U.S. GEOLOGICAL SURVEY CIRCULAR 989

A Workshop on Desert Processes, September 24–28, 1984— Report on the Conference

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By John F. McCauley *and* Jack N. Rinker

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A Workshop on Desert Processes, September 24–28, 1984— Report on the Conference

By John F. McCauley *and* Jack N. Rinker[1]

INTRODUCTION

During the last decade, desert research has seen renewed emphasis as a result of satellite data, improved physical access, military considerations, and economic concerns such as regional desertification and overuse of ground-water resources. Geologists within the U.S. Geological Survey (USGS) have long been involved in desert geology of the Earth (and of Mars since before the first Mars Orbiter Mission, Mariner 9, in 1971). USGS investigators pioneered the use of Landsat remotely sensed data to study the regional distribution and morphology of large-scale sand dunes in desert regions (Breed and others, 1979; Breed and Grow, 1979) and have recently been using Space Shuttle Imaging Radar (SIR) to define newly discovered paleodrainages in the Eastern Sahara of northern Africa (McCauley and others, 1982, 1986).

At present, the USGS is monitoring geometeorological conditions in different types of deserts in Arizona, using data relayed by satellite from solar-powered "Geomet" stations (McCauley and others, 1984). These stations consist of automated data-collection platforms coupled with an array of sensors that measure boundary-layer atmospheric and geologic conditions at frequent intervals, around the clock. Such data are essential to studies of surface geologic processes in deserts, particularly wind erosion, and of the landforms that develop in response to these processes.

The Geomet data are also of interest to the U.S. Army, which must operate in various types of deserts and therefore needs information related to natural hindrances to cross-country movement, selection of aircraft landing sites, cover and concealment, camouflage, dust generation, and location of usable water. The U.S. Army Engineer Topographic Laboratories, Center for Remote Sensing (ETL-CRS), has evaluated a variety of remote sensors and image-analysis techniques in subhumid regions, and a part of its research program is directed toward applying these techniques to the Army's need for information on desert terrain. The complementary research needs of the USGS and ETL-CRS resulted in a workshop held in Flagstaff, Ariz., on September 24-28, 1984, to bring together some of the leading workers in desert processes to exchange information on current programs, to establish general limits of knowledge, to identify areas of research and their priorities, and to discuss the application of results to civil and military problems.

Outline of the Workshop

The plan was to convene a small but focused workshop that would include participants with a broad range of field experience in deserts, to review the overall state of knowledge of desert regions (primarily in the United States) and to attempt to define research directions, tools, and strategies that might be employed in future work. Some of the participants were concerned with experimental methods to determine the physical and chemical bases of present-day surface processes; others used the results of these processes—various types of landforms, sedimentary deposits, and surface coatings—as evidence for interpreting past environments and predicting future conditions. The purpose of the workshop was not to provide an outlet for presentation and publication of formal papers, but rather to provide a forum for lively discussion about selected topics. The individual presentations were informal briefings designed to bring others up to date on current work and opinions.

The workshop was divided into three parts: (1) informal presentations of the highlights of past and current research by the participants as a basis for discussion, (2) aerial and ground field trips to key localities in the Great Basin Desert northeast of Flagstaff (fig. 1) to illustrate the general character and state of knowledge of surface processes and resulting landforms in these arid parts of the southwestern United States, and (3) reassembly of the participants in Flagstaff for two days to discuss processes in the American arid lands in the light of each person's experience.

During the opening sessions, participants presented their thoughts as a means of self-

[1]U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia 22060.

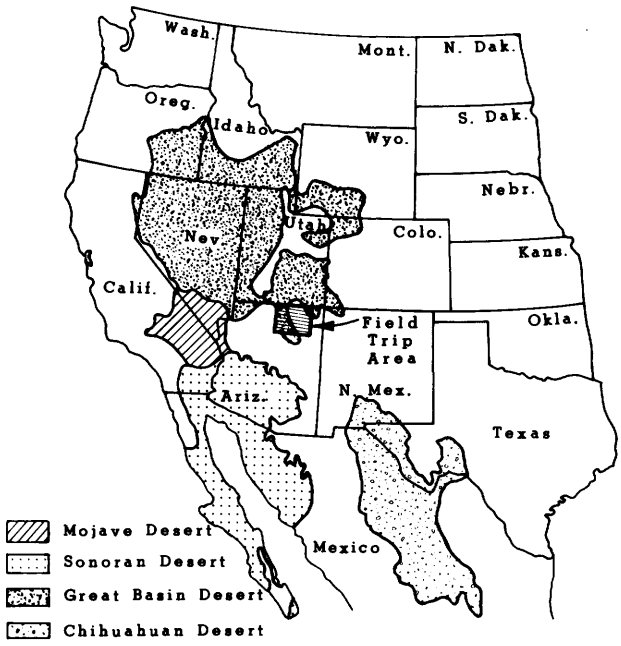

FIGURE 1.--Regional context of Arizona deserts and area of field trip (outlined) in Great Basin Desert (from Sheridan, 1981).

introduction to the group, followed by discussion. Two days were then devoted to the field trips, consisting of a flyover of the Little Colorado River Valley, Moenkopi Plateau, Monument Valley, and parts of the Colorado River (figs. 2, 3), followed by ground traverses on the Moenkopi Plateau and along the east side of the Little Colorado River Valley (fig. 4). The field trips provided a reconnaissance of the great variety of landforms that have developed from the interplay of desert processes operating on different types of surface materials under past and present climatic conditions in northeastern Arizona. The trips served as an introduction to discussion of desert processes--unsolved problems, current methods of study, and promising directions for new research.

Topical discussions related to methods of data collection and interpretation followed the field trips; these sessions emphasized desert geomorphic processes in general, analogs in other parts of the world, vegetation, catastrophic events (droughts, windstorms, dust storms, floods), seasonal events, and climate change. The final day's summary session was a round-table discussion of problems and directions of future desert research, priorities, methods, strategies, new tools, and the need for additional observation stations. Key questions addressed during these discussions, with recommendations for cooperative efforts, are incorporated in the following section of this document to provide guidelines for future research.

Acknowledgments

The workshop was a cooperative effort of the USGS and ETL-CRS. We would particularly like to thank the following people. William J. Breed, Flagstaff, coordinated all workshop activities, prepared a guidebook to the localities visited, and led the ground portions of the field trip with Carol S. Breed, George H. Billingsley, and Paula Helm, USGS. Phyllis Corl, ETL-CRS, coordinated the advance planning at ETL-CRS for the workshop, and assisted in the preparation of aerial photomosaics that were provided to each participant to illustrate the field areas.

OBJECTIVES AND RECOMMENDATIONS OF THE DESERT WORKSHOP

Part I: Summary of Discussions

The two goals of the workshop were (1) to determine the practical limits of knowledge and understanding of surface geometeorological processes in deserts, and (2) to provide a basis for encouraging discussion between scientists of different disciplines. These goals were met. During the conference, several key questions were addressed; these questions, and the consensus of the participants, were as follows:

1. Have we an acknowledged understanding of cause and effect and kinetics regarding landform development and surface characterization in relation to desert processes (eolian, fluvial, mass-wasting, weathering)?

   Consensus: No. The interactions among materials, vegetation, wind, water, weathering, and mass wasting that produce various types of landforms and surface characteristics are not well understood, particularly in regard to the rates of these processes. More research is needed, both to understand better the present-day causes and effects and to interpret more precisely the geologic record. More emphasis should be placed on study of the boundary layer, which is where surface geologic processes develop and modify landscapes. Measurements of weathering and erosion rates should be increased, new techniques for measurement should be developed, and research on individual components of surface processes should be encouraged.

2. Are more field observations and experimental measurements needed, or are existing models adequate?

   Consensus: Field observations and theoretical modeling studies are needed at all levels of endeavor, and long-range experiments should be

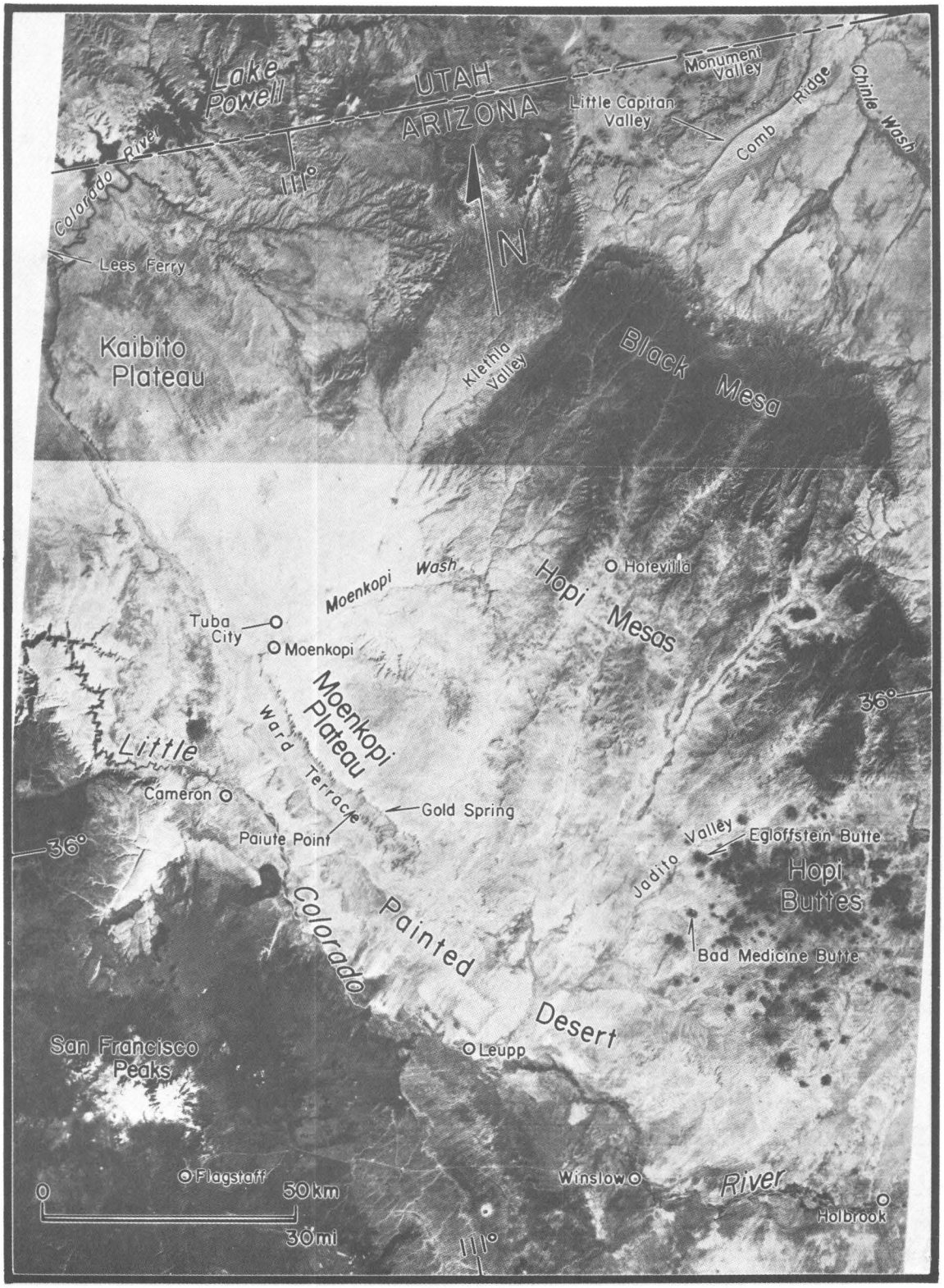

FIGURE 2.--Mosaic of Landsat images showing features of Great Basin Desert in northeastern Arizona.

started that will continue beyond our lifetimes to serve as a data base for future generations. The models discussed in this workshop refer to wind erosion and associated factors. Although the best available, these models are more suggestive than absolute and are restricted in scope. Additional field measurements and observations are needed that can best be supplied by cooperative interagency efforts.

3. Are measurements needed such as those collected at the USGS Geomet stations? If so, are they adequate, or should they be expanded?

Consensus: The measurements are needed, not only to improve basic understanding of eolian processes, but also to help in the development and testing of mathematical models. Existing instrumentation nets should be expanded, and

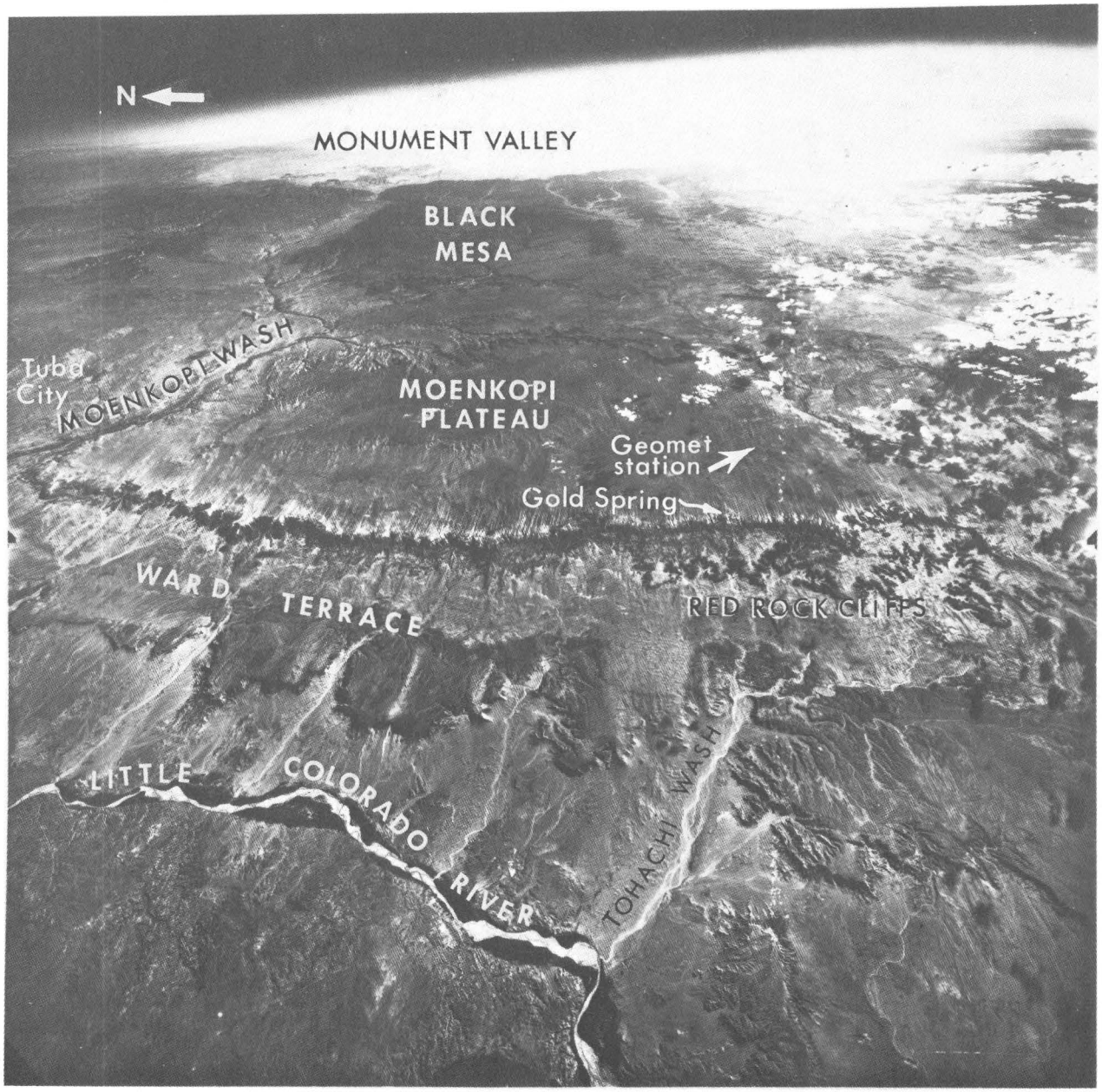

FIGURE 3.--Oblique high-altitude aerial view of parts of desert covered by field trip. View northeast across valley of Little Colorado River to Monument Valley on Arizona-Utah border (fig. 2). Two-day field trip included air and ground visits to key localities (fig. 4).

actual surface conditions should be better defined. For example, systematic measurements should be made over long periods at selected localities around each Geomet site to determine rates of weathering and erosion of the mapped bedrock and surficial units. Wind profiles should be constructed in downwind and crosswind directions, and related to the calculated erosion potential of measured winds, to help characterize the susceptibility of various surfaces to erosion. The vegetative elements of each site should be mapped to provide, as a minimum, estimates of cover (in percent) of four elements: (1) algae, lichen, and mosses, (2) herbaceous plants (grasses and herbs), (3) shrubs, and (4) trees; height and seasonal components should be addressed, as well as vegetative structure.

4. If the Geomet types of measurement are to be expanded, what are the minimum and ideal requirements with respect to instrumentation, site arrangement, and site locations?

   Consensus: Minimum and ideal requirements were agreed upon and are reported in this document by Gillette and Skidmore. The instrumentation, starting at the Gold Spring site, should be increased both laterally and vertically and probably should include sensors for solar radiation. At the Gold Spring site, the USGS is trying to measure the sediment load of the air in relation to wind speed and direction. Although experimental, such measurements are critical to any understanding of erosional processes. These efforts should be expanded, and other sediment-measuring devices developed and tested.

The USGS Geomet sites in Arizona's arid lands (figs. 5, 6) and the ETL-CRS instrumented test site in Virginia are the only places known to us where continuous, around-the-clock measurements are being collected of radiometric, meteorological, vegetation, and soil variables, and where temperature and moisture profiles are produced. Instrumentation and data collection at the two sites are similar, except that sediment flux is measured only at the Geomet station #1 (Gold Spring), and radiometric measurements in the two infrared imaging bands are made only at the ETL-CRS site. The models developed and tested by CRS for predicting time-varying thermal signatures and target-to-background thermal contrast are for a relatively moist, temperate region (eastern Virginia). At least one subhumid site should be fully instrumented so that its data can be compared with the CRS measurements and used to extend the predictive model to desert areas. The proposed Jornada collaborative site near White Sands, N. Mex., would be excellent for this purpose.

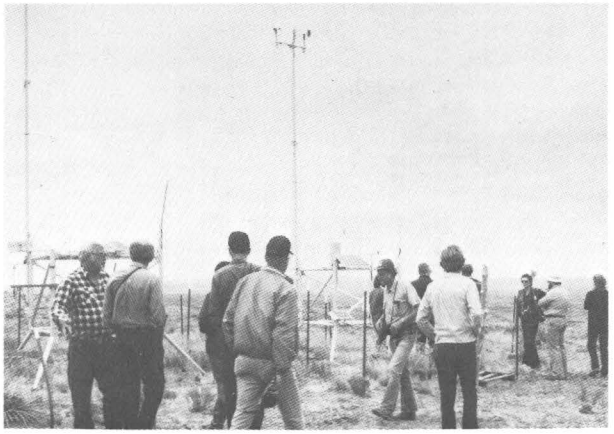

FIGURE 4.--Among the localities that stimulated most discussion were (top) the Geomet site near Gold Spring on the Moenkopi Plateau, where sensors on two stations were being cross calibrated and prototype flux sensors tested, and (bottom) Red Rock Cliffs eroded in Moenave Formation of Triassic age in valley of the Little Colorado River (figs. 2, 3).

Part II: Recommendations for Collaborative Research

Several research tasks that would benefit from cooperative efforts were identified and agreed to, pending availability of resources and permission from parent agencies. These were:

1. The USGS and ETL-CRS will collaborate on collection of data at the Geomet sites (see McCauley and others, this volume). To provide the more complete surface descriptors needed for the models, ETL-CRS will map vegetation at the Geomet sites. Work was to start in fiscal 1985 at the Gold Spring site and continue

as travel funds permit.

2. The USGS and the State Climatology Laboratory, Arizona State University (Marcus, this volume), will exchange data for research use on an informal basis.
3. The USGS and ETL-CRS will collaborate on site layout, expansion, and instrumentation of the Gold Spring Geomet site. E.L. Skidmore, U.S. Department of Agriculture (USDA) Wind Erosion Laboratory, and D.A. Gillette, National Oceanic and Atmospheric Administration (NOAA) will provide expertise and may loan equipment for sampling airborne dust. (See Skidmore, this volume, and Gillette, this volume.) ETL-CRS will provide soil heat-flux sensors and help evaluate soil-moisture measuring techniques.
4. D.A. Gillette (NOAA) and ETL-CRS will collaborate on correlating ground measurements with pattern indicators on aerial photographs, to develop a procedure for estimating dust potential by image analysis.
5. The USGS and ETL-CRS, in cooperation with USDA, Las Cruces, N. Mex., will collaborate on developing a Geomet station in an area representative of the Chihuahuan Desert in New Mexico (fig. 1). CRS will install instrumentation analogous to the ETL-CRS instrumented test site at Fort Belvoir, Va., and will assist in mapping the vegetation. The Jornada Experimental Range of the Agricultural Research Service, USDA, was proposed by E.L. Skidmore (USDA) and accepted as a candidate for collaborative efforts. The range is in a protected area on public land west of White Sands National Monument, New Mexico. It is the site of ongoing wind-erosion research by USDA personnel, who have acquired data there for 50 years. The Jornada area is contiguous with an area mapped in detail by the the Desert Project of the U.S. Soil Conservation Service (Gile and others, 1981). It has been the site for studies of spectral reflectance indexes derived from Landsat data for use in monitoring changes in vegetation type and distribution (Musick, 1984). Beginning in 1986, the Jornada area will be intensively monitored for surface changes due to eolian processes, using Landsat and other remotely sensed data, as part of NASA's Interdisciplinary Research Program in Earth Science (C.S. Breed, H.B. Musick and others, USGS, Flagstaff).
6. ETL-CRS will provide all workshop participants with a list of references on chemical weathering in granites, and will provide future updates.
7. A strong interest was expressed in the activities of the Army Research Office (ARO), and some research proposals from the workshop participants are likely to be submitted to that agency in the future.

CONTRIBUTIONS FROM WORKSHOP PARTICIPANTS

Part I: Monitoring of Processes in Arid Environments

Monitoring Desert Winds

J.F. McCauley, C.S. Breed, P.J. Helm,
G.H. Billingsley, and D.J. MacKinnon
U.S. Geological Survey, Flagstaff, Ariz.

Studies of geologic processes that affect desert surfaces have been severely handicapped by a lack of detailed data on meteorological characteristics, particularly on the intensity and periodicity of peak-gust wind speeds. The need of a quantitative data base for assessing rates of wind erosion became apparent during studies of arid regions on Earth that are considered analogous to certain surfaces on Mars. As a result of this need, in 1979 the USGS initiated a long-term study of the geologic role of wind relative to other processes, adapting the techniques of remote monitoring pioneered in studies of water resources to studies of desert processes. Detailed field measurements of geometeorological conditions are currently being obtained in several different desert environments of Arizona (fig. 5). The goal is to establish and compare rates of change of natural desert surfaces by eolian processes under given geometeorological conditions, and thus to provide some of the long-term basic data needed to assess the effectiveness of wind as a geologic agent.

Measurements of wind speeds (including peak gusts), wind directions, air temperature, humidity, barometric pressure, soil temperature, and precipitation are taken at 1-second intervals and recorded as 6-minute averages around the clock, by nonattended, solar-powered Geomet stations (fig. 6). These stations are data-collection platforms coupled with an array of off-the-shelf meteorological and geological devices. The data are automatically transmitted in real time by GOES satellite and converted to graphic form for analysis by USGS scientists. Since the first station was deployed in 1979, various problems in the system have been largely overcome, and Geomet stations are now operating at four sites in Arizona: Gold Spring, in the Great Basin Desert on the Navajo Indian Reservation; at Desert Wells (near Vicksburg) in the Upper Sonoran (Gila) Desert west of Phoenix; at Yuma, in the Lower Sonoran Desert near the Mexican border; and near Red Lake, on the east edge of the Mojave Desert (fig. 5). A fifth station soon will be deployed in New Mexico, in an area representative of the Chihuahuan Desert (fig. 1); the Jornada Experimental Range has been selected for this purpose.

Each Geomet station was positioned after extensive site studies, which included detailed

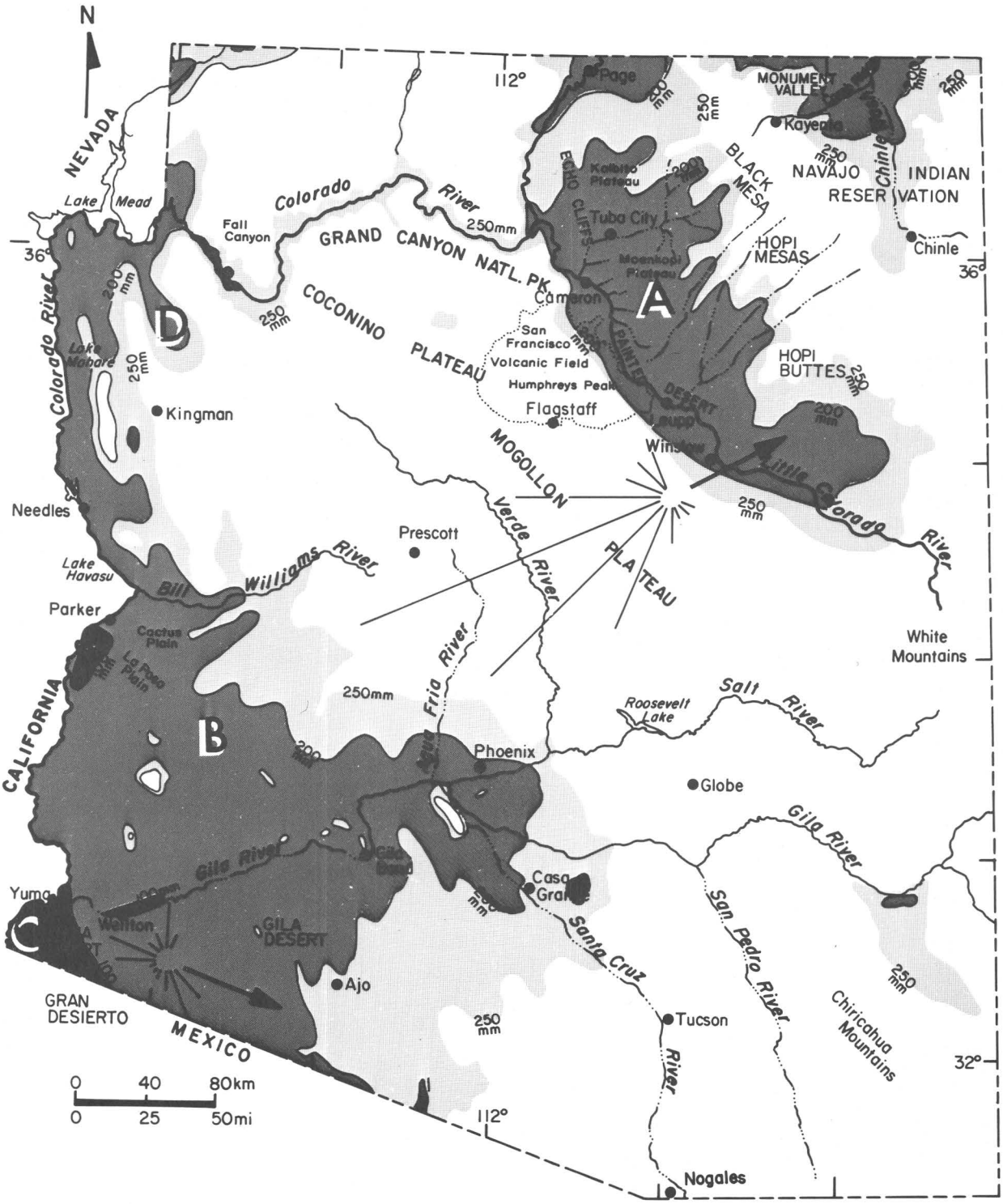

FIGURE 5.--Location map of USGS Geomet station sites in Arizona deserts: A, Gold Spring; B, Desert Wells; C, Yuma Desert; and D, Red Lake. Precipitation isohyets outline shaded areas that receive 100 mm or less (dark shading), 100 to 200 mm (intermediate shading), and 200 to 250 mm (light shading) average annual precipitation. Rose diagrams at Winslow and Yuma are circular histograms that indicate the theoretical sand moving capacity of winds, based on standard weather station records; arrows indicate calculated annual resultant directions of potential sediment transport by winds (from Breed and others, 1984).

geologic mapping and sampling of the surficial units (dunes, sand sheets, playas, channel deposits of ephemeral streams, and alluvial plains). Repeat photography from camera stations established at each site provides long-term documentation of physical changes and their relations to the monitored conditions. Vegetation is being surveyed at all sites in cooperation with ETL-CRS. In addition, effects of eolian processes on surface properties (including vegetation) will be monitored at the Yuma and Jornada sites, using aircraft, Landsat and other satellite remote-sensing data, in cooperation with NASA's Interdisciplinary Research Program in Earth Science.

In early 1984, a second-generation station at Gold Spring was deployed that has specially modified sensors to measure dust and sand flux (fig. 6). The dust sensor is a commercially available

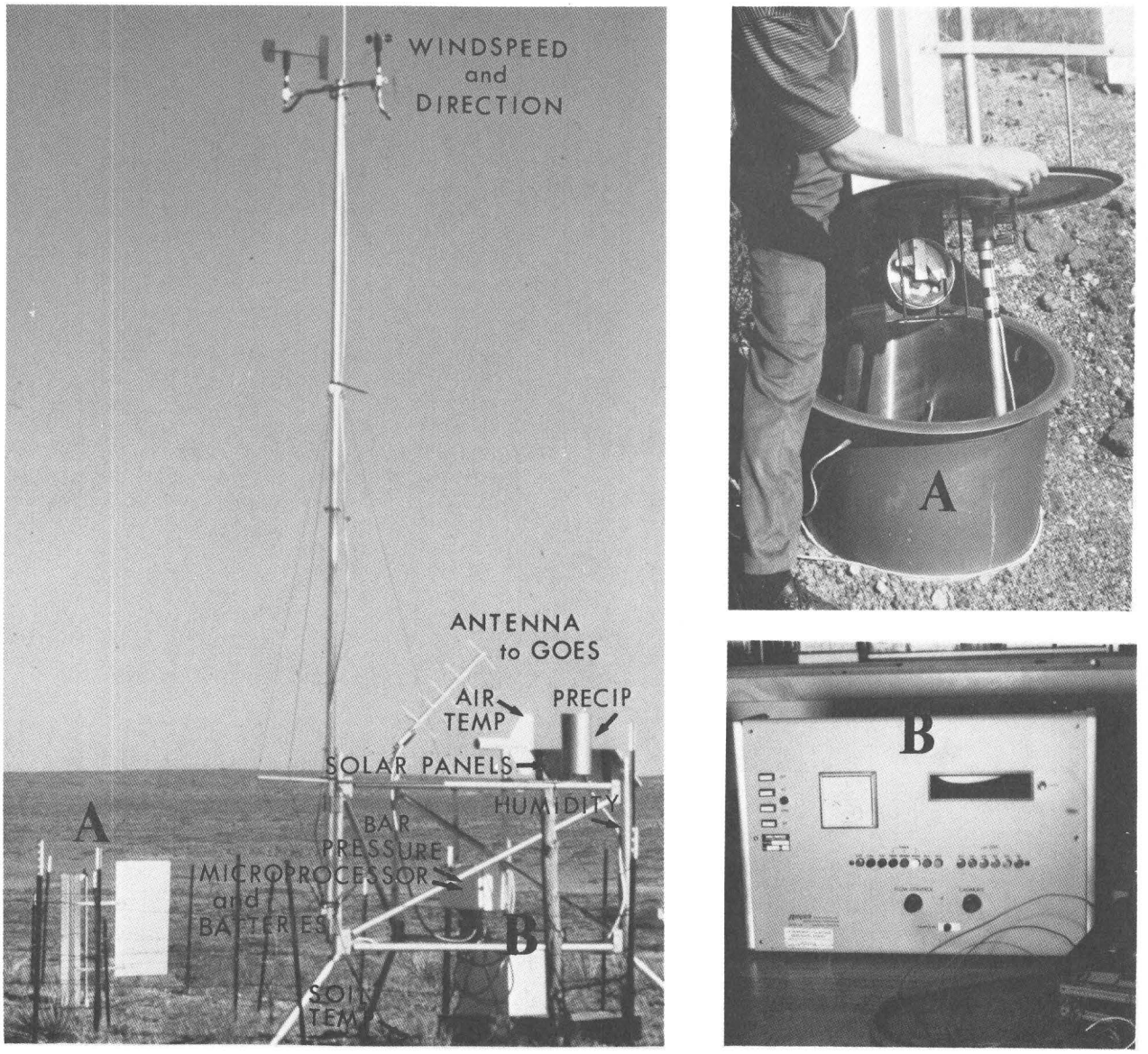

FIGURE 6.--Solar-powered, remote-relay Geomet station with (A) sand-flux and (B) dust-flux sensors deployed near Gold Spring, northeastern Arizona. Sand-flux sensor initially in use had tipping-bucket mechanism (details, upper right), which proved to be too sensitive for field use, and has recently been replaced by a piezoelectric load cell. Dust-flux sensor housed in box (B) is shown in lower right.

particle counter that records numbers of suspended dust particles larger than 5.0 μm in diameter; the sand trap includes a tipping-bucket mechanism that measures amounts of windblown sand collected per unit of time. These sensors are automated to measure the dust and sand flux passing the station and to transmit this information simultaneously with the recorded wind speed and direction. The actual sediment flux that occurs under monitored meteorological conditions can then be compared to the potential sediment-moving capacity of wind predicted by theory. Differences between the theoretical and actual capacity of the measured winds at each site may then be attributed to variables such as the characteristics of the surface materials, topography, rainfall patterns, and type of vegetation cover.

After field testing of the prototype flux sensors, the other stations will be similarly equipped. These two prototype sampling instruments directly measure some elements of sediment transport during the real-time wind erosion process. Suggestions were made in the workshop for additional field measurements and for improvements in the Geomet instrument array. The current approach is to obtain detailed data for use in theoretical transport equations, and to develop such equations to calculate the potential for wind erosion of various natural desert surfaces. Beyond this effort, however, research in eolian processes requires a capability to observe and measure the actual removal and redistribution of sediment by wind. Two problems are apparent in pursuing this capability, as pointed out by D. MacKinnon. First, measurement of sediment particles as passive elements in a dynamic process is extremely difficult, especially in an uncontrolled, abrasive field environment. Second, only short-term funding has been available for new instruments that will require long-term development. Thus we are presently limited to mostly indirect measurements and to theoretical models as representations of the actual process. We should keep in mind that future advances in geophysical studies of wind erosion will require direct measurements of the actual process, and we should pursue the means to accomplish them.

Key Factors in Arid-Land Monitoring Efforts

E.L. Skidmore
U.S. Dept. of Agriculture Wind Erosion Laboratory
Manhattan, Kans.

It has been said that our knowledge of something is limited by the extent to which we can measure it and its properties and (or) its influence on something else. Any measurement system requires constant vigilance to ensure that the numbers being stored represent the truth. Ideally, measurements at the USGS Geomet sites should be sufficient to allow calculation of energy, water, and momentum balances.

1. Energy balance.--The net solar energy received at the Earth's surface is distributed according to the function

$$R_n = LE_t + S + A + M \quad (1)$$

where R_n is net radiation, L is latent heat of evaporation, E_t is evapotranspiration (the amount of water evaporated from soil and transpired by plants), S is energy utilized in heating soil, A is heat utilized in heating the air, and M is energy stored by plants through photosynthesis. (This last value is comparatively small and commonly neglected.)

2. Water balance.--Water balance is determined by partitioning precipitation P as follows:

$$P = E_t + R + D + \Delta S \quad (2)$$

where E_t is evapotranspiration, R is surface runoff, D is water entering the ground water through deep percolation, and ΔS is change in water storage in the profile.

3. Momentum balance.--Vertical transfer of horizontal momentum to the surface can be estimated from measurements of friction velocities:

$$\tau = \rho u_*^2 \quad (3)$$

where τ is surface shear stress, ρ is air density, and u_* is friction velocity. The friction velocity can be determined from measurements of wind speed in the boundary layer and use of the log-profile law:

$$\bar{U}_z = \frac{U_*}{k}\left[\ln\left(\frac{z-d}{z_o}\right) + \Phi\right] \quad (4)$$

where $\bar{U}_z$ is mean wind speed at height z, k is the von Karman constant (0.4), d is wind speed displacement height, and z_o is the roughness parameter. The terms z_o and d are characterized by the surface configuration and can be determined from wind-speed-profile measurements. The term Φ is a correction for adiabatic influence and is a function of the Richardson number, R_i. The term Φ in equation 4 is usually negligible when the wind speed is high enough to cause wind erosion and is commonly neglected. The Richardson number, an indicator of thermal stability, can be expressed by:

$$R_i = \frac{g}{\Theta}\frac{\dfrac{\Theta_2 - \Theta_1}{Z_2 - Z_1}}{\left(\dfrac{U_2 - U_1}{Z_2 - Z_1}\right)^2} \quad (5)$$

where g is acceleration of gravity, Θ is potential temperature, and

$(\Theta_2 - \Theta_1)/(Z_2 - Z_1)$ and $(U_2 - U_1)/(Z_2 - Z_1)$ are

temperature and wind-speed gradients, respectively.

In order to monitor energy, water, and momentum fluxes more completely at the USGS Geomet stations, the following additional measurements are desirable:

1. Wind speed, now measured at 6 m above the ground, should also be measured at about 1 m above the ground (about twice the height of the vegetation). Once the surface aerodynamics (z_o and d) have been characterized, the wind-speed gradient obtained in this way would enable calculations of the friction velocity and hence the momentum flux.
2. Air temperature should also be measured at an additional height. The existing air-temperature sensor and an additional one should be placed at the same heights suggested above for the two anemometers. Both air temperature and wind-speed data are needed at two heights to measure air stability. Measurements of the humidity gradient (water-vapor pressure profile) can be used to calculate evapotranspiration by the Bowen ratio technique, but the needed accuracy is difficult to achieve because of instrumentation problems.
3. Incoming and outgoing solar and net radiation should be measured for calculation of surface albedo. The albedo indicates whether the surface is wet, dry, or snow covered. Net radiation is important in considerations of energy and water balances.
4. Water in the profile should be measured and modeled, because the activity of water influences many surface processes.
5. The protection offered by the surface vegetation against wind erosion, and the partitioning of the momentum flux between the vegetation and the ground surface, should be characterized. Consult with the USDA's Wind Erosion Research Unit for their procedures and with Dale Gillette, NOAA.
6. The displacement height and the roughness parameter of the log-profile law (equation 4) should be characterized for the surfaces at the Geomet stations. Those parameters change as vegetation character changes.
7. The erodibility of the surface material in a dry state should be characterized. If the material is single grained, the erodibility is a function of grain-size distribution. If the material is aggregated into secondary particles, its erodibility is a function of aggregate-size distribution and aggregate stability. A consolidated or crustal surface represents another set of conditions even more complex.
8. Lastly, the spatial sampling requirements of the sand- and dust-flux measurements (and others) should be evaluated. Is one getting samples sufficient to characterize the process as intended?

Recommendations for Measurements and Expanded Instrumentation at the USGS Geomet Sites

Dale Gillette
National Oceanic and Atmospheric Administration (NOAA),
Boulder, Colo.

Specific parameters to be measured (table 1):

A. The characteristics to be measured (as related to existing wind-erosion equations) are:

1. Dry-aggregate structure of the sediment. Related to the "I" factor of the USDA Wind Erosion Laboratory (WEL), and to the U_{*t} (threshold friction velocity) of Gillette. This measurement is local and has a scale of a few square centimeters.
2. Nonerodible-element distribution. Related to nonerodible elements of WEL and to L_c (ratio of silhouette area to erodible soil area) of Gillette. Nonerodible elements include vegetation cover (including algal mats) and rock cover.
3. Wind. The probability distributions used for wind are either Rayleigh (one parameter), as with Gillette, or Weibull (two parameters), as with WEL. Actual empirical data from the Geomet stations would be best. The objective is to determine the momentum flux (F') at the ground surface. The first step is to measure the wind speed (U) or friction velocity (U_*) above the vegetation canopy by (1) estimating the drag coefficient from the aerodynamic roughness of the canopy and measuring the wind speed well above canopy height, or (2) measuring the wind profile above the canopy. For neutrally stratified air, U_* may be determined from

$$U(z) = \frac{U_*}{K} \ln[(z-d)/z_o] \qquad (1)$$

Then the momentum flux F' may be determined as

$$F' = \rho_{air} C_D \bar{U}^2 (F'/F) \qquad (2)$$

$$\text{or} \quad \rho_{air} U^2 (F'/F) \qquad (3)$$

where F is momentum flux above the canopy,

$$F = \rho_{air} C_D \bar{U}^2 \text{ anemometer}$$

F'/F is related to L_c, C_D is the drag coefficient, and ρ_{air} is air density.

4. Fetch. Length of erodible material. Related to the term L of both WEL and Gillette.
5. Soil moisture. Combined with wind in C factor of WEL; virtually neglected for sand surfaces by Gillette. The reduction of surface stress is

TABLE 1. Techniques and standards for measurements at Geomet sites

Parameter	Minimum approach/equipment	Ideal approach
1. Dry-aggregate structure	Measure percent mass greater than 0.84 or 1.00 mm; crust thickness, hardness. Use mode of loose material	Measure (a) full seive-size distribution of surface materials, (b) modulus of rupture (if greater than 1 bar), and (c) thickness (if greater 1 cm, won't erode)
2. Nonerodible-element distribution	Determine from visual observations and photographs	Determine from digitized photographs, topographic maps, and L_c: $\frac{\text{silhouette area}}{\text{erodible area}} = f(L_c)$
3. Wind	Measure with one anemometer located well above surface-roughness elements	Add (a) stress plate at ground, or (b) microscale wind profile within roughness element, or (c) two to five anemometers above canopy
4. Fetch	Quantify from visual observations	Quantify by remote monitoring observations plus ground observations over time
5. Soil moisture	Oven-dry samples; correlate with precipitation by empirical methods; correlate with albedo, conductivity	Need to develop
6. Vegetation	See no. 2 above	See no. 2 above
7. Sediment transport	For sand: creep collector, pie tins, drumcatcher, Bagnold catcher, textile bags, textile/Bagnold combination, fly paper	For sand: piezoelectric sensor with logarithmic amplification (Gillette, work in progress), or get signal from pressure transducer under bucket instead of tipping bucket; or (for about $60 million) an optical array probe (OAP) particle-measuring system (PMS), or visibility (mass concentration) meter, in which $V = aM^{-1}$ where M is mass concentration. Unfortunately, these systems depend on optical characteristics of the particles and are very vulnerable to damage in the field
	For dust: petri dishes or marble; records dust settlement, not flux (mass concentration)	Automated particle counter as present on Geomet station #1. Fancier models are available with manifold intake for measuring at different levels and at different particle-size distributions; or electrostatic precipitators

expressed as

$$0.5 \frac{W}{W_{15}} \quad \begin{matrix}\text{(actual soil moisture)} \\ \text{(potential moisture at 15 b pressure)}\end{matrix}$$

and is measured in newtons/m^2.

6. Vegetative cover. Equivalent to R of WEL, part of L_c of Gillette.
7. Sediment transport.
8. Ridge roughness (K). Can be ignored, as it is an insignificant influence on erosion of desert surfaces.

B. What time scale is optimum for monitoring? The minimum acceptable period of record is 5 years, which is only a snapshot. For comparison, the longest period of record for geophysical monitoring in the United States is that for CO_2 at Mauna Loa, Hawaii, a period of about 30 years. A reasonable minimum would be 10 years, but the lifetime of project funding is usually much less, and a problem of data storage usually develops.

Soil-Moisture Measurement

G.I. Smith, U.S. Geological Survey,
Menlo Park, Calif.

Several geologic processes depend on the chemical activity of water in soils. This factor differs from moisture content because even after all liquid water has been lost, water in vapor form continues to react with minerals, although in some instances at lower effective concentrations. The effective concentration of water (a_{H_2O}) is defined as the ratio of the activity in a particular solution to the activity of pure water, under the same conditions of temperature and pressure. The chemical activity of any water in vapor form is the ratio of the partial pressure of the water vapor in question (p_{H_2O}) to the partial pressure of vapor that is in equilibrium with pure water, under the same conditions of temperature and pressure ($p^*_{H_2O}$) These ratios are numerically related, by definition, to the meteorologist's "relative humidity" (RH):

$$RH = \frac{p_{H_2O}}{p^*_{H_2O}} \times 100 \qquad (1)$$

Therefore, when both liquid water and its vapor coexist in a soil, if at equilibrium,

$$a_{H_2O} = p_{H_2O} \qquad (2)$$

and if the water is pure,

$$\frac{p_{H_2O}}{p^*_{H_2O}} = a_{H_2O} = 1 \qquad (3)$$

and RH = 100 percent.

A device to measure the activity of water in soil gases in the field has been devised by Fred Trembour (USGS, Denver). It is most useful for long-term (about 1-year) measurement of (1) relative humidity, or a_{H_2O}, and (2) temperature at a succession of horizons in a soil or rock. The values measured are the integrated effective chemical activity and temperature, as they pertain to an ongoing chemical reaction, for the period of measurement. All chemical weathering involves these variables, and gaining a knowledge of them by other means is difficult or expensive or both. The sensors are two plastic vials, calibrated in the laboratory for rate of water loss as a function of temperature. The vials are partly filled with water and buried at the same horizon in the soil. One is exposed to the soil atmosphere, and the other is encased in a desiccant. The "exposed" vial loses water in proportion to the combined effects of temperature and the relative humidity of the soil gases; the other vial, in a relative humidity of 0 percent, loses water solely as a function of temperature. The vials must be removed and weighed each year.

The author and I. Friedman have been testing these devices in the southeastern California desert. We have data for 1 year (4/83 to 4/84), and the method appears to be producing reasonable results. However, more testing and better methods of annually placing and removing the sensors are needed.

Instrumented Field Sites

Jack N. Rinker
U.S. Army Engineer Topographic
Laboratories, Center for Remote Sensing,
Fort Belvoir, Va.

Research of the Center for Remote Sensing (CRS) is directed toward the development and evaluation of remote-sensing techniques for obtaining general terrain information and for detecting specific items, materials, or conditions. Information is needed in subhumid regions for such factors as probable locations of usable water, surficial characteristics affecting cross-country movement and aircraft landing sites, potential for dust generation, and soil-mantle depth and characteristics. Involved in these research efforts are analyses of image-pattern elements and the correlation of spectral and radiometric measurements. Over the years, many useful relations have been established among landforms, soil texture, and vegetation, between landforms and types of materials, and between vegetation and depth of soil mantle, but many more relations remain to be evaluated for their practicality and universality.

We recognize a critical need for fieldwork on eolian processes in desert regions. Such work should include long-range measurements of wind-velocity profiles, of surface characteristics (including vegetation), of soil-mantle characteristics, and of characteristics of the airborne sediment load. The USGS Geomet sites are a first step in this direction, and more sites should be set up. Instrumentation at each site should be expanded both laterally and vertically. Because this undertaking will be large,

and because the information is needed by several agencies, it should be a joint effort as far as possible in terms of money, equipment, and personnel. Although the USGS Geomet stations and the ETL-CRS instrumented test sites were established for different purposes and are in different climatic zones, they collect similar types of information. Our CRS research is directed toward the radiation environment and an evaluation of the factors that influence it. Consequently, our site at Fort Belvoir is instrumented so that we can measure different backgrounds and targets for soil moisture and soil-temperature profiles, air-temperature profiles, wind speed and direction, dew point, soil heat flux, incoming and outgoing radiation, and radiometric brightness (8-14μm wavelength band). (A list of the instruments used at the CRS site is appended.) These measurements are the minimum that we need to understand the ever-changing thermal characteristics of surfaces and their corresponding radiation variations. Note that these same factors--soil moisture, thermal conductivity (heat flux), and temperature--also establish the susceptibility of a given soil to wind movement. Because the USGS is interested in wind erosion and associated characteristics of the airborne sediment load in relation to wind velocity, many of their measurements and instrumentation needs overlap those of ETL-CRS. The exceptions are their measurement of sediment load and our measurement of soil moisture, heat flux, radiation exchange, and the infrared radiation brightness of surfaces. The predictive models that we are developing are limited to moist temperate regions. We need to extend such models into arid regions, and the Geomet sites can provide the needed measurements. With more instruments, they can enlarge their data base to support other modeling efforts (NASA/Goddard, Optimetrics/Air Force, and the U.S. Army Engineer Waterway Experiment Station or USAWES).

To better understand erosional and depositional processes in unconsolidated materials and to develop realistic models, measurement of the texture of the airborne sediment load in relation to wind velocity and soil-mantle characteristics is critical, and this effort must be increased. As no suitable device for measuring characteristics of the airborne sediment load over long periods of time is yet developed, this phase will in itself be experimental. Because vegetation acts as a barrier or filter to the wind stream at the surface and thus greatly alters air-flow characteristics, it should be examined in greater detail with reference to spacing, species, envelope shape, internal structure, and porosity.

Of necessity, the Gold Spring Geomet site had to be fenced to protect it from grazing cattle. This fencing has noticeably changed the vegetation, at least its density: the enclosed area now supports more vegetation than does the area outside, and is probably no longer representative of local conditions. The Gold Spring station has, in itself, induced turbulence and needs a "cleaner" arrangement. We should be able to find a better type of tower that we all could use, one that is stable, portable, easily erected and taken down and one that offers a minimum of wind resistance. Those involved in instrumentation, field measurements, and modeling should, as a group, visit each agency's instrumented sites and the proposed Jornada site and prepare a joint recommendation for an increase in instrumentation.

Instrumentation at the ETL-CRS Test Site, Fort Belvoir, Va.

(distances are above, below, or at ground surface, as appropriate)

Air temperature, Tower 1: 10, 50, 120 cm, 2, 3 m
Air temperature, Tower 2: 10, 50, 120 cm, 2, 3, 4, 6, 8, 10, 12 m
Soil temperature, Plots 1-4: 1, 4, 10, 20, 40, 80, 160 cm
Soil heat flux, Plots 1, 2: 4, 12 cm
Soil moisture, Plots 1-4: 4, 12 cm
Precipitation, tipping bucket method
Dew point temperature
Wind speed, Towers 1, 3: 120 cm
Wind speed, Tower 2: 15 m
Wind direction, Tower 2: 15 m
Incoming short-wave radiation (Swi): 0.28-2.8μm
Incoming long-wave radiation (Lwi): 3-50μm
Net short-wave radiation, Plots 1-3: 0.28-2.8μm
Brightness or apparent blackbody temperature
Surface features: Plots 1,4, cut grass, Plot 3, uncut grass, Plot 2, bare soil, Plot 5, gravel
M114 armored reconnaissance vehicle

Characterization of Vegetation and other Nonerodible Elements

Melvin Satterwhite
U.S. Army Engineer Topographic Laboratories
Center for Remote Sensing, Fort Belvoir, Va.

Vegetation stabilizes the soil surface and, by altering the flow of air and water, affects deposition and erosion of surface particles. At all sites of sensor systems or monitoring nets, two types of maps should be prepared, one showing distribution of plant communities and geomorphic features, and the other showing distribution (in percent) of bare, inorganic surface and of each of the three vegetation types listed below.

The total vegetative cover is divided into its physiognomic (life-form) parts, for each of which the cover, height, and seasonality should be described. The vegetation can be described simplistically as:

1. Mat-formers: algae, moss, lichen
2. Herbaceous plants: grasses, herbs
3. Woody plants: shrubs and trees

This general scheme can be subdivided into very detailed classes at the species level. Classification systems have been developed for local, regional, continental, and global vegetation.

As plants progress through their annual growth cycle, differences occur in the percentage of stems, branches, and leaves that make up the canopy. The seasonal cycle of active plant growth and dormant stages varies by species. Thus both the seasonal growth and the type of vegetation affect geomorphic processes in complex ways.

Plant species are indicators of surface or near-surface substrate conditions, such as chemistry, moisture, and texture. These plant/factor associations must be ascertained from field investigation. The plant species' soil-binding versus soil-passing characteristics should be described. Some plants may allow the passage of windblown particulates, whereas others trap them. The latter type must survive partial burial either by rapid growth or by a specialized canopy whose lower part is a catching type and whose upper part is a passing type. The characteristics of the catching- and passing-type canopies, such as those of mesquite and ephedra, require study. Species such as mesquite can stabilize a surface because the plant can survive burial by means of adventitious root growth. Profiles in coppice dunes can document recent periods of dune stability and dune instability, but the time-rate sequence must be studied; for example, the height of the shrub crown above the soil surface and the presence of litter beneath are indicators of present-day stability.

In wind-erosion equations, the vegetative roughness factor summarizes several vegetative parameters, but different plant parts (leaves, flexible stems, and rigid stems or branches) may have different roughness values. In order to characterize a given locality, a roughness value must summarize all values for a physiognomic class, vegetation type, or plant community.

Vegetation can be readily described by using large- to medium-scale aerial photography in association with conventional phytosociological sampling procedures. Satellite imagery can be used for general regional vegetation investigations, by association of the various image patterns with different plant communities. Numerous techniques are available for describing the vegetation within map units of an image.

Factors that affect the erodibility of inorganic surface materials should also be studied: the distribution of salt crusts (powdered or indurated), of granular surfaces (gravel and cobbles or sand, silt, or clay particles), of bedrock, moisture levels, and surface soil structure (granular or vesicular). Several of these surface characteristics can occur in combination and can vary within very short distances in arid and semiarid regions.

Military Aspects of Desert Processes

Ponder Henley
U.S. Army Engineer Topographic Laboratories
Center for Remote Sensing, Fort Belvoir, Va.

The military significance of terrain is well known, and the ability to predict terrain conditions and their effects on military operations is a national necessity. The use of increasingly delicate and sensitive equipment in the modern battlefield environment requires an increased ability to predict and measure surface and atmospheric conditions. Dust generated by vehicles, by wind, and by explosions affects visual and electro-optical visibility and performance of equipment. The predictability of potential dust hazards by field and remote-sensing methods is thus of great interest to the Army, and cooperative work toward this goal with NOAA, USDA, and USGS is desirable. NOAA is modeling and measuring the effect and character of atmospheric dust; USDA is working with problems of soil erosion by wind and methods to predict and prevent soil removal; the USGS is examining processes that shape desert surfaces; and the Army is looking for ways to predict, by remote-sensing techniques and interpretation, areas that produce dust due to military operations.

Through cooperative efforts by these agencies, some problems can be lessened. The use of remote sensing to characterize the surface (source materials, wind regimes, nonerodible elements, and soil moisture), coupled with the wind-erosion and dust-production formulas developed by NOAA and USDA, may allow some prediction of dust potential in a given area. Research is needed in the methods used to characterize nonerodible elements of the surface (vegetation, soil crusts, gravel veneers, and moisture). The remote-sensing research should include photointerpretation techniques and spectral measurements to characterize the various elements that could be used as indicators of surface conditions.

Influence of Chemical Weathering

Judy Ehlen
U.S. Army Engineer Topographic Laboratories
Center for Remote Sensing, Fort Belvoir, Va.

The effects of wind erosion have generally been considered secondary to effects of water, even in desert environments. Although wind has obviously played a significant role in forming desert landscapes, many desert landforms and surface textures may be relict from past humid climates. The effects of even slightly more water than presently available in arid lands probably played a major role in forming these features. For example, pans and tafoni (honeycomb weathering) probably were originally formed by chemical weathering and

have been merely modified and enlarged by wind erosion. Chemical weathering is active even in an arid environment, particularly in porous, fractured rocks. Although desert varnish and other coatings and crusts may effectively seal the rock surfaces, fractures allow moisture to enter the rocks. Formation of salt crystals, and the freeze-thaw mechanisms that accompany great variations in diurnal temperatures, may strongly affect landform development in arid lands. Subsurface weathering above the water table has been suggested as the primary cause of many landforms in fractured sandstone and granitic rocks in presently arid or semiarid regions; such fractures not only may have controlled the development of these landforms in past, more humid, temperate environments, but they may also control development in today's arid environments. In porous, highly fractured rocks, the variations in fracture spacing, fracture type, and grain size may control the shapes of resultant landforms, whereas the amount of moisture available may merely affect the rate of their development.

Heat-Balance Investigations

Melvin Marcus
Laboratory of Climatology/Department of Geography, Arizona State University, Tempe, Ariz.

The establishment of the USGS Geomet network is an important beginning in understanding desert processes at the earth-atmosphere interface. Climatic investigations in three areas can enhance the current effort: (1) increased measurement and determination of factors affecting air movement near the surface and transport of particles; (2) development of full heat-balance relations, including all aspects of the radiation balance; and (3) relation of the Geomet station observations to the regional climatic network and synoptic climatology.

The first issue has been addressed by J.F. McCauley and others, D.A. Gillette, and E.L. Skidmore in this report. The second question is considered by Skidmore and J.N. Rinker, but I would like to elaborate upon it. The chain of events that produces desert landscapes relies on important links to the atmosphere, especially heat balance and water balance. These factors, in turn, significantly affect weathering processes, rates and timing of eolian erosion and transport, and the nature of the vegetation cover (expressed in surface roughness).

The full set of heat-balance components should be known in order to allocate meteorological cause and effect. For example, short-wave and long-wave radiation fluxes react differently depending on such factors as surface material, soil moisture, and snow cover. These differences feed back through the weathering system and the production of movable sediment grains. We need not, however, monitor all heat-balance components (or the elements from which they are determined) on a continual basis. The time and cost prohibitions are serious. In any event, sampling by season and weather type can provide a satisfactory link to process. Such sampling can be accomplished with 48-hour runs of a portable instrument array that can be brought to each Geomet site as appropriate. These measurements are an example of how cooperative efforts with other organizations (such as universities and the Office of the State Climatologist) could expand the instrument and personnel base.

Heat-balance investigations should discriminate transfers by sensible heat, latent moisture flux, conduction toward or away from the surface, and radiation. A basic measurement array should include two levels of temperature, vapor, and wind speed; incoming and outgoing short-wave radiation; incoming all-wave radiation; net all-wave radiation; two levels of ground temperature; temperature of precipitation under snow-cover conditions; and soil moisture. If possible, infrared thermometers should also be available to measure ground, cloud, and sky temperatures. Important goals of this effort should be to obtain meaningful comparative data and to explain the interplay of land-surface properties with physical climatology in the several desert types under study.

One of the major gaps in climatological research is the determination of scale linkages between micro-, meso-, and macro-climatic events and phenomena. The Geomet desert stations provide an excellent opportunity to attempt to relate sets of highly localized data to ongoing longer term, synoptic weather patterns. Such relations require analysis not only of daily Geomet station weather but of surface and 500-mb weather charts and of satellite weather imagery.

We are just beginning to realize many of the potentials for remote sensing as finer resolution imagery is being developed. We still need to make meaningful ground-truth validations of the imagery. Both the interface physical climatology and synoptic assessments discussed above provide excellent means to this end.

Part II: Relevance to Paleoclimatic Studies

General Statement

Juergen Reinhardt
U.S. Geological Survey, Reston, Va.

Recognizing that local climate is a complex interplay of many factors both physical and biological, we must increase our efforts to understand local climates and their perturbations. Integration of data from Geomet stations over various time periods should enable us to understand

better the differences in scales of change--oscillations, fluctuations, or discontinuities--that may be recorded in the sedimentary record of desert environments. The uniqueness of every desert and of virtually every spot in the desert requires that our data sets be horizontally integrated, but without degrading their quality. Data have been collected in an integrated manner in a variety of other sedimentary environments. For example, along shorelines, long-term tidal gauge records indicate that the eustatic sea level is rising, yet local marine regression is being produced (at least in the short term) by deltas and barrier islands that are prograding due to a local surplus of sediment. Similarly, local perturbations in surface or groundwater flow or changes in wind pattern can produce local changes in aridity that are out of phase with worldwide or even regional trends.

Magnitude of Changes in Past Climates

G.I. Smith
U.S. Geological Survey, Menlo Park, Calif.

Abundant evidence exists for major changes in past climates in all parts of the world. In arid regions, now identified by their low precipitation relative to evaporation and evapotranspiration, evidence of less aridity in the past is abundant, but evidence of greater aridity appears to be less commonly recorded.

Studies of the magnitude of past climate change in now-arid regions must first identify the elements of climate (such as precipitation, temperature, wind, humidity, storm tracks, and seasonality) that are of most interest. Most paleoclimate indicators ("proxy data") are indirect indicators of several elements of climate. Interpretive difficulties arise from this ambiguity when reconstructing past climates themselves. However, many measurements of the proxy data--of stream-flow increases, erosion intervals, lake expansion or shrinkage, periods of aridity and eolian activity--are records of geologic processes, and for purposes of reconstructing variations in near-surface geologic processes caused by climate changes, they are direct measurements.

Both the intensity and magnitude of past climatic cycles also set the stage for the character of the landscape that preceded the present. Knowledge of this starting point is necessary to reconstruct correctly the processes that led to the present landscape, as some of its characteristics may have been inherited from the earlier forms.

My own interests lie in the fundamental causes of major climatic change. Much evidence indicates that high-latitude, glacial-interglacial cycles are forced, in part, by the global orbital perturbations that become most additive on cycle lengths of about 20,000, 40,000, and 100,000 years. Some evidence exists, however, that although these cycles are represented by variations in the low-latitude sea-surface temperatures and $CaCO_3$ content, and by mid-latitude continental pluvial changes, the pluvial cycles of largest magnitude found in the record are forced by a 400,000-year orbital eccentricity. Much more work needs to be done to test the latter hypothesis.

Investigating Climate Change

Stephen G. Wells
University of New Mexico, Albuquerque, New Mex.

Climatic changes involve changes in the solar-energy regime of a given region that affect (1) water hydrology, (2) air movement, and (3) heat energy (temperature). The adjustments of these variables to climatic change are recorded in the geology of the earth's surface. A problem facing those who attempt to interpret climatic changes from the geologic record is to determine the sensitivity of a particular geomorphic system to climatic change, and therefore how well it records climatic change. As indicated in this workshop, our present understanding of how the atmosphere and the earth's surface interact in modern times is poor; therefore, attempts to reconstruct past interactions are at least as poor.

Because the earth's surface is the boundary where the biosphere, atmosphere, and hydrosphere interact with geologic processes, the surface geologic record reflects many factors in addition to climate. In order to evaluate climatic effects accurately, these other variables must be studied, too. As pointed out by Schumm and Lichty (1965), the variables can be classified as independent and dependent:

Independent	Dependent
Time (geochronology)	Vegetation
Geology (lithology, structure)	Total sediment yield
Climate	Total discharge
Tectonic relief	Morphology and other landform characteristics

Evaluations of interactions (past and present) between climate and the earth's surface require that processes be analyzed over time scales that are appropriate to the methodology and degree of accuracy available. For example, the impact of climatic change on geologic processes could be evaluated for the following time periods, using the following methods:

1. Historic (less than 200 years ago): by long-term monitoring using Geomet stations, photoarchive analysis, and satellite imaging.

2. Holocene (200 to 10,000 years ago): by carbon-14 and cultural-artifact dating to develop a time framework and identify moderate climatic fluctuations.
3. Pleistocene (more than 10,000 years ago): by K-Ar, desert varnish, and other absolute dating methods to develop a time framework and identify large-scale fluctuations in climate.

The problem then is, how comparable are the time scales for analog models? Comparing data for historic and Holocene periods may have more validity than comparing data for historic and Pleistocene periods. The use of modern geologic-climatic relations as analogs for past or future conditions must involve a clear understanding that what we see in the present landscape also reflects past processes and events. Attempts to compare one geographic area with another by relying entirely upon remote-sensing methods are difficult and often unsatisfactory, in that the history of one area may differ significantly from another. An area's history cannot be filtered from any analog model.

The study of climatic change for a given time scale and region should involve the following aspects: (1) the causes, types, magnitude, and timing of climatic change; (2) the sensitivity of earth's surface systems to climatic change; (3) the sequence of responses by earth's surface processes; and (4) the interdependence of geologic, atmospheric, biologic, and hydrologic processes during an episode of climatic change. Geomorphologists have recently begun to understand and quantify the interdependence of modern systems, but these studies have not been truly interdisciplinary. As indicated in this workshop, future studies should be interdisciplinary.

Remarks on Desert Research and Data Sources

Theodore Oberlander
University of California, Berkeley, Calif.

Research on desert processes could have two alternative goals: (1) to characterize and quantify the processes currently affecting desert environments, as at the USGS Geomet stations, or (2) to explain the visible details of desert landscapes, which record past as well as present influences, and which may, in fact, be the result of oscillations between processes of different types or intensities. The necessity for the first type of study is too obvious to require further emphasis. Obvious examples of the second type are exposed granitic pediments that formed by slope retreat under semiarid conditions, followed by regolith stripping triggered by loss of vegetative protection due to increased aridity. Much more compressed in time is the phenomenon of cyclic arroyo cutting and filling, which may be either regional or local in scale, depending upon the nature of the triggering mechanism. The point is that process measurement at a specific time (the first goal) may or may not explain all the visible features of desert landscapes, which is a separate problem.

Of course, we can learn the specifics of processes operating in the desert environment by collecting data on what is happening today. But not necessarily only in deserts! To understand the effect of process oscillations we also need data from areas both more arid and less arid, to provide the full range of climatic possibilities that may have been relevant to desert landscapes throughout the period of their development. Accordingly, studies in progress now or in the future in nondesert settings may be pertinent to desert landscapes. Many studies have been made of pediments in the southwestern United States, where they are one of the most conspicuous of all desert landforms, but the studies are inconclusive. The problem is that nearly all of them are studies of moribund pediments, some stagnant for millions of years. The "live" ones, still expanding by vigorous slope retreat, and still unstudied, as far as I am aware, are not to be found under desert shrubs, but in well-vegetated locations such as the Sierra Prieta, west of Prescott, Ariz. (Willhoit-Skull Valley area), under chaparral scrub and grass. To understand pediment formation we need information on processes affecting such places.

Perhaps some sort of data bank or clearing house should be set up for measurements of environmental processes, with attention to the exact characterization of both the climatic context and the procedures followed in data collection. For our own purposes we might be interested in data from subhumid to hyperarid regions, but coverage of all climates, including cold and wet ones, would make such a fund of information useful to a wider audience. Perhaps the USGS could organize and publicize such a data bank. For example, slope forms in the northern Great Basin (presently arid) give more than just hints that they were once subject to cryergic (periglacial) processes. Likewise, the effects of hurricane precipitation in a humid, deforested environment might shed light on the effects of torrential downpours in a desert setting, where a geomorphologist is rarely on the scene during the crucial hours (which are often at night).

A specific example illustrating the value of such a data bank is the work of one of our graduate students in the Forestry Department. He has just completed a superb dissertation on talus processes in the Venezuelan Andes. It contains many original conclusions based on voluminous data collected under very trying conditions. Perhaps the information will be dribbled out in publications over the years, but interested persons should know about this work now, and have access to it as a unit. We need a more organized system for learning about such research that is pertinent both to present deserts and to features formed during less arid interludes in desert regions.

General Comments

Erhard Schulz
University of Würzburg
Würzburg, West Germany

1. A prerequisite for continuing work in arid lands is to define the landscapes or environments in which the research or measurements are done, in order to ensure that correlations are made only between comparable environments.
2. Time is an important factor in interpreting physical environments, which are only in part the results of present climatic conditions; many are relict and reflect processes that operated under different climatic conditions.
3. Stable landscapes that have sufficient rainfall and permanent, diffuse vegetation, and which are formed by relatively uniform processes, are very different from unstable landscapes subject to catastropic events. "True" deserts seem to be stable environments, whereas many areas described as undergoing desertification are unstable.
4. Desert climate is characterized not only by low precipitation and strong seasonality, but also by irregular and unpredictable rainfall in all seasons.
5. "True" desert vegetation must undergo a great quantitative change before it changes in quality following climatic fluctuations.

Interpretation of Arid Landscapes: Some General Ideas for Future Research

John C. Dohrenwend
U.S. Geological Survey, Menlo Park, Calif.

To achieve a comprehensive understanding of desert landscapes, much additional research is needed to answer the following questions:

1. What processes operate in and on arid landscapes?
2. How do these processes interact and how are they interrelated?
3. How sensitive are these processes to climatic change? What processes dominate under specified climatic conditions?
4. At what rates have these various processes operated over time? For how long? In what sequence?

To determine what processes are presently operating on the landscape, additional field-based measurement, monitoring, and analytical description of active processes are required. Some knowledge of the general geology of a region provides a useful framework for such investigations, but detailed information directly relevant to specific monitoring sites is essential to this work. The results of monitoring active processes cannot be usefully applied to a general understanding of landscapes unless the geologic contexts of the monitoring sites and their immediate vicinities are thoroughly and precisely documented and analyzed.

An understanding of the interrelations between processes can perhaps be best achieved through combining the measurement of active processes and the reconstruction of process changes through time as revealed from analyses of the surficial geologic record. Many feedback mechanisms of process-response operate much too slowly to be detectible by the monitoring of active processes. Yet it is these long-term interactions that are probably most important to the evolution of landscapes. Therefore, a complete understanding of landscapes requires knowledge of: (1) how processes operate and interact, and (2) how these processes and their interactions change through time.

An understanding of what processes are dominant under what climatic conditions requires a very carefully planned and documented monitoring system involving the coordinated simultaneous measurement of multiple processes. Such an effort would require a substantial and very long term commitment of scientific resources. Even if such a comprehensive monitoring effort could be mounted and maintained, its results could not be realistically extrapolated to interpretations of landscapes without precise and detailed knowledge of the surficial geology of the monitoring sites.

Detailed knowledge of process rates and the relative importance of various processes in the shaping of any landscape can be achieved only by a thorough and insightful analysis of the surficial geologic record. To interpret this record for analyses of the types, rates, periods, and sequences of processes responsible for the shaping of a given landscape, three factors are critical. We need precise and detailed time control for the late Cenozoic. We must identify reliable geomorphic and stratigraphic indicators of climate. We must correctly interpret these indicators relative to the types and magnitudes of processes and the directions and magnitudes of climatic change that they represent.

With respect to the development of precise and detailed time control, the following general categories of research are required: (1) verification and calibration of both radiometric and relative age-dating techniques, primarily techniques such as rock-varnish chemistry, K-Ar dating of young volcanic rocks, secular paleomagnetic variations, and analyses of rare light isotopes (^{36}Cl, ^{10}Be, and ^{129}I); and (2) identification of areas where precisely datable geologic phenomena are reliable indicators of climate or process. Ideally, such studies should be conducted in areas where several dating methods can be cross-calibrated and where these calibrated methods can be directly applied to the study of arid processes and landforms.

With respect to geomorphic and stratigraphic

indicators of climate and climatic change, collaborative studies between earth, hydrologic, and atmospheric scientists are required. The validity of geologic indicators of climatic change must first be judged in terms of how well they reflect changes in surficial processes and, in turn, how well process changes reflect changes in meteorologic and hydrologic variables. Also, process changes induced by climatic change must be differentiated from those induced by nonclimatic factors; the two types can easily be confused in the geologic record.

Human Factors in Arid Lands

Howard Wilshire
U.S. Geological Survey, Menlo Park, Calif.

In addition to supporting scientific investigations of present and past climate variability and its causes and products, we should give attention to the present condition of our arid lands and their limits in providing for ever-increasing human demands. We should examine the rates of human consumption of land and water; the primary and secondary effects of massive changes in runoff patterns and in composition of air and water; the changes in local climate; the spread of diseases endemic in arid soils, and the loss and replacement of native plant and animal species resulting from urbanization, agriculture, mining, energy production, silviculture, road building, recreation, military activities, and waste disposal. Such studies are not necessarily on the cutting edge of earth science, and generally do not require expensive or sophisticated monitoring devices. Yet, even very short term responses to human-induced changes in natural states of equilibrium can yield important information on the character and rates of geomorphic processes; thus they can support investigations of past events for which the geologic record is incomplete. Specific subjects for study are:

1. Past disturbances in a large variety of climate-landform-soil-vegetative assemblages, to assess processes of natural recovery and indirect consequences that may affect the human environment, and to provide a basis for planning future uses to minimize adverse effects. Study areas should include abandoned urban sites (mining towns and, if feasible, archeological sites); agricultural land; military and recreational sites; logged lands and those deforested for range conversion; overgrazed rangelands; and waste-disposal sites.
2. The effectiveness of rehabilitation and reclamation efforts. Study areas should include mined sites (such as Black Mesa, northeast of Flagstaff, Arizona), utility corridors, rangeland, and farmland.
3. Urban effects on runoff, composition of air and water, and local climate.
4. Rates whereby the products of historic natural events, such as debris flows, floods, and fire, are modified.

REFERENCES CITED

Breed, C.S., Fryberger, S.G., Andrews, S., McCauley, C.K., Lennartz, F., Gebel, D., and Horstman, K., 1979, Regional studies of dunes in sand seas observed by remote sensing, Chap. K, in McKee, E.D. (ed.), A study of global sand seas: U.S. Geological Survey Professional Paper 1052, p. 305-397.

Breed, C.S.,and Grow, T., 1979, Morphology and distribution of dunes in sand seas observed by remote sensing, Chap. J, in McKee, E.D. (ed.), A study of global sand seas: U.S. Geological Survey Professional Paper 1052, p. 253-302.

Breed, C.S., McCauley, J.F., Breed, W.J., McCauley, C.K., and Cotera, A.S., Jr., 1984, Eolian (wind-formed) landscapes, in Smiley, T.L., Nations, J.D., Pewe, T.L., and Schafer, J.P., eds., Landscapes of Arizona—The Geological Story: University Press, p. 359-413.

Gile, L.H., Hawley, J.W., and Grossman, R.B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico—Guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 p.

McCauley, J.F., Breed, C.S., Helm, P.J., Billingsley, G.H., MacKinnon, D.J., Grolier, M.J., and McCauley, C.K., 1984, Remote monitoring of processes that shape desert surfaces: The Desert Winds Project: U.S. Geological Survey Bulletin 1634, 19 p.

McCauley, J.F., Breed, C.S., Schaber, G.G., McHugh, W.P., Issawi, B., Haynes, C.V., Grolier, M.J., and El Kilani, A., 1986, Paleodrainages of the Eastern Sahara--the radar rivers revisited (SIR-A/B implications for a mid-Tertiary Trans-African drainage system): IEEE Transactions, Geoscience and Remote Sensing, v. GE-24, no. 4, p. 624-648.

McCauley, J.F., Schaber, G.G., Breed, C.S., Haynes, C.V., Grolier, M.J., Issawi, B., Elachi, C., and Blom, R., 1982, Subsurface valleys and geoarchaeology of Egypt and Sudan revealed by Shuttle Radar: Science, v. 218, no. 4576, p. 1004-1020.

Musick, H. B., 1984, Assessment of Landsat Multispectral Scanner spectral indexes for monitoring arid rangeland: IEEE Transactions, Geoscience and Remote Sensing, v. GE-22, p. 512-519.

Schumm, S.A., and Lichty, R.W., 1965, Time, space, and causality in geomorphology: American Journal of Science, v. 263, p. 110-119.

Sheridan, David, 1981, Desertification of the United States: Washington, U.S. Council on Environmental Quality, 142 p.

PARTICIPANTS IN DESERT PROCESSES WORKSHOP

Sue Beard
U.S. Geological Survey
Flagstaff, Arizona 86001

George Billingsley
U.S. Geological Survey
Flagstaff, Arizona 86001

Carol Breed
U.S. Geological Survey
Flagstaff, Arizona 86001

William Breed
1456 Meade Lane
Flagstaff, Arizona 86001

John C. Dohrenwend
U.S. Geological Survey
345 Middlefield Road, MS 941
Menlo Park, California 94025

Judy Ehlen
U.S. Army Engineer Topographic Laboratories
Center for Remote Sensing
Fort Belvoir, Virginia 22060-5546

Dale Gillette
R/E/AR 4, National Oceanic and
Atmospheric Administration
325 Broadway
Boulder, Colorado 80303

Maurice Grolier
U.S. Geological Survey
Flagstaff, Arizona 86001

Paula Helm
U.S. Geological Survey
Flagstaff, Arizona 86001

Ponder Henley
U.S. Army Engineer Topographic
Laboratories
Center for Remote Sensing
Fort Belvoir, Virginia 22060-5546

Guo Huadong
Department of Research Development
National Remote Sensing Center
Beijing, People's Republic of China

Eric Karlstrom
Department of Geography
Northern Arizona University
Flagstaff, Arizona 86003

David J. MacKinnon
U.S. Geological Survey
Flagstaff, Arizona 86001

Melvin G. Marcus
Department of Geography
State Climatology Laboratory
Arizona State University
Tempe, Arizona 85281

John F. McCauley
U.S. Geological Survey
Flagstaff, Arizona 85281

Dorian Mills
Leighton and Associates
4393 Viewridge Ave., Suite D
San Diego, California 92123-1619

Theodore Oberlander
Department of Geography
University of California
Berkeley, California 94720

Juergen Reinhardt
U.S. Geological Survey, MS 908
Reston, Virginia 22092

Jack N. Rinker
U.S. Army Engineer Topographic
Center for Remote Sensing
Fort Belvoir, Virginia 22060-5546

Melvin Satterwhite
U.S. Army Engineer Topographic
Laboratories
Center for Remote Sensing
Fort Belvoir, Virginia 22060-5546

Gerald G. Schaber
Chief, Branch of Astrogeology
U.S. Geological Survey
Flagstaff, Arizona 86001

Erhard Schulz
Geographisches Institut
University of Würzburg
Würzburg, West Germany

Edward L. Skidmore
U.S. Department of Agriculture
Wind Erosion Laboratory
Room 204, E. Waters Hall
Kansas State University
Manhattan, Kansas 66506

George I. Smith
U.S. Geological Survey
345 Middlefield Road, MS 902
Menlo Park, California 94025

Stephen G. Wells
Department of Geology
University of New Mexico
Albuquerque, New Mexico 87131

John Whitney
U.S. Geological Survey
Box 25046, DFC, MS 913
Denver, Colorado 80225

Howard Wilshire
U.S. Geological Survey MS 75
345 Middlefield Road
Menlo Park, California 94025

GPO 785-048/48024