of dunes, thus exposing them to erosion by wind and occasional torrential rain. Thus exploitation continually provides new sources of sand which are exposed and drifted by the winds of the Thar Desert.

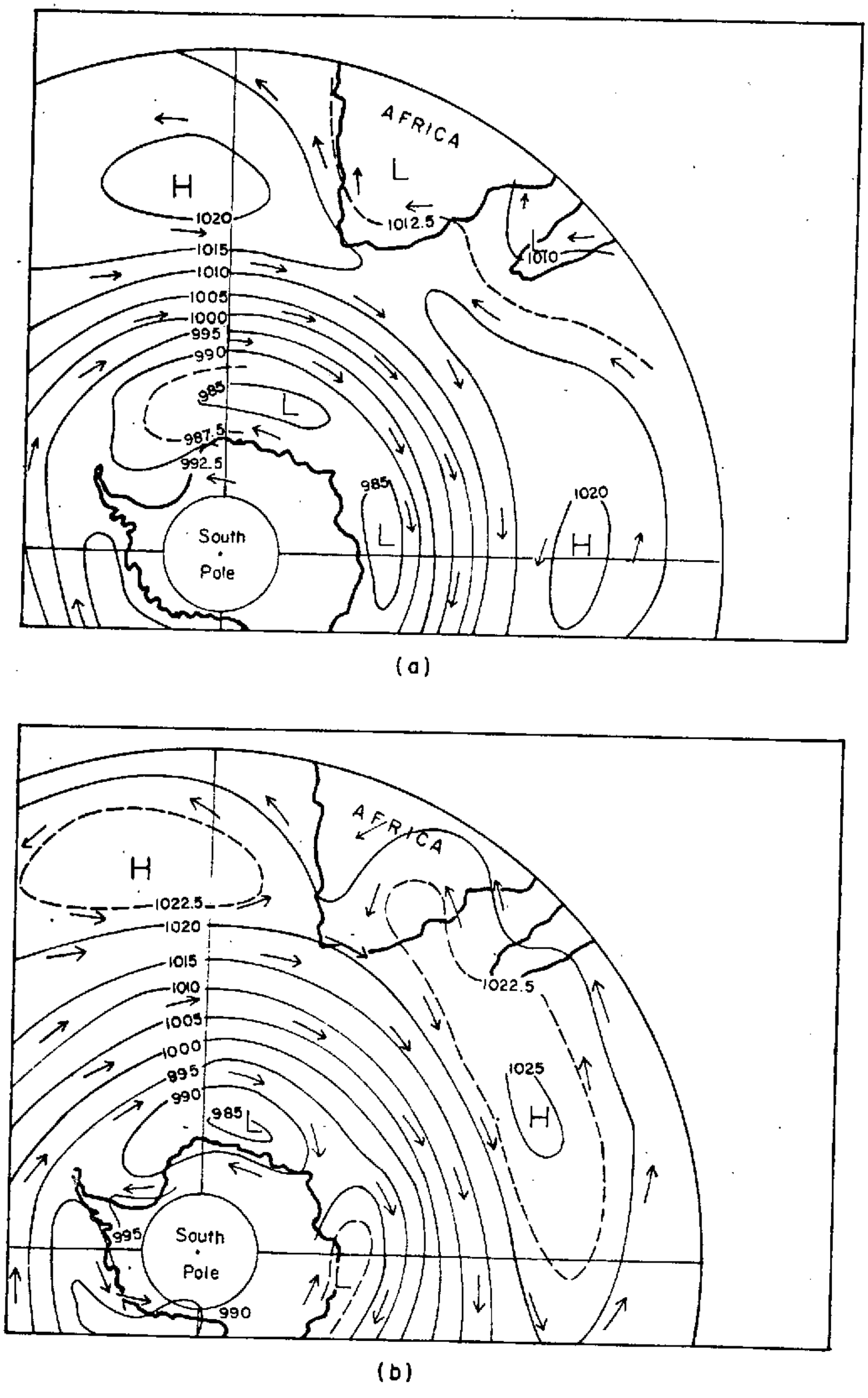


Figure 23. Sea level mean pressure map (in mb) of part of the southern hemisphere: (a) summer; (b) winter (from Van Loon, 1961).

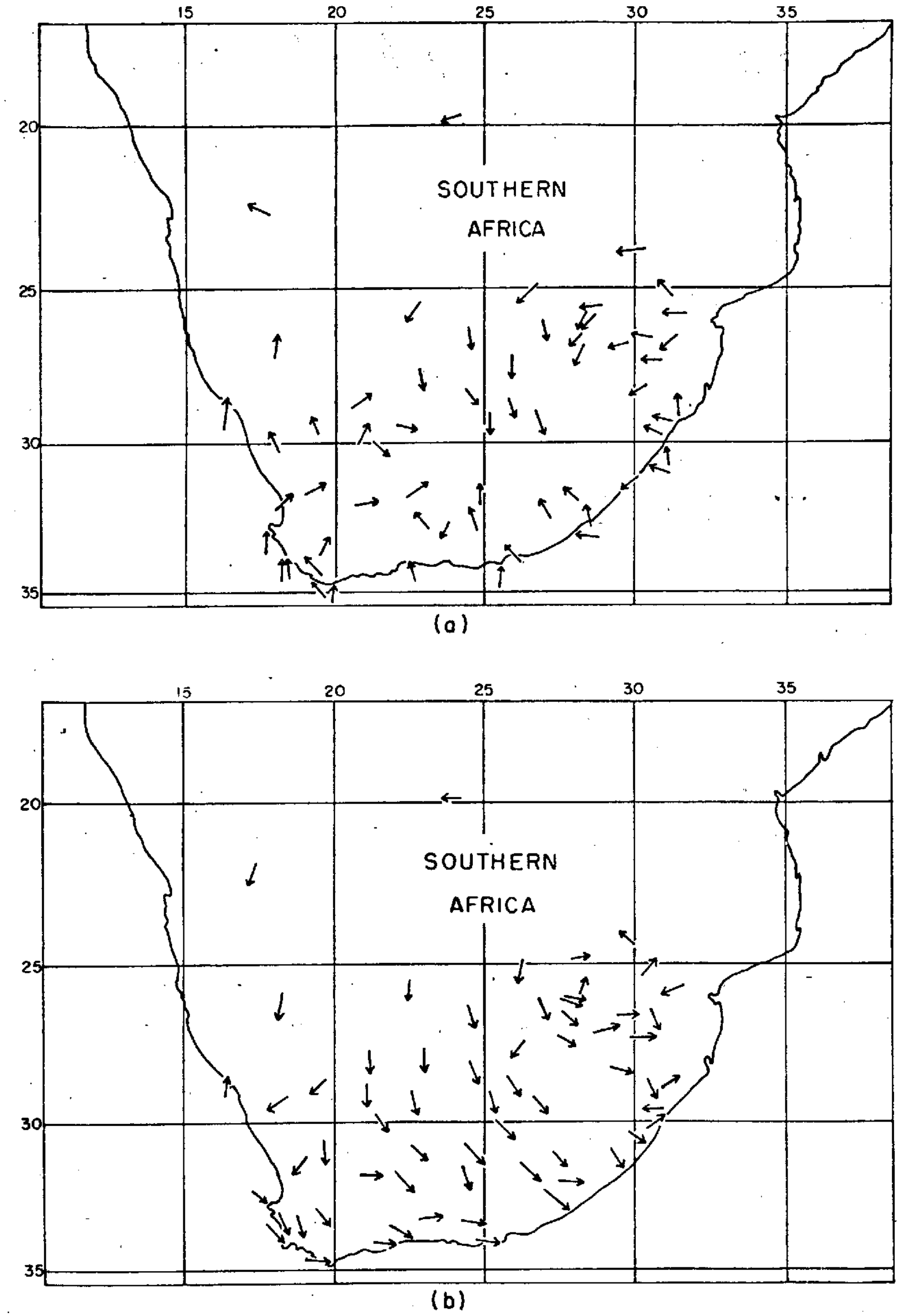


Figure 24. Wind resultants for southern Africa: (a) summer; (b) winter (from Schulz, 1965).

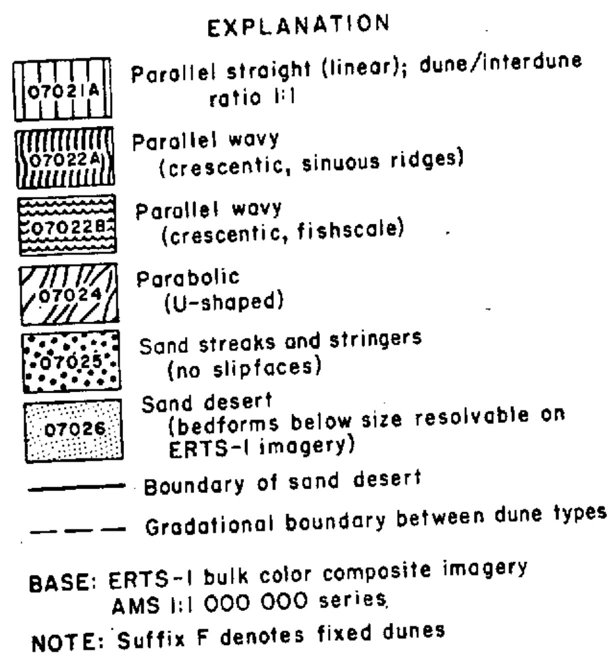
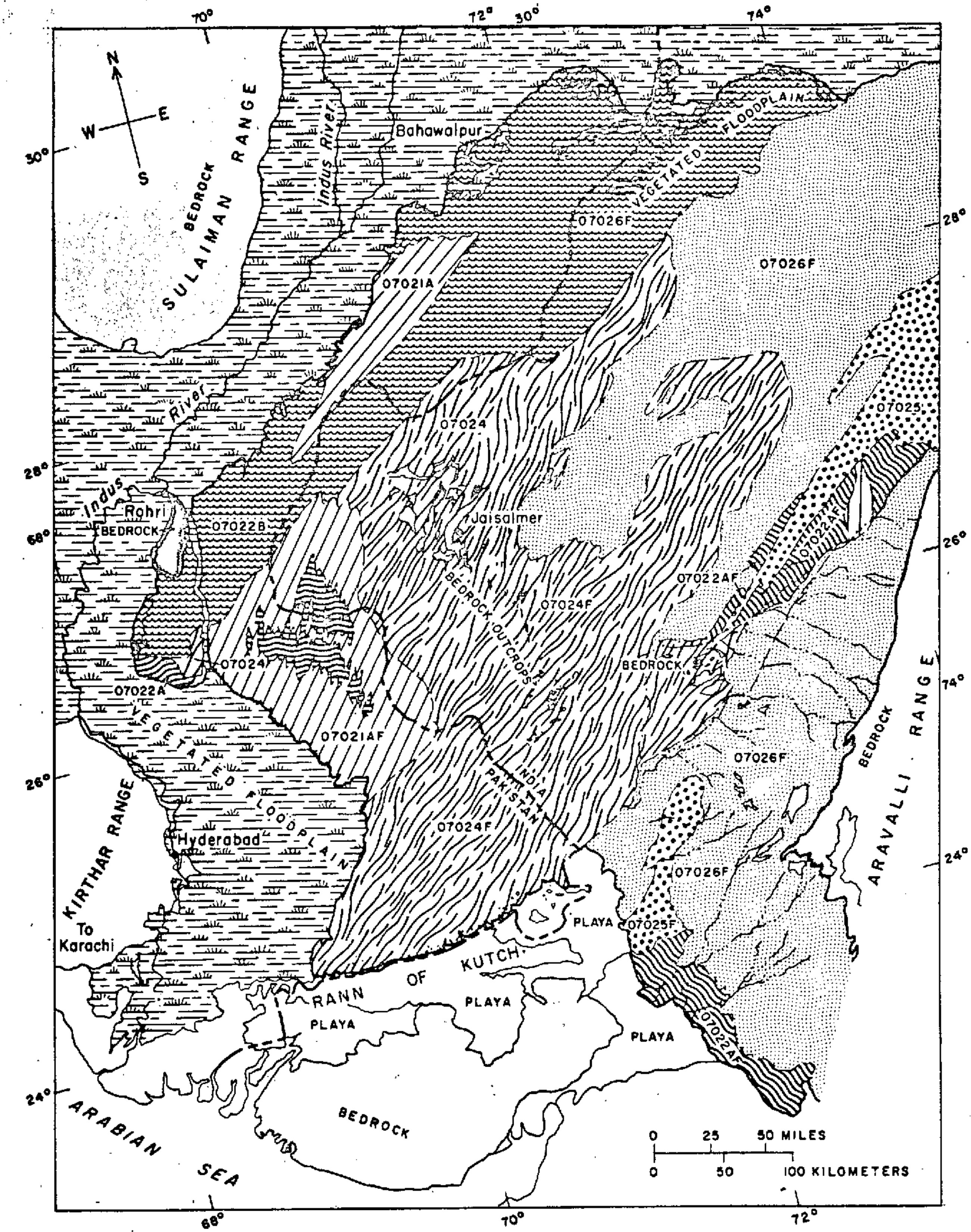


Figure 25. Thematic map showing patterns and distribution of eolian sand in the Rajasthan-Thar Desert of India and Pakistan.


70°
72°
30°
74°
N
W
E
S
30°
28°
26°
24°
68°
70°
72°
74°
BEDROCK
SULAIMAN RANGE
Indus River
Bahawalpur
VEGETATED FLOODPLAIN
07026F
07021A
07026F
07025
07024
Indus
Rohri
BEDROCK
07022B
Jaisalmer
07022AF
07022AF
BEDROCK OUTCROPS
07024F
07024
BEDROCK
07022A
VEGETATED FLOODPLAIN
07021AF
INDIA
PAKISTAN
07026F
BEDROCK
ARAVALLI RANGE
KIRTHAR RANGE
Hyderabad
07024F
07026F
To Karachi
PLAYA
07025F
RANN OF KUTCH
PLAYA
PLAYA
PLAYA
07022AF
ARABIAN SEA
BEDROCK
0 25 50 MILES
0 50 100 KILOMETERS

In several areas of the Thar, notably in Punjab and western Uttar Pradesh, windblown sand is encroaching on fertile, cultivated land at a rate of up to 50 square miles (80.45 km) each year (Seth, 1963; Raheja, 1962). This sand movement has been a source of concern to the Indians for several decades. The desert is reportedly advancing "north-eastwards, in a great convex arc through Multan, Montgomery, Ferozepur, Bhatinda, Bhiwani, Aligarh and Kasganj***[and] there is another area of deposition between Phalodi and Jodhpur. The deposits are taking place in low-lying areas through the funnel between Barmer and Jaisalmer and along the sources of the Sutlej, old Ghaggar bed and between Loharu and Shiwani" (Seth, 1963, p. 449-450).

Types of dunes.--Scientists at the Central Arid Research Institute at Jodhpur have made local studies of dunes in the Indian (Rajasthan) part of the desert since 1959, when the Institute was established to develop methods for control of sand and improvement of the desert environment for human habitation. Their studies have produced a threefold classification for dunes of the Rajasthan Desert: (1) old, dissected dunes and sand shields; (2) stabilized parabolic, longitudinal, and transverse dunes; and (3) active, small-scale barchan, shrub coppice, and low longitudinal ridges. Unanswered questions remain, however, regarding the definitions of these terms, which carry genetic implications, and regarding the correlation of these terms with the dune types seen on ERTS-1 imagery.

Dunes of the first category have been described from the Jodhpur region as old, well-vegetated, dissected dunes and shields composed of fine-grained sand, their flanks cemented by lime nodules 20-50 mm in diameter, and their surfaces covered by lime concretions 0.5-3.0 mm in diameter. Such features probably have been mapped from the ERTS imagery as falling in the categories of sand streaks and stringers without slipfaces and sand forms below a size resolvable on ERTS-1 imagery, with the suffix "F" indicating that the sand forms are fixed in place. Ground checks will be necessary to determine whether the classification derived from the imagery truly fits the ground-based classification made by members of the Institute.

Numerous ancient dunes occur in parts of Gujarat and eastern Rajasthan along the western slopes of the Aravalli Range. These dunes occur 150-400 km east of the present margin of major active dunes--indicating that the desert was formerly much more extensive, presumably during the late Pleistocene. Although heavily vegetated, these ancient dunes are deeply gullied, and show strong weathering profiles, indicating two major phases of dune accumulation, separated by a zone of marked weathering. Remnants of the early period of dune activity occur as small knobs and protuberances showing through later accumulations of calcreted sand. The older dunes are dark-brownish-red (7.5 YR/5/8) in contrast to the overlying whitish calcreted dunes. These, in turn, are overlain by yellow sands of Holocene age (Goudie, Allchin, and Hegde, 1973).

Dunes of the second category comprise the majority of forms in the Rajasthan Desert and their patterns dominate the ERTS-1 imagery (fig. 14). These are stabilized parabolic, longitudinal (parallel straight) and transverse (parallel wavy) dunes which coalesce to form dune complexes that are readily mappable from the ERTS imagery. Stabilization of the dunes of the second category took place under conditions wetter than at present, according to Verstappen (1968), and they are better stabilized than would be expected under the present climatic conditions in the region.

Parabolic dunes have been described (McKee, 1966), in general, as fixed by vegetation. However, observation of vegetation patterns on the repetitive ERTS-1 imagery (fig. 18a, b) shows less vegetation than might be expected on this type of dune; also vegetation occurs in areas other than those containing a single type of dune pattern. Local studies of dunes of the second category have been made by Indian workers at Jodhpur, Bikaner, and Jaisalmer. Parabolic dunes in the Jodhpur area have coalesced into groups of 15-20 and formed continuous chains that range in length from 1 to 3 km, attaining heights of 30-70 m (Singh, Ghose, and Vats, 1972). Study of the ERTS imagery indicates that coalescing of the dunes proceeds far beyond the scale that local workers describe, for parabolic dune complexes up to 40 km in length are common, especially west of Jodhpur in the central part of the desert.

In the Jaisalmer area, dunes similar to those near Jodhpur have been described and measurements have been given by the Indian workers, although, from the average size (length 384-1,152 m; width 384-1,024 m), it seems that only individual horns of the parabolic dune complexes were measured. Similar comments could be made about the so-called "longitudinal" and "transverse" dunes of the second category; indeed, parallel straight and parallel wavy forms, both fixed and active, can readily be seen on the imagery, but their occurrences and sizes have little or nothing in common with published accounts of the dunes.

Apparently, from ground level, the local workers are unable to recognize the regional patterns of dune complexes that are so noticeable on ERTS-1 imagery. For example, at Bikaner, in the northeast part of the Rajasthan Desert, so-called parabolic dunes are, according to local workers, the oldest sand form; they are coalesced and occur in chains 2-3 km apart, range in height from 10 to 45 m, and are oriented southeast-northwest. However, this information is not apparent from the imagery, particularly the orientation, which is opposite to that of the parabolic dune complexes we have observed elsewhere in the desert. Possibly the so-called parabolic dunes of the Bikaner region are not comparable with the parabolic dune complexes observed on ERTS-1 imagery, for close study of the Bikaner region reveals only vegetated sand, with no sand forms large enough to be identified as dunes.

Thus, information regarding color, vegetation types and abundance, water-table position and water quality, sand and soil samples, and climatic data are available from the local studies of small-scale dunes and parts of dune complexes. Mostly these data cannot be applied to generalizations of this study, and so fieldwork specifically designed to interpret features of the ERTS-1 images will be necessary in order to understand the large-scale development.

Dunes of the third category are the active, small-scale barchans, shrub coppice, and longitudinal ridge dunes that are far too small to be seen on ERTS-1 imagery, but that apparently results from liberation of sand from the fixed dunes as a result of poor grazing and agricultural practices. The active dunes in the Jodhpur region are considered to be "the perennial source of sand that affects the agriculture, settlements, roads and railway lines" (Singh, Ghose, and Vats, 1972, p. 53). Fresh sand also commonly occurs on top of many of the older, stabilized dunes of the Rajasthan Desert.

Dunes of the first two categories generally are cemented and stabilized and are formed upon a substrate of old alluvium, which is in turn underlain by an impervious limy concretionary zone, according to reports of Indian workers. These conditions cause water to be concentrated in the lower slopes of the dunes, which may explain the presence of great numbers of linear ponds between the dunes along the vegetated floodplain of the Indus River (fig. 14).

Only 10 percent of samples analyzed from ground water of the Bikaner region in India were nonsaline (Roy, 1969). The water table in that area ranges from 13 to 130 m below the surface. Soil salinity of the Rajasthan Desert is generally high, and soils occur only on the slopes of hills and along stream and river valleys. The shrubs (*Calligonum polygonoides*, *Haloxylon salicornicum*) were found by Roy (1969) thriving on the dunes in the Bikaner region, but are in great demand as fuel. *Acacia* sp. and *Prosopis* sp. grow both on the dunes and in the interdunal plains.

Color of sand.--Unlike dunes of the other middle-latitude deserts being observed on ERTS imagery, the Rajasthan-Thar dunes are not bright yellow on the ERTS-1 false-color images, and in fact, have a definite bluish cast. These dunes apparently do not have the bright red true color of dunes in many other deserts, as suggested in the literature and confirmed by aerial and Skylab photographs. One possible explanation for this anomaly is that the Rajasthan dunes are partly cemented by a calcareous cement. Oxidation of iron compounds in dune sands does not take place in the presence of a calcareous cement, according to Glennie (1970). Whatever the cause, the Rajasthan-Thar dunes lack the deep red coloration which produces the characteristic yellow color common to most eolian sand on ERTS-1 false-color imagery.

Precipitation data.--Ninety percent of the total precipitation in the Rajasthan-Thar Desert occurs during the summer (June-September) southwest monsoon season; some moisture is precipitated by passing midlatitude cyclones in the northern part of the desert. This concentration of rainfall into one season results in other periods of extreme aridity, particularly during the hot months of April and May. Furthermore, precipitation varies regionally within the desert, from 300 mm per year, which is sufficient to support grasses and scrub vegetation, near Jodhpur and Bikaner, to less than 100 mm in the desert east of the Kirthar and Sulaiman Ranges in Pakistan. (100 mm rainfall per year is considered the minimum necessary to sustain vegetation.)

A trend of increasing variability of annual precipitation occurs from east to west across the Rajasthan-Thar Desert, and so those areas near the Indus River flood plain that receive the least total rainfall also suffer from the greatest fluctuations in total rainfall (Pramanik, 1952; Rao, 1958). Most of the active dunes seen on the imagery and shown on the map (fig. 25), therefore, are located in this region of greatest environmental stress, along the western edge of the desert. The general lack of rainfall in that region also may explain the sharp demarcation on the ERTS-1 imagery of the boundary of the dunes, which is at the very edge of the Indus flood plain. This area of least rainfall contrasts sharply on the imagery with the areas of vegetated sand near Jodhpur on the wetter eastern margin of the desert.

The Rajasthan-Thar Desert seems to be getting progressively drier, according to some investigators (Seth, 1963), and this desiccation trend has produced visible changes within historical time. A shortage of 7 in. (18 mm) of rainfall at a place that normally receives only 10 in. (25 mm) per year is a disaster, whereas a similar shortage in a place that normally receives 50 in. (127 mm) might pass unnoticed (Pramanik, 1952). On the other hand, extensive fields of parallel wavy and parallel straight fixed dunes to the north, east, and south of the Jodhpur area are apparent on the ERTS imagery. These dune fields, designated 07022AF and 07021AF on the map (fig. 25), are now barely visible on the imagery beneath vegetation and soil, yet in the past the region they occupy may have been more arid in order for such dune patterns to have formed.

Much of the rain that falls on the Rajasthan-Thar Desert is lost by evaporation. A comparison of annual precipitation with annual potential evapotranspiration for the desert results in an average annual water deficit in excess of 1,000 mm (Kayane, 1971).

Wind data.--The flow of surface winds in the Rajasthan-Thar Desert tends to be from either southwest or northeast, depending upon the season, with local variations attributable to topographic barriers. Surface flow is related to the position of the Intertropical Convergence Zone (I.C.Z.), a region in the atmosphere of moist, converging air which shifts position seasonally (Das, 1968, p. 3). This zone is located south of the desert during winter months, but shifts northward during summer in response to intense solar insolation on the Asiatic landmass.

The results of shifts in the I.C.Z. are analogous to the diurnal alternation of airflow due to heating of land near the seashore, as observed along the coast of South Africa. Thus, surface flow in summer is from the sea to the land as the result of a thermal low inland, and in winter is from land to sea because of cooling and subsidence of large air masses over the continental areas. The existence of an I.C.Z., however, is discounted by Ramage (1971, p. 132), who attributes circulation changes to the development of a low-level heat trough at about lat. 25°N. during the months of June through September, rather than to migration of the I.C.Z. some 15° or 20° northward.

Although surface circulation during the summer monsoon is mostly from southwest to northeast, the monsoon proper advances over the Indian subcontinent from southeast to northwest and withdraws along the same path. Thus, the effects are felt gradually from southeast to northwest across the Rajasthan-Thar Desert, but simultaneously from southwest to northeast. Rainfall and wind strength and duration vary considerably within this framework, but some consistency can be identified. Generally winds are strongest in the south, particularly during the southwest monsoon, diminishing in strength as one proceeds northeastward from Bhuj to Ganganagar (fig. 26). On the basis of available information, wind circulation from the northeast (winter) is weak and does not account for the movement of much sand.

A significant relationship exists between the pattern of winds and the pattern of rainfall in the Rajasthan-Thar Desert. The time of maximum wind speeds and the maximum amounts of precipitation do not coincide, as the records for Jaisalmer and Barmer confirm (fig. 27). Whereas rainfall is associated with sand-moving winds at Jaisalmer and with peak winds at Barmer from mid-June through September, a period also exists from late April to mid-June during which winds at both stations are approaching maximum monthly average speeds with no coincident precipitation. This circumstance seems to result in a drying out of the land surface by evaporation, coincident with a likelihood of strong winds. In brief, a sand-moving season occurs during the time of year when both stations are already subjected to other environmental stress. Average monthly wind speeds at Barmer are about half those at Jaisalmer; thus, other factors being equal, efforts to stop the movement of sand at Barmer might be more successful than at Jaisalmer.

Wind roses for most localities in the Rajasthan-Thar Desert (fig. 14) reveal a southwest-northeast bimodality that greatly favors the southwest component of the wind regime. An analysis of the energy structure of this southwest component, using observations from the south-southwest, southwest, and west-southwest during the month of June along a line from Bhuj to Ganganagar (fig. 26), reveals the following: (a) a diminution in a northeast direction of the frequency of southwest winds from 80 to 60 percent of total occurrence; (b) an increase from southwest to northeast in the number of calms from 1 percent at Bhuj to 16 percent at Ganganagar (off the map near the northern edge of the desert); and (c) a decrease in the percentage of observations during which sand-moving winds occurred, from 68 percent at Bhuj to 12 percent at Ganganagar, with a corresponding increase in the representation of low-speed winds from 11 percent at Bhuj to 29 percent at Ganganagar.

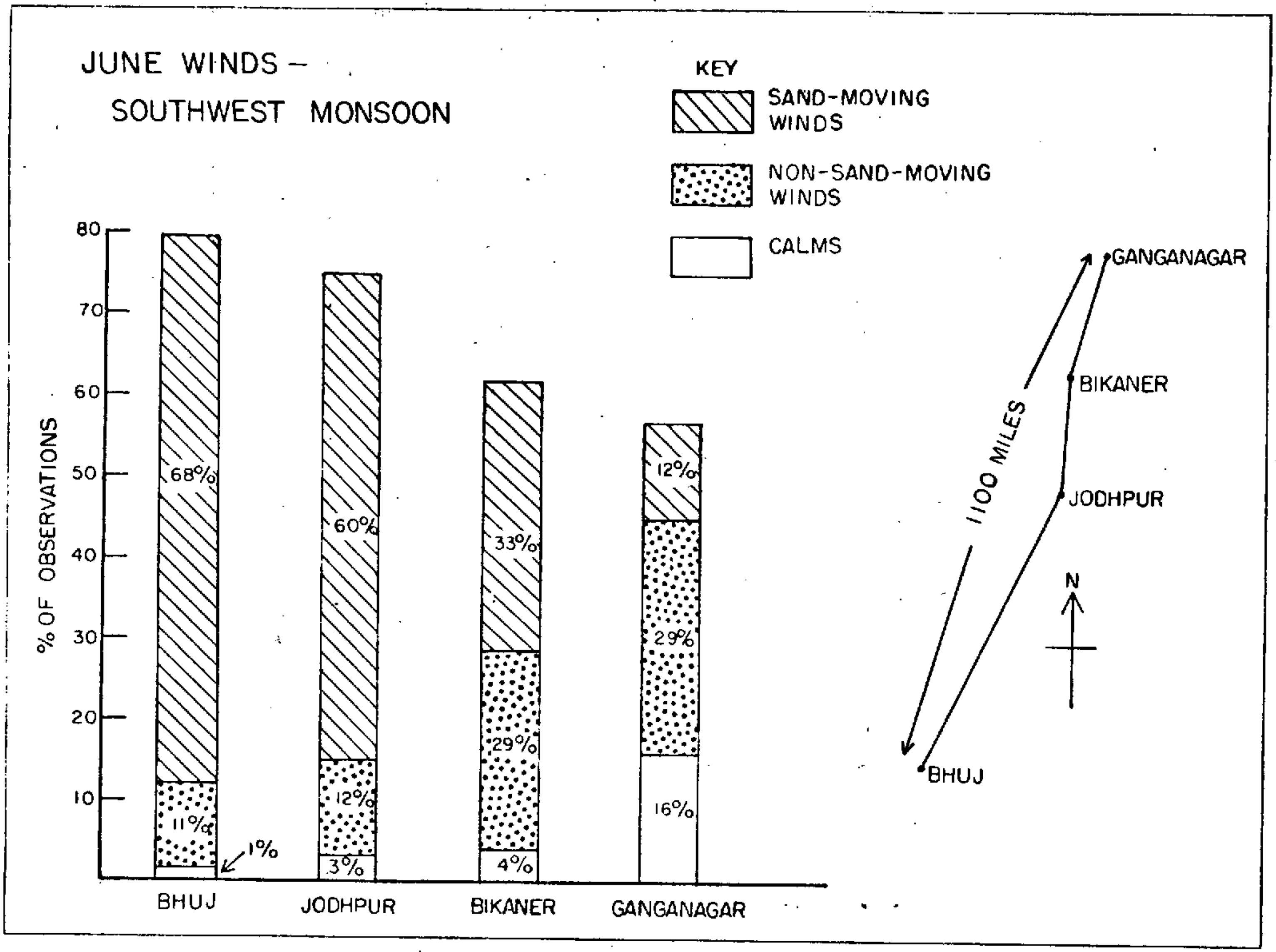


Figure 26. Changes in wind energy from southwest to northeast across the Rajasthan-Thar Desert during the southwest monsoon season (prepared by Steven Fryberger).

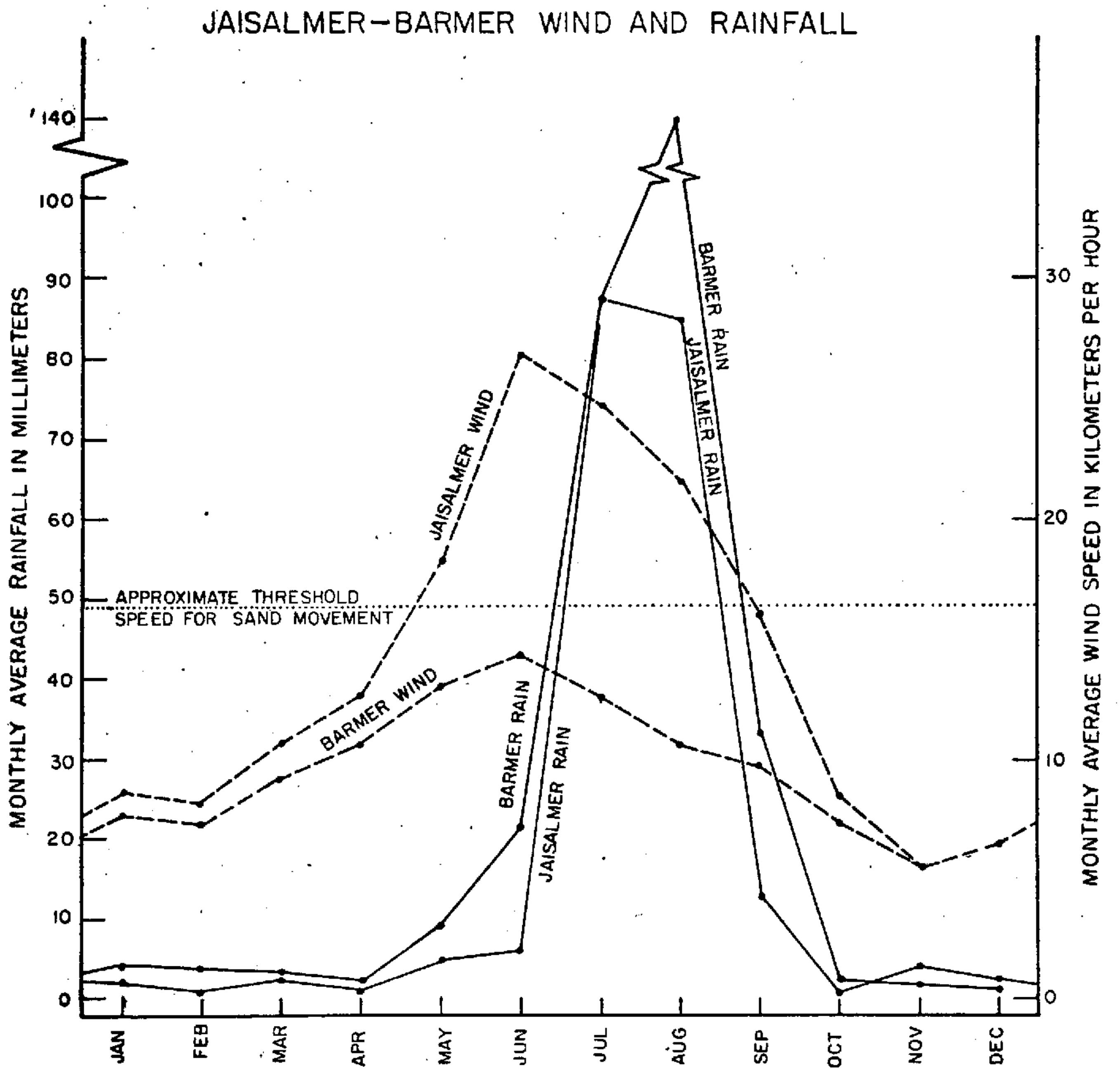


Figure 27. Coincidence of wind and rainfall patterns at Jaisalmer and Barmer, Rajasthan-Thar Desert (prepared by Steven Fryberger).

The information cited above indicates that although the onset and termination of the southwest monsoonal flow occur at approximately the same times across the desert, considerably more energy is available for sand movement and for evaporation of the surface moisture in the southern part of the desert than farther north. Observations also indicate that the environmental stresses brought on by a drought in the southern part of the desert would be intensified by the strong, drying winds that blow there, particularly during late May and early June. It follows that dune patterns should be most strongly developed in the southern part of the desert, and ERTS-1 imagery shows that such is actually the case.

The sand-moving potential of the winter northeast monsoon is minimal compared to that of the southwest monsoon, especially because the energy of the southwest monsoon is at work partly during the dry season, whereas the winter monsoon occurs after the summer rains. Wind roses for Jodhpur reveal some sand-moving potential from the northeasterly direction during the winter monsoon, but this is small compared to the potential of the opposing southwest wind.

Wind roses other than those described, but based on direction data only, reveal a pattern that conforms well to a monsoonal circulation. Some anomalous directional features occur and are not as yet understood, but these may result from topographic effects. In general, trends of the major dune patterns (parallel straight, parabolic, and parallel wavy) as shown on the imagery are in good agreement with the dominant southwest wind regime.

Because the Rajasthan-Thar Desert may be undergoing increasing aridity, dunes that were fixed during a former, wetter period apparently are now subject to reactivation when sufficient stress occurs in the form of drought or high winds. The patterns of vegetation visible on ERTS-1 imagery may be a key to identifying those areas that are most capable of being protected from degradation by a reseeding and fencing conservation program.

4. Southern California; the Algodones sand sea

Extent and character.--The Algodones sand sea (figs. 15a, 19) forms an elongate northwest-southeast belt of continuous sand that extends some 75 kilometers in length and up to 10 kilometers in width, from near the Salton Sea in California southeastward to and across the international border into Sonora, Mexico, where it ends abruptly at the edge of the irrigated flood plain of the Colorado River. The dunes lie within a structural depression called the Cahuilla Basin, which includes the Imperial Valley and the Coachella Valley. The surrounding mountains are composed of crystalline igneous and metamorphic rocks of Precambrian to Tertiary age.

Much of the Cahuilla Basin is below sea level and its lowest parts are now occupied by the Salton Sea. From the late Pleistocene until perhaps a few hundred years ago, the basin was intermittently occupied by Lake Cahuilla (Lake LeConte), a large forerunner of the Salton Sea. Lake Cahuilla was about 160 kilometers long, 56 kilometers wide, and up to 100 meters deep at its maximum extension; its former levels are marked by extensive shoreline deposits, 13 to 20 meters above present sea level, particularly along the northeast side of the basin.

Types of dunes.--The term "mega-barchan" was coined by Norris and Norris (1961) to describe the dominant pattern of the dune forms they studied in the Algodones field. Their description of the dunes is summarized as follows: in plan, these huge crescentic dune complexes are up to 87 meters high and commonly a mile or so wide from horn to horn. In the northern part of the field, dunes are overlapping, but southward they become more and more separated by interdune hollows. The dune mass as a whole is characterized by well-developed slipfaces that are transverse to the trend of the sand belt, and which are progressively more prominent southward.

The western boundary of the central and southern parts of the Algodones field is marked by a series of nearly parallel ridges some 170 to 200 meters high, whose trend parallels the trend of the sand belt. These ridges are superimposed on the main dune mass. The westernmost ridge is most prominent, extending for 12 to 14 kilometers in a continuous line some 270 meters from the outermost margin of the dune field. The inner ridges are progressively less distinct toward the center part of the field, where they blend into "mega-barchans."

Other types of dunes occur in the general region west of Yuma, Ariz., including the well-known barchan dunes southwest of the Salton Sea, but individual dunes in this area are too small to be seen on ERTS-1 imagery.

Interdune areas.--Several observations on the nature of the interdune surfaces in the Algodones dune field have been recorded (Norris and Norris, 1961). Interdunal areas occur mainly in the central and southern sections of the Algodones, and are progressively wider and better defined southwards. The interdune surfaces are flat-floored or gently sloping depressions composed of sandy silt and scattered pebbles up to 5 cm in diameter. They are bounded on the northwest by the nearly continuous slipfaces, 50-65 meters in height, of the megabarchans. The southeastern sides of the interdunal areas are bordered by the gentle back slopes of dune complexes. In some places sand ridges have developed across the slipfaces of these complexes and into the hollows; these ridges may be 1-5 meters high and up to 500 meters long. Such sand streaks occur most typically in the smaller interdunal areas.

Within the large interdune hollows, sand streaks tend to separate downwind to form embryonic barchans (Norris, 1966). The sand streaks generally develop near the ends of megabarchans and so the smaller barchans are usually clustered on the sides of the hollows. Some of the largest hollows, towards the extreme southern end of the Algodones, are completely sand free; others are occupied by swarms of small barchans, which are 1 to 2 meters high and 7 to 33 meters wide. Near the United States-Mexico boundary the hollows form double or triple longitudinal series along the axis of the dune field (Norris and Norris, 1961). The average interdune width in the southern part of the Algodones is 1,300 meters (Norris, 1966, p. 296). On the basis of a rate of movement of 11 meters per year, the smaller barchans are probably no older than 40 years.

Comparable dune types in other regions.--Norris and Norris' description (1961) of the Algodones Dunes is in good agreement with our classification of the sand patterns discernible in that area on ERTS-1 imagery, with two exceptions: (1) the linear ridges that they describe as occurring along the western margin of the dune field cannot be seen on the imagery; and (2) the overall parallel wavy pattern formed by the megabarchans, clearly seen on ERTS imagery, is not mentioned by Norris and Norris (1961) and may not have been apparent from their vantage point. Clearly, the major pattern produced on ERTS images by the coalescing megabarchans of the Algodones is similar to the overall pattern produced by parallel wavy dunes in Nebraska, in the U.S.S.R., in the Sahara, and in Saudi Arabia. The pattern formed by the Algodones Dunes, however, is limited by the narrow confines of that field between topographic barriers.

Color of sand.--The color of the sand in the Algodones Dunes was described as light reddish brown by Norris and Norris (1961), who noted that the dunes appear to be slightly darker in the southern part of the field than in the northern part. This color change, though subtle, is also noticeable on the ERTS-1 color imagery.

Between 25 and 60 percent of the sand grains are coated with iron oxide, both on exposed surfaces and in pits on the grains. This coating occurs on both angular and rounded grains, and in areas where the dunes are active as well as where they are stabilized (Norris and Norris, 1961, p. 612).

In contrast to the Algodones Dunes, the relatively small dunes in the Coachella Valley to the north are composed of grayish-white to white sand on which staining by ferric oxide is generally absent. These dunes are active and are receiving sand from streams draining the adjacent mountains.

The only part of the Algodones field receiving large amounts of new sand is the northernmost end, near Mammoth Wash. The sands introduced into the field by way of Mammoth Wash are grayish white, whereas most of the Algodones Dunes have a reddish appearance.

Sand sources and character.--The main source of sand in the Algodones field is a matter of dispute. This sand is believed by Merriam (1969) to have been derived chiefly from deflated Colorado River delta sediment of Cenozoic age. The delta sediment "***underlies much of the dune area and extends westward over hundreds of square miles" (Merriam, 1969, p. 533). Samples collected by him throughout the area are said to be similar in mineral composition and texture to sand in the delta sediments. Both dune sands and delta sediments have potash feldspar in excess of plagioclase (3:1), abundant volcanic fragments, detrital calcite and dolomite, and detrital Cretaceous Foraminifera.

Some other workers in the Cahuilla Basin area (Brown, 1923; Norris and Norris, 1961; McCoy, Nockleberg, and Norris, 1967) believe that sand of the Algodones field was derived primarily from the beaches of Lake Cahuilla, and that this beach sand was derived in turn from crystalline bedrock carried by the Whitewater River and other streams which enter the Salton Basin.

An attempt to trace the source of sand in the Algodones Field by comparing its composition to that of sands from the Coachella Valley and from the beaches of Lake Cahuilla was made by Norris and Norris (1961), but their results were inconclusive.

Vegetation data.--Widely scattered clumps of creosote bush (Larrea glulinosa), along with tiny annuals and grasses which sprout after infrequent rains, occur within the interdune areas. Dark patches develop on the interdune floors on the windward sides of many of the small barchans (Norris, 1966). These dark areas are similar in size and shape to the adjacent barchans, and seem to have been formed under the barchans and only recently uncovered as the dunes advanced. Except for dead creosote bushes, the dark patches lack vegetation and are deficient in sand cover. Because seeds, covered by barchan dunes during a period of rainfall, would fail to germinate, these areas probably "coincide with the dune's position at the time of the last substantial late winter or early spring rain" (Norris, 1966, p. 297).

Sand texture data.--Sands from several California dune fields have been compared by Norris (1966) as shown on table 2. Comparative sizes and sorting of the grains illustrate the type of ground truth which should be obtained for many localities before definitive conclusions can be attempted regarding the origin of sand, age of dunes, and relation to other dune fields on a global scale.

Table 2. Texture of sand in some southern California dune fields (from Norris, 1966, p. 298)

Dune field	Sand size median diameter (mm)	Sand sorting Trask sorting coefficient
Algodones dunes------	0.23	1.13
Tule Wash barchan----	0.29	1.26
Salton dunes---------	0.26	1.41
Kelso dunes----------	0.23	1.22
Thousand Palms-------	0.19	1.94
Borrego Valley-------	0.18	1.69

Precipitation data.--Average annual precipitation at Yuma, near the Mexico-Arizona border, is about 55 mm per year, and some adjacent areas receive even less. The Algodones dune field supports little or no vegetation. Hot, dry winds during most of the year create an evaporation rate which exceeds precipitation by a factor of ten. Vegetation occurs in the mountains adjacent to the Algodones Dunes in southern California, presumably due to runoff. Irrigation of the dry valley floor by diversion of Colorado River water, through canals both north and south of the international border, accounts for the vegetation prominent on ERTS imagery of this area. Away from the water provided by irrigation canals, the desert character of this region is very evident.

Wind data.--Local wind regimes within the region seem to be strongly modified by topography. For example, winds at the airport at Yuma are definitely bimodal, coming principally from the south during summer and from the north in winter. Winds at El Centro Naval Air Station, about 80 kilometers away, however, seem to be unimodal, and from the west.

The linear ridges of the Algodones sand sea are attributed by Norris and Norris (1961) to variations in wind regime. On the eastern margin of the dune field, the sand forms an apron (sand sheet) which extends for about a mile (1.6 km) in width before tapering off as feather edges against the desert floor. The eastern sand sheet is attributed to transport away from the main dune mass by "infrequent southwesterly sand-driving winds" (Norris and Norris, 1961, p. 609). The occasional flow of streams into the eastern border of the dune field apparently removes sand deposited on the outer fringes of the field.

Several modes of wind movement appear to exist within the sand-sea area, on the basis of available station records. In spite of local, lush vegetation, made possible by irrigation, the sand-dune area is arid to extremely arid (Meigs, 1951) and largely unvegetated, so the sand is free to be moved about by the wind. This circumstance partly explains the variety of dune morphologies visible on ERTS imagery.

5. Sonora, Mexico; Gran Desierto sand sea

Extent and character.--Extensive areas of sand dunes occur in the area northwest of Pinacate Mountains in northwestern Sonora, Mex. (fig. 1, insert). Dunes of this field, which is referred to as the Gran Desierto, have not been systematically studied, in spite of the fact that they probably form the largest active sand sea or "erg" in North America.

Types of dunes.--Dune complexes in the Gran Desierto dune field (fig. 7d) include forms that resemble the megabarchans of the Algodones dune field to the northwest in California, as described by Norris and Norris (1961). Judged from ERTS imagery, however, the Sonoran forms are much larger. The presence of northwest-southeast parallel sand ridges in the western part of the Gran Desierto was noted by Merriam (1969). Probably he was referring to the linear dunes that appear very prominently on ERTS imagery. Star dunes on the crests of those ridges have not previously been described from this area, however. These stars, the presence of which is confirmed by aerial photograph (fig. 8c), are identical to, though smaller than, star dunes of the Great Eastern Erg of Algeria, and of the southeastern Empty Quarter of Saudi Arabia. Here then, on the North American continent, are relatively accessible areas for future structural studies of this unusual type of dune complex. Until ERTS-1 imagery was studied, the presence of these complexes was not recorded.

Color of sand.--Eolian sands of the Gran Desierto are deeper reddish brown and finer grained than the sands of the Algodones dunes, according to Norris and Norris (1961, p. 612).

Wind data.--No wind-recording stations are located inland in the Gran Desierto, but wind records from Punta Peñasco (Rocky Point), a few kilometers to the southeast (just off the area covered by the mosaic), indicate that winds in the upper Gulf of California are probably bimodal, coming from the south and south-southwest during winter and spring, and from the southeast in summer. Why strong northerly winds recorded by the Yuma, Ariz., station during winter do not appear on the wind rose for Punta Peñasco is not known, although the distance between the two stations is considerable.

X. GROUND TRUTH

The acquisition of ground truth from field studies, especially data on the internal structure or stratification, represents the final and critical stage of sand-sea investigation. This is best done by a direct approach consisting of wetting the sand, cutting trenches to expose stratification in three dimensions, and recording the patterns on rubber peels, scale drawings, or photographs (fig. 28). Such field methods have been successfully tested in Libya, Saudi Arabia, U.S.A. and elsewhere. Although tedious and time-consuming, they furnish excellent records of the internal structures representative of each type of dune, thus enabling a reconstruction of subsurface patterns critical to various geological interpretations.

Ground truth should assist in establishing a new model for understanding eolian sand bodies. A general concept in the past has been that dunes are basically the result of sand migration by the processes of saltation and avalanching under the influence of a prevailing wind. This concept doubtless still applies in some regions, but a revised model is needed, which incorporates the effects of multidirectional and variable winds that produce a complex of dune forms, with growth both vertically and laterally. Many aspects of this model are being tested in the present study.

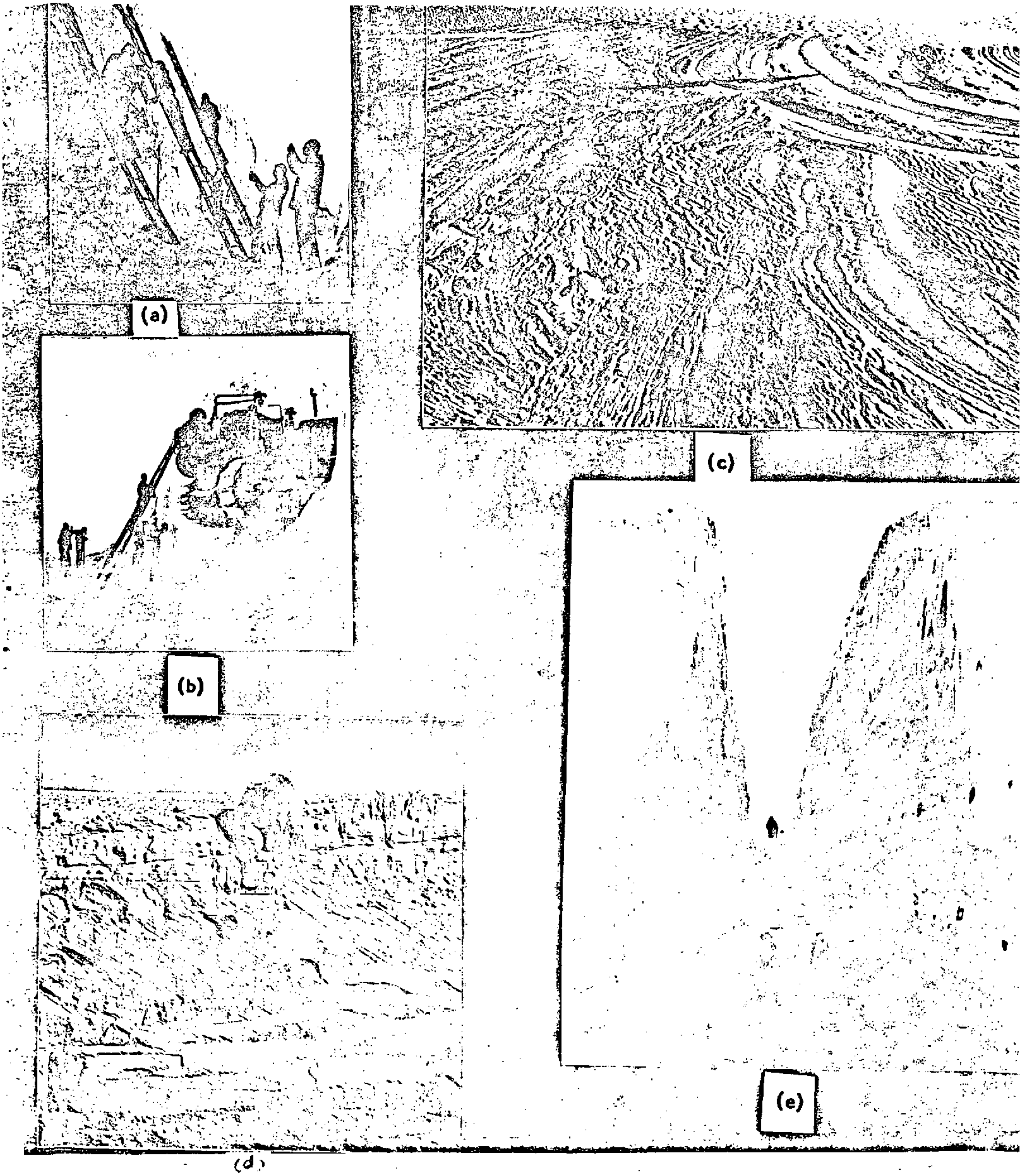


Figure 28. Methods of obtaining and sources of ground-truth data and studying structures in eolian dunes: (a), (b) trench cutting with bulldozer and trimming walls for study; (c) horizontal surface of barchan dunes, naturally bevelled and etched by wind, showing structure; (d) foreset beds exposed by trenching in dome-shaped dune; (e) 45-foot trench in transverse dune cut by bulldozer to expose internal structure. (All photographed at White Sands, New Mexico, by E. Tad Nichols).

XI. ECONOMIC APPLICATIONS AND SIGNIFICANCE

1. Implications for exploration for oil, water and other fluids

Ground truth determined in conjunction with the ERTS-A project on sand-sea studies has revealed some basic principles related to dune structures or cross-stratification and these tend to modify earlier concepts regarding the accumulation of desert sand bodies. In the past, it was generally assumed that dunes are basically the result of sand migration by the processes of saltation and avalanching under the influence of a prevailing wind.

After a study of sand patterns derived from ERTS images and further analysis using Skylab and aerial photographs, it seems clear that in many regions a unidirectional movement of wind results in a lateral migration of sand, with characteristic dune patterns; in certain other places, however, a much more complex wind movement, involving rotation, reversal and other types, results in different dune patterns. Resulting internal structures differ greatly from one area to another and the recognition of such differences should assist greatly in understanding the structures that control fluid migration and reservoir location in ancient rocks.

Many quartz sandstones of the type commonly referred to by geologists as "clean sands" characteristically have large-scale, high-angle cross stratification and fine, even grains but no matrix and are interpreted as eolian. Well-known examples are the Coconino Sandstone of Permian age in Arizona, the Navajo Sandstone of Triassic(?) and Jurassic age in Arizona and Utah, and the Lyons Sandstone of Permian age in Colorado. Additional examples of eolian-type sandstones are in England, Germany and other parts of the world.

Sandstones of the type described are, in general, good aquifers and have high permeability. Both the Coconino and the Navajo are important sources of ground water in Arizona and the Navajo locally contains copper deposits, apparently accumulated by percolating waters. The large-scale, southward-dipping foresets in both formations clearly are major factors in determining the direction and rate of movement of water and other fluids. These foresets are believed to be the slipfaces of ancient wind-formed dunes.

2. Implications for controlling the movements of sand bodies affecting human projects.

Through the study and analysis of ERTS images, the basic patterns of sand-sea accumulations throughout the world have, for the first time, been directly compared under conditions of a uniform, constant scale. The obvious advantages of these comparisons are that basic types of sand bodies can be recognized, their global distribution determined, and their relationship to other physical features such as mountains, water bodies, and wind directions ascertained.

Following a consideration of the type and position of major sand bodies made possible by ERTS images, it commonly is necessary to determine the nature of detailed components that are not visible at the ERTS scale. Such data, especially relative to the form and spacing of small sand bodies, are furnished by aerial photography or by Skylab pictures. A careful study of such photographic materials has established the detailed character of most composite forms recognized in ERTS imagery.

A final step in the interpretation of sand-sea processes involves an understanding of the relationship between the detailed geomorphic form and the internal structure or cross-stratification. The stratification characteristic of particular dune forms can be positively determined only by methods of trenching or sectioning, but ground truth of this type is essential to developing a program involving the control of sand movements. In brief, the type of information derived from an analysis of dune structure is a key to determining the basic factors concerned in rate, volume, and direction of dune migration.

Where sand movement affects projects of human development as through burial or by altering the surface water regime, drought conditions commonly develop. Such conditions are present today in the Rajasthan Desert of India and near Lake Chad and elsewhere along the margins of the Sahara Desert. Thus, the basic facts concerned with the growth and development of sand seas as developed by ERTS imagery, supplemented by Skylab photography and by ground truth furnished through trenching, are essential to a successful management program in these drought areas.

3. Significant cost benefits

Examples of preliminary analyses of sand seas given in this report show that the cost of analyses of various remote deserts by interpretation of satellite imagery is only a fraction of the cost of surveying even one desert by means of airplane, jeep, or camel. Because of the very difficult conditions for carrying out aerial and ground surveys, no reliable and comparable data base for many of these regions was available before ERTS-1 began to acquire imagery. The vast sand seas of the world are probably the last remaining land areas of which the surfaces have not been reliably mapped by civilian agencies, so information supplied by ERTS-1 is a unique contribution of knowledge of these areas.

XII. PUBLISHED REPORTS RESULTING FROM ERTS-A PROJECT
(plus in-house reports, abstracts and unpublished papers)

McKee, E. D., 1972, A study of morphology, provenance, and movement of desert sand seas in Africa, Asia and Australia: Type I Progress Report ERTS-A, 7/1/72-8/31/72.

McKee, E. D., 1972, A study of morphology, provenance, and movement of desert sand seas in Africa, Asia and Australia: Type I Progress Report ERTS-A, 9/1/72-10/31/72.

McKee, E. D., 1973, A study of morphology, provenance, and movement of desert sand seas in Africa, Asia, and Australia: Type I Progress Report ERTS-A, 11/1/72-12/31/72, in NASA Earth Resources Survey Program Weekly Abstracts, National Technical Information Service, 93-73, March 12, 1973, NASA-CR-130335, E73-10058, PC$3.00/MF$0.95.

McKee, E. D., 1973, A study of morphology, provenance, and movement of desert sand seas in Africa, Asia, and Australia: Type I Progress Report ERTS-A, 1/1/73-2/28/73, in NASA Earth Resources Survey Program Weekly Abstracts, National Technical Information Service, 93-73-20, May 14, 1973, 4 p. NASA-CR-131145, E73-10409, PC$3.00/MF$0.95.

McKee, E. D., 1973, A study of morphology, provenance, and movement of desert sand seas in Africa, Asia, and Australia: Type I Progress Report ERTS-A, 3/1/73-4/30/73, in NASA Earth Resources Survey Program Weekly Abstracts, National Technical Information Service, 93-73-25, June 18, 1973. 28 p. NASA-CR-131618, E73-10542, PC$3.00/MF$0.95.

McKee, E. D., Breed, C. S., and Harris, L. F., 1973, A study of morphology, provenance, and movement of desert sand seas in Africa, Asia, and Australia: Type I Progress Report for 5/1/73-6/30/73, in NASA Earth Resources Survey Program Weekly Abstracts, National Technical Information Service, 93-73-32, August 6, 1973. 5 p. NASA-CR-133061, E73-10710, PC$3.00/MF$0.95.

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McKee, E. D., and Breed, C. S., 1973, A study of morphology, provenance, and movement of desert sand seas in Africa, Asia, and Australia: Type I Progress Report ERTS-A, 7/1/73-8/31/73.

McKee, E. D., and Breed, C. S., 1973, A study of morphology, provenance, and movement of desert sand seas in Africa, Asia, and Australia: Type I Progress Report for 9/1/73-10/31/73, in NASA Earth Resources Survey Program Weekly Abstracts, National Technical Information Service, 93-74-05, February 4, p. 10-11. NASA-CR-136174, E74-10129, PC$3.25/MF$1.45.

McKee, E. D., and Breed, C. S., 1974, A study of morphology, provenance, and movement of desert sand seas in Africa, Asia, and Australia: Type I Progress Report ERTS-A, 11/1/73-12/31/73, in NASA Earth Resources Survey Program Weekly Abstracts, National Technical Information Service, 93-74-10, March 11, 1974, p. 30. NASA-CR-136 326, E74-10187, PC$3.00/MF$1.45.

McKee, E. D., and Breed, C. S., 1973, A study of morphology, provenance, and movement of desert sand seas in Africa, Asia, and Australia [abs.]: in Symposium on significant results obtained from ERTS-1, Abstracts NASA/Goddard Space Flight Center, New Carrollton, Md., March 5-9, 1973, Paper G8, p. 34.

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McKee, E. D., and Breed, C., 1973, An investigation of major sand seas in desert areas throughout the world [abs.]: in Third ERTS Symposium, Abstracts NASA/Goddard Space Flight Center, Washington, D. C., Dec. 10-14, 1973, Paper G6, p. 42.

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McKee, E. D., Breed, C. S., 1973, An investigation of major sand seas in desert areas throughout the world: (To be published in Proceedings of Third ERTS Symposium, NASA/Goddard Space Flight Center, Washington, D. C., Dec. 10-14, 1973, 5 p., 11 figs. (In press).

McKee, E. D., and Breed, C. S., Sand seas of the world: (To be published in EROS book entitled "Selective Guide to Operational and Scientific uses of ERTS.").

McKee, E. D., and Moiola, R. J., Geometry and growth of the White Sands, New Mexico, dune field (in press).

XIII. GLOSSARY

AKLE: French term for a network pattern of dunes in the western Sahara: a fishscale pattern of parallel wavy dune ridges.

ALAB (ELB): French term describing parallel straight dune arrays in the western Sahara.

ALLUVIUM: unconsolidated gravel, sand silt and clay transported and deposited by water.

ANCHORED DUNE: see fixed dune.

ANGLE OF REPOSE: maximum angle at which loose material such as sand is stable (commonly 32°-34° for dune sand).

BARCHAN: crescent-shaped sand dune in which the horns or arms point downwind.

BARCHANOID RIDGE: asymmetrical wavy dune ridge, separated from neighboring wavy dune ridges by open interdune corridors.

BASKETWEAVE DUNE PATTERN: type of parallel wavy dune complex in which the dune ridges are offset forming a chevron or herringbone pattern of ridges and interdune hollows.

BEDROCK: solid rock, commonly beneath a veneer of surficial alluvium or eolian sand.

BERG WIND: an east wind (Namib Desert).

BLOWOUT: saucer-shaped hollow in eolian sand, formed by wind deflation of dune areas.

CALCRETE: hard, dense calcium carbonate layer in soil (see CALICHE).

CALICHE: lime-rich deposit in soils of arid and semiarid regions, formed by the capillary rise of lime-bearing water toward the surface, and the accumulation through evaporation of caliche. Also, the gravel, sand, or silt cemented by calcium carbonate or the calcium carbonate cement itself.

CLAY PAN: Playa or dry lake formed in a shallow, undrained depression; commonly it has a hard, sun-baked surface.

CLIMBING DUNE: sand piled up against a cliff or mountain front by wind.

COMPLEX DUNE: large-scale accumulation of eolian sand formed by the coalescing or combining of individual dunes.

CRESCENTIC DUNE: see BARCHAN.

DEFLATION: removal (erosion) of loose material by wind (see BLOWOUT).

DELTA SEDIMENTS: deposits of gravel, sand, silt and clay accumulated by a stream at or near its mouth.

DESERT: an arid or semiarid region characterized by an excess of evaporation over precipitation.

DRAA: Arabic term for a large-scale accumulation of eolian sand (see DUNE COMPLEX).

DUNE: an accumulation of windblown sand, commonly having a gently upwind slope and a steep lee slope or slipface, or two slipfaces.

DUNE COMPLEX: an eolian sand accumulation formed from a combination of dunes (locally referred to as DRAA in parts of North Africa).

DUNE MASSIF: see STAR DUNE.

DUNE SPACING INDEX: a measure of the average number of linear dune ridges crossing a 50-km-long line normal to the trend of the dune ridges in a given area.

EOLIAN SAND: windblown sand.

EOLIAN SANDSTONE: sedimentary rock formed of consolidated windblown sand.

ERG: desert region in which at least 20% of the land surface is covered with wind-deposited sediments, and which contains complex dunes; a sand sea.

FALLING DUNE: dune sand that accumulates on the side of a cliff or mountain front as the result of wind blowing sand off the top.

FISHSCALE DUNE PATTERN: type of parallel wavy dune pattern in which the interdune areas are enclosed by the crescentic elements of the dune ridges (locally referred to as peak-and-fulje topography).

FIXED DUNE: nonmigratory dune held in place by cementation and/or vegetation.

GIANT CRESCENT DUNE PATTERN: type of parallel wavy dune pattern in which the ridges are composed of coalesced megabarchans with either open or closed interdune hollows.

HORNS: the pointed ends of a dune, especially the forward extending arms of a barchan dune or the backward trailing tails of a parabolic dune.

INSELBERG: prominent residual steep-sided rocky hills rising abruptly from plains or desert.

INTERNAL STRUCTURES: bedding planes (stratification), ripple marks, and other features preserved inside sand dunes and eolian sandstones.

INTERDUNE CORRIDOR, HOLLOW or AREA: flat or gently sloping, windswept desert floor between dunes.

ISOHYET: line on a map connecting points which receive equal amounts of average annual rainfall.

KHURD: a radial dune.

LEE DUNE: a dune formed to leeward of a barrier.

LIME CONCRETIONS: spherical or ellipsoidal aggregates of precipitated calcium carbonate or other material cemented by calcium carbonate.

LINEAR DUNES: parallel, straight dunes (also called longitudinal dunes, alab, seifs) whose lengths are many times greater than their widths.

LONGITUDINAL DUNE: a linear dune ridge which grows or migrates in a direction parallel to its long dimension.

MASTODONS: radial or star dunes.

MEGABARCHANS: giant crescentic (barchan-shaped) complex dunes, several hundred meters in height, commonly coalescing into chains, and forming a parallel wavy dune pattern. Each dune complex normally has one major slipface.

MIDDLE LATITUDE DESERTS: deserts that lie between approximately lat. 30°N and lat. 30°S.

MIGRATORY DUNES: dunes which are active and move laterally.

MONSOON: a wind system in which wind direction varies with season of the year.

MORPHOLOGY: the shape or physiography of land surface features.

OGHURD: a radial or star dune.

ONSHORE WINDS: winds that blow from the sea onto a land surface.

PAN: a natural depression or basin that periodically contains water but at other times is dry, forming a dry lake or playa (see also PLAYA, CLAY PAN).

PARABOLIC DUNE: a U-shaped or V-shaped dune, representing a type of blowout in which the middle part has moved forward with respect to the sides or arms. The arms commonly are anchored by vegetation.

PARALLEL STRAIGHT DUNE: a linear ridge of windblown sand whose length is much greater than its width, and which commonly has slipfaces along both sides; it moves in a lengthwise direction.

PARALLEL WAVY DUNE COMPLEX: an array of crescentic dune segments aligned in wavy ridges. Each crescentic segment of the ridge is approximately as wide as it is long, and the segments are asymmetrical, with all segments of a ridge having their major slipfaces oriented in the same direction.

PEAK-AND-FULJE TOPOGRAPHY: a pattern of dunes (peaks) and enclosed inter-dune hollows (fuljes); also known as akle or fishscale variety of the parallel wavy dune pattern.

PEDIMENT: a broad desert surface or plain formed by erosion at a mountain base; it may be bare bedrock or partly veneered by alluvium.

PLAYA: an extremely flat, nonvegetated desert surface formed of clay, silt, and/or evaporite minerals in the bottom of a basin of interior drainage (also known as CLAY PAN, dry lake, inland sebkha, salt pan, and salt flat).

PLEISTOCENE: an epoch of the Quaternary Period of geologic time ending approximately 10,000 years before the present time, also known as the Glacial Period or the Ice Age.

POLYPYRAMID: a radial or star dune.

PYRAMIDAL DUNE: a radial dune (also known as KHURD, OGHURD, RHOURD, MASTODON, POLYPYRAMID, STAR DUNE).

RADIAL DUNE: a complex dune, roughly star-shaped, whose segments or arms radiate from the high central cone; slipfaces on the dune segments face in at least three directions, resembling a pinwheel.

REGIONAL SETTING: the physical geography of an area: its geology, climate, water resources, and other physiographic features.

RHOURD: a radial dune.

SALTATION: the bouncing movement of sand-sized particles being transported by wind.

SAND DUNE: a pile of wind-transported sand.

SAND RIDGE: a parallel straight or linear dune.

SAND ROSE: a circular histogram depicting the amount of sand moved by winds of certain speed groups in various compass directions, at a given geographic locality.

SAND SEA: a region of extensive eolian sand deposits, including dunes and dune complexes that form characteristic patterns (also known as and ERG, nafud, sand-ridge desert).

SAND SHEET OR STREAK: a flat-surfaced eolian sand deposit, without slipfaces, but with distinct geographical boundaries.

SEIF: a North African (Arabic: sword) term for a parallel straight (LINEAR) dune.

SHEETS OR STREAKS OF SAND: see SAND SHEET or STREAK.

SHRUB-COPPICE DUNE: a small dune formed in the lee of vegetation, on a wide, smooth, shallow sand surface.

SLIPFACE: steep face on the lee side of a dune, which is usually at the angle of repose of sand (commonly 32°-34°).

SOUTHEAST TRADES: winds persistently from the southeast in the Southern Hemisphere, caused by counterclockwise circulation about permanent oceanic high-pressure cells, centered about lat. 30°S.

STABILIZED DUNE: see FIXED DUNE.

STAR DUNE: a RADIAL DUNE.

STELLATE ROSES: radial dunes.

SURFACE WINDS: winds at ground-surface level.

THEMATIC MAP: interpretive drawing, based on ERTS-1 color mosaics, which expresses patterns and relationships of features observed on the imagery.

THERMAL LOW: an area of low pressure caused by heating of the land surface by solar radiation.

THRESHOLD VELOCITY: minimum wind speed at which sand grains of .25 mm begin to saltate; generally considered to be 16 km per hour (9 knots).

TRANSVERSE DUNE: an asymmetrical dune ridge oriented normal to the dominant wind direction in a particular area (see parallel wavy dunes).

U-SHAPED DUNE: a PARABOLIC DUNE.

UPSILOIDAL DUNE: a PARABOLIC DUNE.

WIND REGIME: the pattern of winds characteristic of a particular region.

<u>WIND ROSE</u>: a circular histogram depicting the percentage occurrence of wind speed groups from a given set of compass directions, at a certain geographic locality.

XIV. SELECTED BIBLIOGRAPHY

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