of the stereo model, Equations (64) and (65)

(X_p, Y_p) = normalized coordinates of the location of the viewing-screen, Equations (66) and (67)

(X_R, Y_R) = normalized coordinates of the target in a radar frame, Equations (70) and (71)

$z_R = x_R + iy_R$

Δy_p = half the y parallax, as defined in Equation (34)

ΔY_p = normalized value of Δy_p, Equation (68)

θ = angle of the target in the (x_R, y_R) coordinate system, measured counterclockwise from the positive x axis

ρ = apparent radar ground range at the scale of the radar photograph, uncorrected for relief displacement

Descriptions and Airphoto Characteristics of Desert Landforms

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ABSTRACT: *A brief discussion of desert landforms and their characteristic appearance on aerial photographs is presented. Annotated air photos are included of areas currently being studied at the Terrestrial Sciences Laboratory, Air Force Cambridge Research Laboratories. Air photo interpretation is particularly suited for the assessment of desert surface conditions.*

INTRODUCTION

AERIAL photographic interpretation offers a most effective and efficient means by which terrain studies of desert regions may be undertaken. The Terrestrial Sciences Laboratory of the Air Force Cambridge Research Laboratories is currently conducting such studies on selected desert areas in the Middle East and in the southwestern United States with emphasis placed on geomorphology, structural geology, engineering geology, soils, hydrology and vegetation. In addition to increasing our knowledge of the natural processes at work in desert regions, the present study program should materially aid the Air Force in improving its ability to assess terrain in all environments.

During these studies problems have arisen on the interpretation of surface character of certain desert landforms. It is anticipated that current research in remote sensing will provide the capability to further the interpretability of desert surface conditions.

CAPABILITIES AND LIMITATIONS OF ARID REGION PHOTO INTERPRETATION

Desert lands allow a great amount of information to be gleaned from aerial photoggraphy; more so than any other climatic region. In deserts the barren rock surfaces clearly reveal fractures, bedding and contacts. The general sparsity of vegetation permits runoff to erode gullies that may reflect the grain size of the soil mantle. Vegetation is highly specialized and can provide a clue to the presence of salts or the depth to the water table. Seepage zones and springs reveal their presence by darker tones from increased moisture and resulting denser vegetation. Practically every variation in topography is evident with only a minimum of soil or vegetation to conceal it. The remote southern desert of Israel, the Negev, was mapped recently with aerial photographs. At the end of the program it was stated that this map would not have been possible without aerial photography (Bentor, Y. K., 1952, p. 157).

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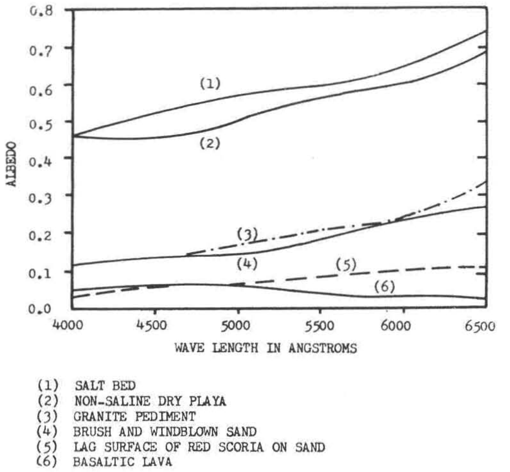


FIG. 1. Spectral diffuse reflections of desert surfaces. The graph (after Ashburn and Weldon) illustrates the similarity in reflectance between a playa with a salt surface and a dry playa with a clay surface.

Certain techniques of interpretation must be altered in analyzing features of arid regions. For instance, in humid regions cohesive soils usually are associated with darker tones because these soils retain moisture longer than granular soils. In arid regions the clay surface of a dry playa often has greater reflectance than sand surfaces, and clay and salt have almost the same reflectance when dry (Ashburn, E. V., and Weldon, R. G., 1956, p. 585). This emphasizes the difficulty in determining whether a surface is salt or clay—an important decision with respect to engineering potential of the surface (Figure 1).

Microrelief could help to identify the composition of some surfaces. If one could see cracks in the clay surface or pressure ridges and pinnacles in salt, the similarity in reflectance would not be as significant. These cracks and pinnacles are not visible at scales of 1:40,000 to 1:60,000. Without shadows to provide some contrast they may be difficult to see at 1:5,000.

Other events common in deserts such as dust storms and haze may restrict the interpretability of some photography; however, in general the capabilities far exceed the limitations. An amazing amount of detail can be interpreted from conventional black and white photography. The use of color has some supplementary advantages in distinguishing certain problem surfaces, wherein quite different surficial materials may render similar gray tones on black and white photographs.

DESERT LANDFORMS

Deserts are distinguished by interior drainage; rocky, sandy, alkaline and saline soils; highly specialized vegetation; dust storms; high daytime temperatures and great diurnal range; and very little precipitation.

The processes of desert erosion include deflation, corrosion by wind, sheetfloods, and streamfloods. Usually a local base-level rather than sea-level controls most of the erosion and transport by water in deserts. The rare rivers that flow through deserts rise in areas outside the desert and are supplied with sufficient water at their sources to maintain their flow to the sea.

The following paragraphs describe briefly the major landforms that occur in deserts. Having identified a landform, certain valid assumptions about surface conditions and engineering potential of the landform then can be made.

1. RIVER FLOODPLAINS OF THROUGH-FLOWING STREAMS

Examples of major rivers rising outside arid regions are the Colorado, the Nile and the Euphrates. These receive sufficient moisture from rain or melting snow to maintain their courses to the sea. Bench-like terraces of sand and gravel may border parts of the fairly narrow floodplain, and the channel itself may have stretches with sand bars. Frequently terraces become cemented and then may display a zone of caliche. Vegetation may take advantage of the abundant supply of water with thicker growth emphasizing former channels. Through-flowing streams provide access routes into and out of desert areas while deposits along the floodplain provide sand and gravel as well as landing areas for light aircraft and helicopters.

2. STRUCTURAL PLAINS

Where the underlying bedrock rests at a low dip, there is formed a rather flat monotonous landscape, punctuated by shallow dry washes and local depressions. These structural plains or hamadas may be quite extensive. Bedrock forming structural plains presumably would consist either of sandstones, conglomerates or limestone. Shales in arid regions generally will erode too easily to maintain the required flat surface. These surfaces of low relief are readily apparent on air photos, but the identification of the type of bedrock is made more difficult by the level surface and disorganized drainage (Figure 2).

Wind removes the fine-grained products of weathering from the bedrock surfaces leaving a veneer of residual or lag gravels. In the Al Hamad Plain of eastern Jordan and western Iraq, the surface is strewn with the chert that weathers out of the underlying limestone. Vegetation may be restricted to phreatophytes growing along wadi channels and halophytes and phreatophytes in and around local depressions, filled with the fine-grained particles brought down the wadis. Any precipitation falling in such an area runs off the rocks and gravel-strewn slopes into the wadi channels, eventually to disappear into the sandy bottoms after a short run. Some mositure may reach nearby depressions only to evaporate. Logical places to seek water are along the main wadi channels and around local depressions although water from these may often be brackish.

Bedrock underlying structural plains may be used for foundations, or if the rock is limestone, it may be quarried for stone, lime or cement. The wadi channels contain sand and gravel. Depressions may be considered for landing sites depending on their size.

3. PLAYAS

Playas occur in the lowest portions of interior basins and from time to time become the beds of ephemeral shallow lakes (Figure 3). Numerous playas marking the sites of Pleistocene lakes occur in the arid western United States. Some of these still receive water and sediments, but the water evaporates rapidly. A series of playas may be strung together by subterranean drainage so that water can move through the entire basin, a process which may prevent salt from forming except perhaps in the lowest playa of the series. Playa-like depressions occur in other deserts of the world although these may not be playas in the strict sense of the word.

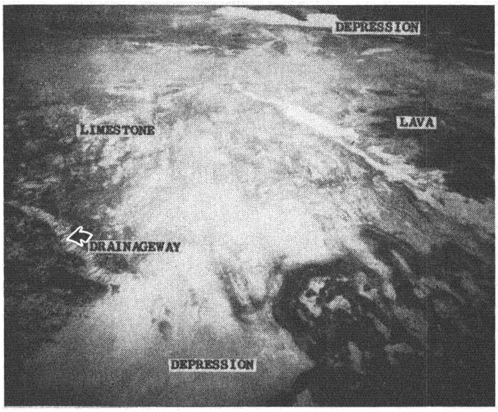


FIG. 2. Structural plain, eastern Jordan. Bedrock forming this structural plain consists of limestone resting at a low dip. Dark-toned lava has flooded part of the surface providing some relief to an otherwise monotonous landscape. The light-toned area in the foreground is a shallow depression slowly being filled with fine-grained sediments.—USAF

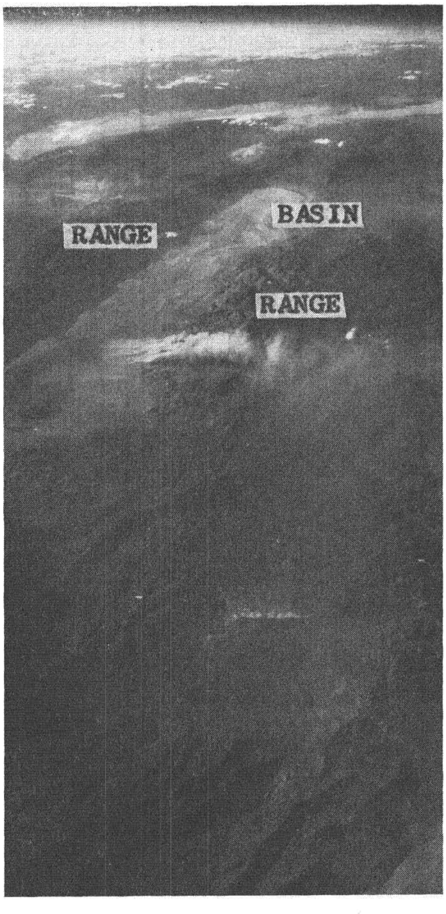


FIG. 3. Interior basin and flanking ranges, northern Nevada. Smokelike dust can be seen being blown off the surface of this soft playa and across the bordering mountains. Surfaces like this become quite powdery when dry, and strong winds may stir up appreciable amounts of dust.—USAF

Playas have many geological differences and have been distinguished accordingly (Clements, T. *et al.*, 1955, pp. 10, 11). For purposes of photo interpretation, playas may be classified more simply according to the relative firmness or hardness of the surface; thus, *hard* and *soft*.

Soft playas generally occur in areas of groundwater discharge (Figure 4). This type of playa includes surfaces that are moist and salt-encrusted as well as surfaces that are rather dry but puffy with thin, intermittent stains of salt. Soft playa surfaces may be distinguished on aerial photos chiefly by lines of drainage, but also by an intricate pattern of tones, ranging from light to dark (Figure 5). The proximity of the watertable to the surface, generally within ten to fifteen feet, allows water to rise by capillary action. Water having reached the surface evaporates to form salt pinnacles and pressure ridges. Such as does not quite reach the surface deposits salt in the sediments to form a bumpy, puffy surface. This consists of a thin crust of clay and silt over several inches of loose powdery material.

Hard playas, in contrast, have firm dry clay surfaces that can support heavy vehicles. These dry playas are distinguished on air photos by lack of well-defined drainage lines, by an even light-gray tone when dry, and by large desiccation cracks. Islands of vegetation also may be used to distinguish hard playas, as may dark-toned stripes that occur near the playa edge (See Figure 4). Occasionally a series of darker tones of gray on a playa betray a recent stand of water and express a variation in the degree to which the surface has dried and hardened (Figure 6). Dry playas generally are sources of potable water, but it may be deep and occasionally too saline for human consumption. Potable water usually may be obtained from sandier sediments bordering the playa. Hard playas are frequently utilized as auxiliary landing fields. In the western United States some of these surfaces are utilized for emergency and scheduled landings by the X-15 aircraft.

Exceptions to this two-fold playa classification exist, as several playas possess extremely hard salt crusts, while retaining the essential characteristics of soft playas. Several hard playas of dry clay are known which possess relatively soft surfaces. In addition, some playas exhibit characteristics of both types. This system has proven valid for hundreds of playas.

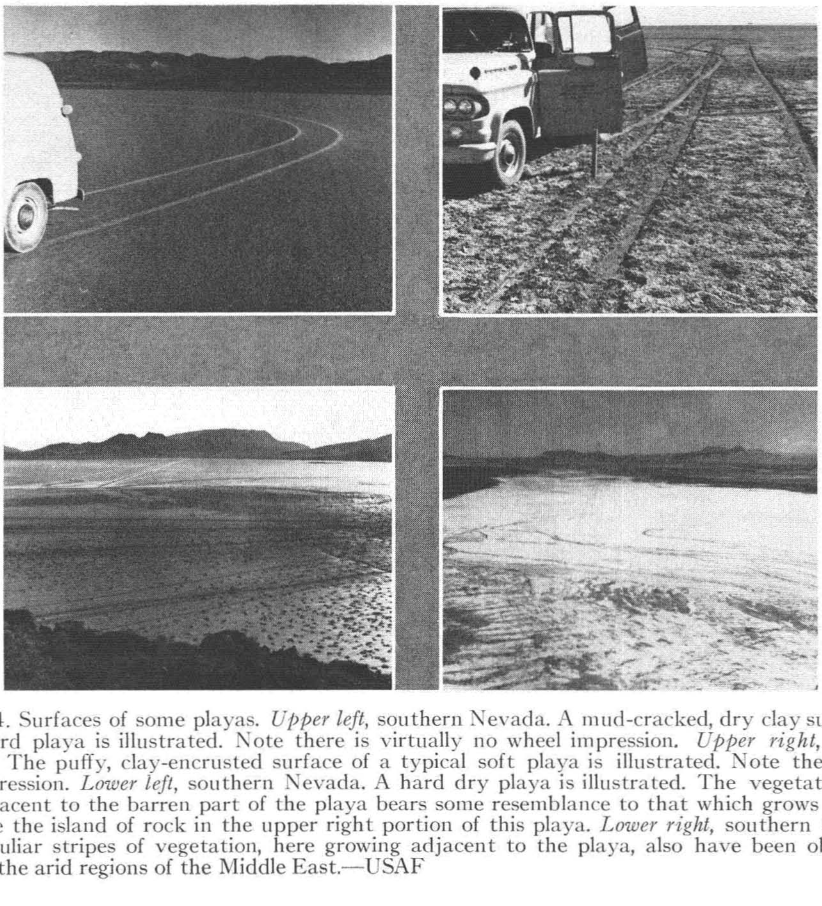


FIG. 4. Surfaces of some playas. *Upper left,* southern Nevada. A mud-cracked, dry clay surface of a typical hard playa is illustrated. Note there is virtually no wheel impression. *Upper right,* southern California. The puffy, clay-encrusted surface of a typical soft playa is illustrated. Note the two-inch wheel impression. *Lower left,* southern Nevada. A hard dry playa is illustrated. The vegetation which occurs adjacent to the barren part of the playa bears some resemblance to that which grows on desert flats. Note the island of rock in the upper right portion of this playa. *Lower right,* southern California. These peculiar stripes of vegetation, here growing adjacent to the playa, also have been observed in washes in the arid regions of the Middle East.—USAF

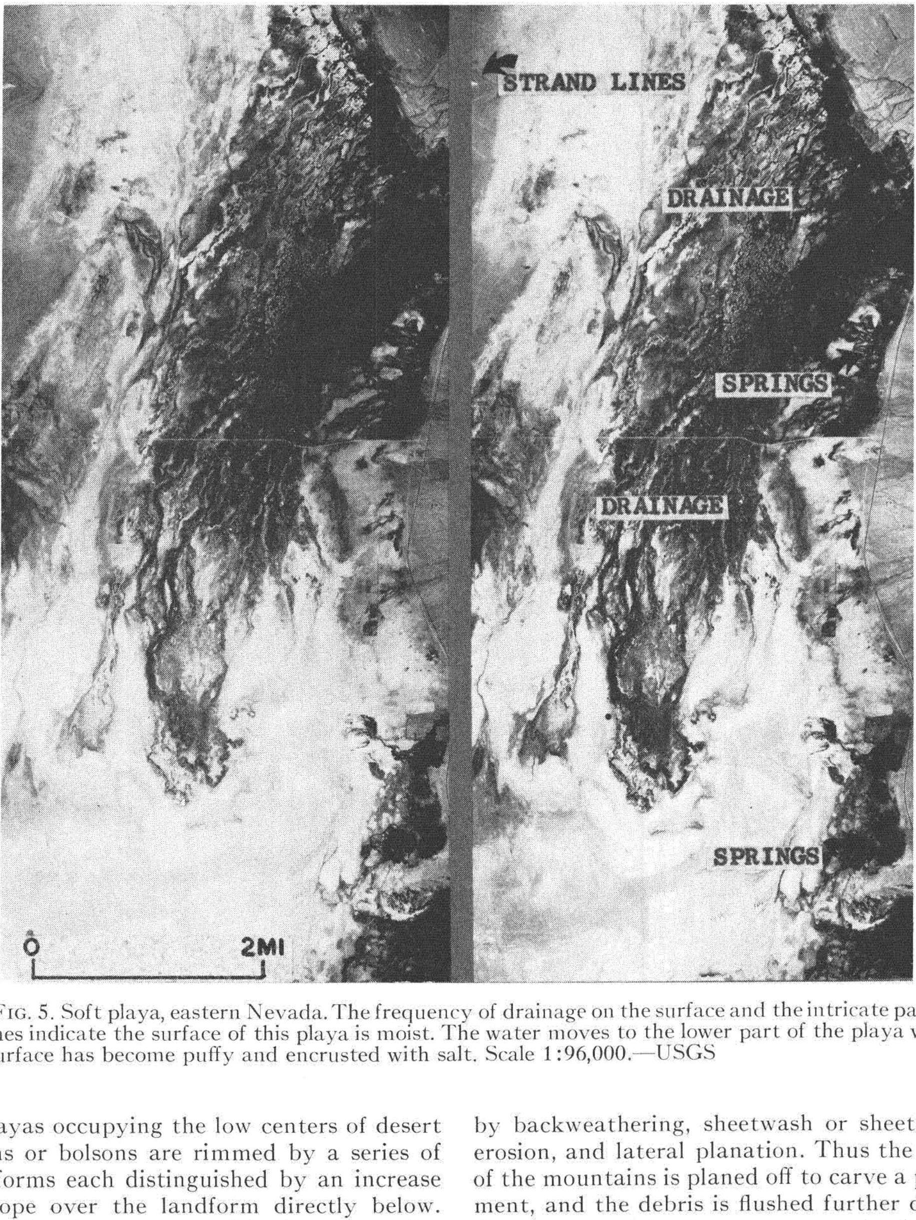


FIG. 5. Soft playa, eastern Nevada. The frequency of drainage on the surface and the intricate pattern of tones indicate the surface of this playa is moist. The water moves to the lower part of the playa where the surface has become puffy and encrusted with salt. Scale 1:96,000.—USGS

Playas occupying the low centers of desert basins or bolsons are rimmed by a series of landforms each distinguished by an increase in slope over the landform directly below. These landforms start with the desert flat bordering the playa, and rise through the encroaching alluvial fans onto the steeper pediment until the front of the bordering mountains is reached. The slopes vary from a few minutes on the flat to a degree or so on the lower fans, increasing to seven degrees or so on the pediment. The mountain front usually is quite steep varying from 15 degrees to nearly vertical (Thornbury, W. D., 1954, p. 284).

The retreat of the mountain front and the formation of these landforms is accomplished by backweathering, sheetwash or sheetflood erosion, and lateral planation. Thus the base of the mountains is planed off to carve a pediment, and the debris is flushed further down the slope to help form coarse-grained fans and bajadas. Some sand and gravel are transported further into the basin to be deposited as the desert flat, while the fine-grained particles ultimately reach the playa (Figure 7).

4. DESERT FLAT

This landform comprises a transition zone between playa and alluvial fan, and displays on the aerial photo some of the characteristics of both. Frequently a distinct change in tone signals the edge of the playa and the start of the flat. A sudden increase in vegetation, the presence of small dunes, and the lack of pronounced drainage also distinguish the desert flat from the playa and the alluvial fan (Figure 8). Desert flats are composed of sand and silt with some gravel and occasional depressions floored with clay that resemble extensions of the playa. Subsurface lenses of sand and gravel provide channels and pools for the accumulation of water to be tapped by wells. Vehicles may cross desert flats without too much difficulty provided areas of soft sand are avoided. Occasionally the clay areas are large enough to be utilized as landing strips.

5. ALLUVIAL FANS AND BAJADAS

Alluvial fans are those fan- and cone-shaped deposits immediately apparent on air photos. Fans are formed where streams emerge from their steeper mountain canyons. As more streams along a mountain front construct fans and as the fans grow in extent, they eventually merge into an extensive alluvial apron or bajada. The surfaces of these landforms are distinguished by the numerous distributaries radiating from the mouth of the canyon (Figure 9). Fans and bajadas both are composed of cobble and boulder gravels and gravelly sand with some silt. The sediments are poorly sorted and poorly graded, and in general the material varies from coarser at the apex to finer at the base. Alluvial fans frequently are drilled for water. The depth of the water table varies from area to area, but the density of vegetation sometimes is a

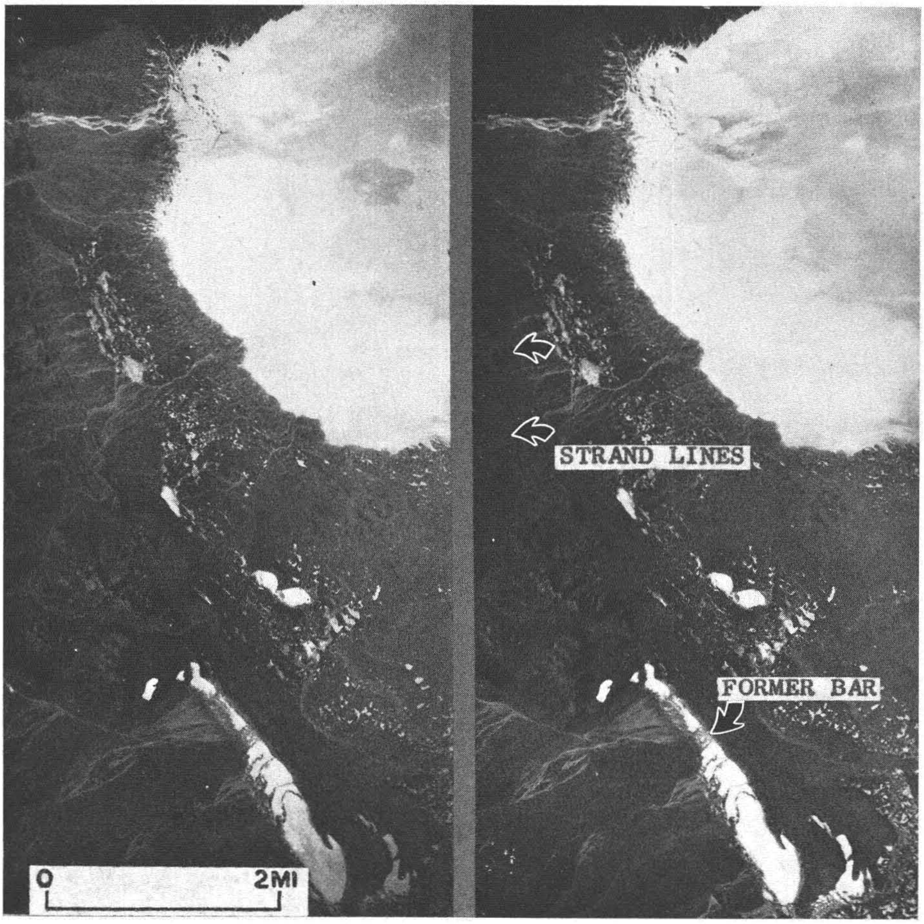
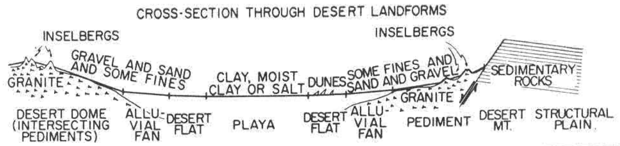


FIG. 6. Hard clay playa, western Nevada. Shallow ephemeral sheets of water that occupy parts of a playa leave surface stains, causing tonal variations such as seen on this dry lake. At times in the history of the ancient lake some strand lines may have stood offshore as bars, trapping fine sediments behind and forming playas in miniature. These strand lines continue to trap sediments during the infrequent rains in this area. The miniature playas are distinguished by light tones similar to those of the main playa. Recent drainage has breached the strand lines in a number of places. Scale 1:96,000.—USGS



LANDFORM	APPROX SLOPE	PI CHARACTERISTICS	PI PROBLEMS*
PLAYA	5"	FLAT, LIGHT TONE, NO VEGETATION, LOWEST PART OF BASIN, DRAINAGE LINES MAY INDICATE SALT.	SIMILAR REFLECTANCE BETWEEN CLAY AND SALT, MAY NOT BE ABLE TO SEE DIAGNOSTIC MICRORELIEF-MUD CRACKS AND SALT PINNACLES, MAY NOT BE ABLE TO DIFFERENTIATE BETWEEN END OF PLAYA AND START OF DESERT FLAT.
DESERT FLAT	15' TO 1°	FLAT, LIGHT TONE, STIPPLED PATTERN OF VEGETATION, DUNES MAY BE PRESENT ON LEE OF PLAYA.	DIFFICULT TO DETERMINE VARIATIONS IN SURFACE MATERIAL, MAY BE UNABLE TO DIFFERENTIATE BETWEEN END OF PLAYA AND START OF FLAT.
ALLUVIAL FAN	1° TO 3°	FAN SHAPE, DRAINAGE, VEGETATION ALONG CHANNELS, SPRINGS AT BASE.	MAY NOT BE ABLE TO SEE SUCH MICRORELIEF AS LOW SCARPS OR LARGE BOULDERS.
BAJADA (COALESCED FANS)	1° TO 3°	UNDULATING SURFACE OF ADJOINING FANS, DRAINAGE, VEGETATION ALONG CHANNELS, SPRINGS AT BASE.	MAY NOT BE ABLE TO SEE SUCH MICRORELIEF AS LOW SCARPS OR LARGE BOULDERS.
PEDIMENT (INTERSECT TO FORM DESERT DOME)	2° TO 7°	RELATIVELY SMOOTH SLOPE ENCROACHING ON MOUNTAIN FRONT, DRAINAGE MAY REFLECT BEDROCK CHARACTERISTICS.	DIFFICULT TO DETERMINE WHERE PEDIMENT STOPS AND FAN OR BAJADA BEGINS, DIFFICULT TO DETERMINE THICKNESS OF OVERBURDEN, PEDIMENT MAY BE ON DIFFERENT ROCK THAN ADJOINING MOUNTAINS. MAY NOT BE ABLE TO SEE LARGE BOULDERS OR DIFFERENTIATE PATCHES OF BEDROCK FLOOR.
STRUCTURAL PLAIN (HAMADA)	2° TO 7°	VERY EXTENSIVE LEVEL SURFACE, MAY BE NUMEROUS LOCAL DEPRESSIONS, NO INTEGRATED DRAINAGE, THIN SOIL MANTLE, ROCK FLOOR IS SEDIMENTARY.	DIFFICULT TO DETERMINE TYPE OF SEDIMENTARY ROCK, DIFFICULT TO DETERMINE THICKNESS OF OVERBURDEN.

* A FUNCTION OF SCALE.

DESERT MOUNTAINS MAY BE COMPOSED OF SEDIMENTARY, IGNEOUS OR METAMORPHIC ROCKS.

FIG. 7. Cross-section through desert landforms. This cross-section illustrates an idealized desert basin. Characteristics and problems of interpretation are tabulated.

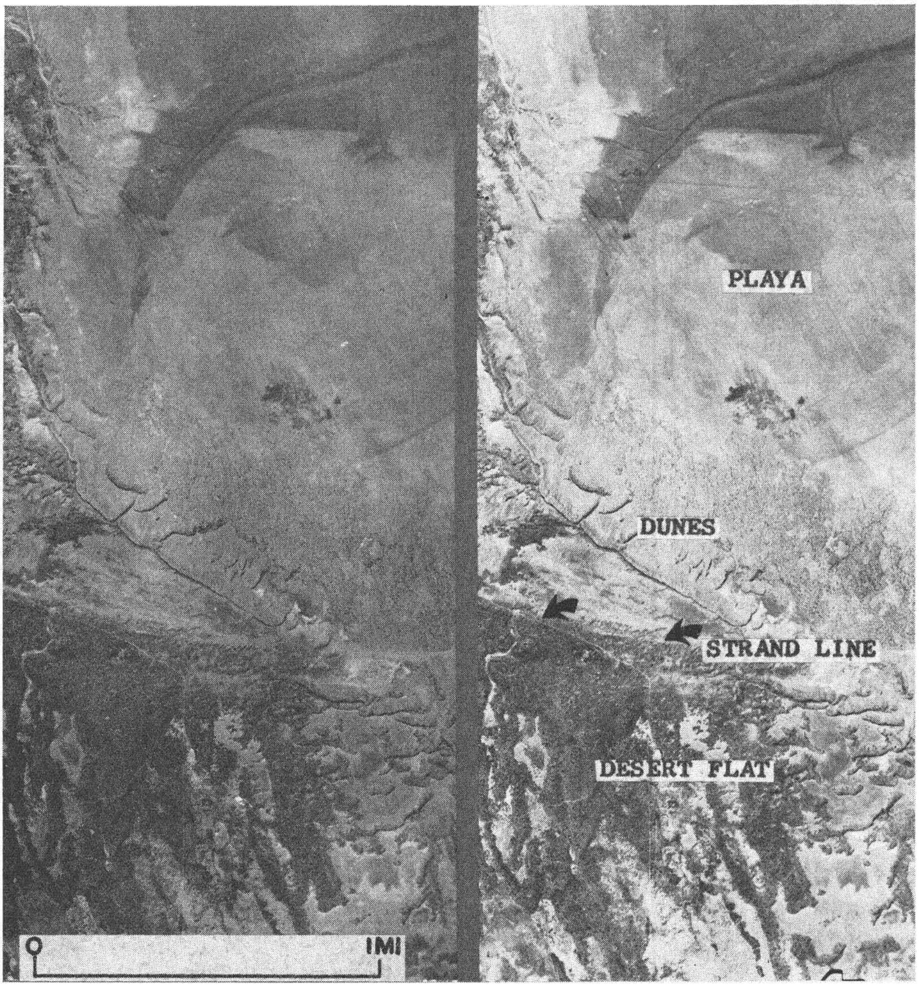


FIG. 8. Desert flat and playa transition, southern California. The barren, hard clay playa changes to low dunes stippled by vegetation. Patches of the playa floor appear between some dunes. A strand line of the ancient lake distinguishes this desert flat. Scale 1:32,000.—PMA

clue. The shallower water table at the base of the fan may cause springs and seepage zones to occur.

Fans and bajadas are a source of sand and gravel. Vehicles may experience some difficulty in traversing the fans depending on the frequency and depth of the distributaries. The lower slopes of these landforms may be utilized as sites for landing strips for airplanes provided the strips are laid out parallel to instead of transverse to the drainage. This orientation avoids unnecessary fills and subsequent washouts from flash floods down the distributaries.

6. PEDIMENTS

Pediments are the slightly inclined rock plains extending from near the base of the mountain rim down toward the basin where they disappear beneath the bajada or alluvial fan. Pediments may be distinguished on air photos by residual knobs of bedrock, and by a greater slope than the adjoining alluvial fans (Figure 10). At times the boundary between fan and pediment is vague and indistinct, especially when the upper twenty feet consists of alluvial material. Pediments may be considered as a transition zone between the alluvial fans and the mountain front. Some information about minimum thickness of the soil mantle as well as its composition may be obtained from air photos by analysis of the gullies and wadi courses. Any soil mantle over pediments is well-drained, and the sloping rock surface beneath ordinarily does not permit water to accumulate. Vegeta-

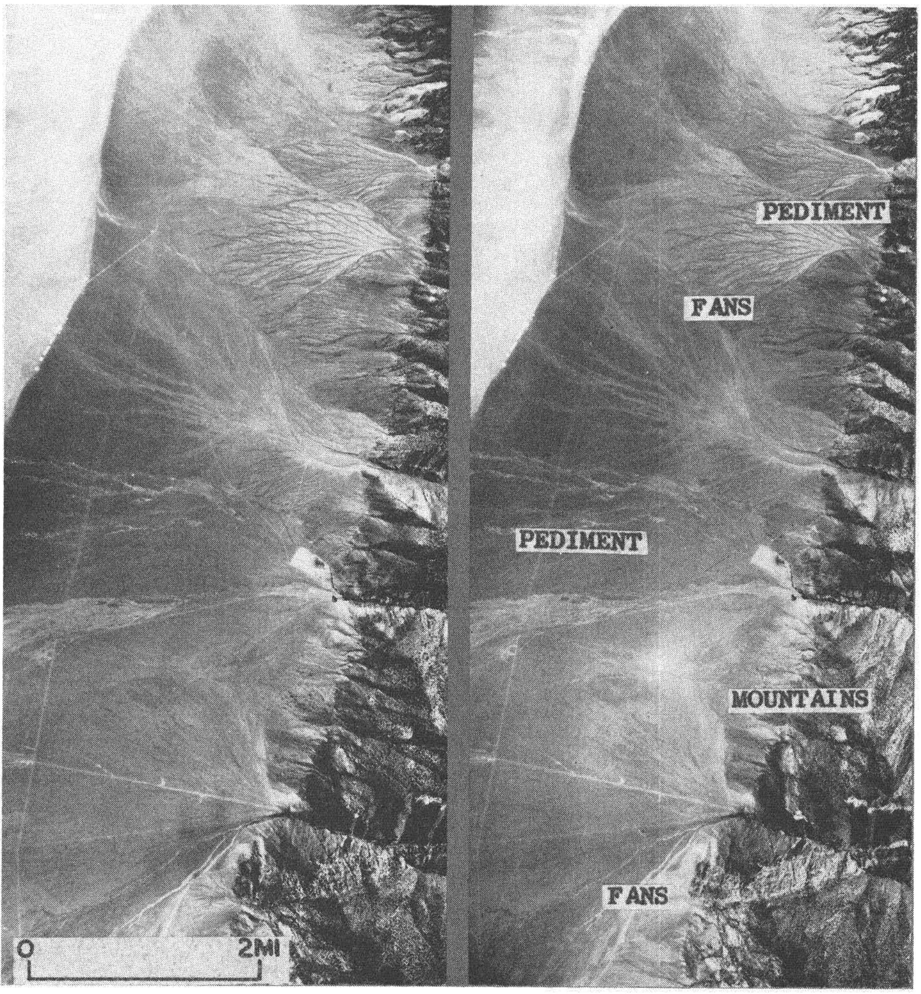


FIG. 9. Alluvial fans and pediment, central Nevada. Coalesced alluvial fans being deposited in this narrow valley are burying the pediment surface. The linearity of the mountain front indicates that the contact between pediment and mountains is a fault scarp. Scale 1:96,000.—USGS

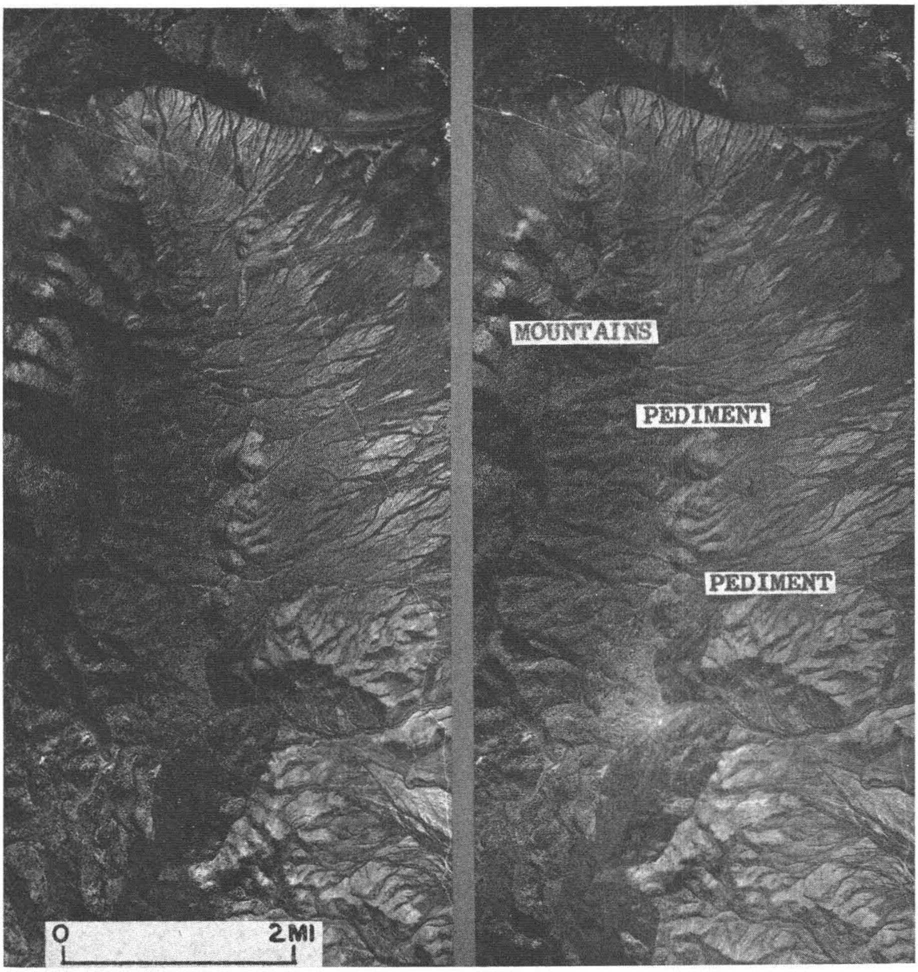


FIG. 10. Pediment and desert mountains, northern Nevada. Outliers or inselbergs of dipping sedimentary rock rise above the surface of the pediment, covered with alluvial sands and gravel. The form of these outliers indicates that this pediment has been formed across the face of the bedding. Scale 1:96,000.—USGS

tion therefore will seek out fractures, hollows, and obstructions to the movement of water such as dikes. The pediments are sources of gravel, and the wadis are good sources of sand.

7. DESERT DOMES

This landform ideally represents the ultimate stage in the cycle of desert erosion. It may be formed on any kind of rock and occurs when pediments finally cut through mountains to intersect each other, leaving a few isolated residual knobs of bedrock. This surface also has been called a pediplain to distinguish it from the peneplain of the humid erosion cycle. Some xerophytic vegetation may exist on the higher parts of desert domes. Because desert domes are essentially extensive pediments, the same restrictions on vegetation and water that apply to pediments, also apply to the upper surfaces of desert domes.

8. DESERT MOUNTAINS

Upland surfaces in the desert vary from low isolated hills to relatively prominent ranges; however, mountains tall enough to intercept precipitation and support stands of timber, do not belong in desert climatic regions.

These upland surfaces may consist of sedimentary, igneous, or metamorphic rocks, or any combination of the three. The mountains themselves are recognized by their increased relief, while the type of rock may be identified by the shape of the topography, by the pattern of drainage, and by other more subtle clues such as bedding and fracture patterns.

Material weathered from rocks of the mountains moves down slope coming first to rest perhaps on a pediment. Flash floods carry great amounts of alluvial material out on the fans. Sand, silt and some fine gravel eventually reach the depression or low area and settle there. The type and nature of the rock greatly affect the amount and to some extent the coarseness of the alluvial material.

The availability of water depends on the presence of channels or layers through which water can move and areas of confinement in which water can collect. Springs and seepage zones may be discerned on aerial photographs not only from the dark tones of increased moisture, but also from the increased vegetation taking advantage of the water.

The various kinds of rock found in desert mountains may be used for foundations, crushed rock, lime, or road material.

9. DUNES

Approximately one-third of the area of arid regions is covered with sand (Holm, D. A., 1960, p. 1369) available for the wind to work into dunes, their shape depending chiefly on the direction and continuity of the

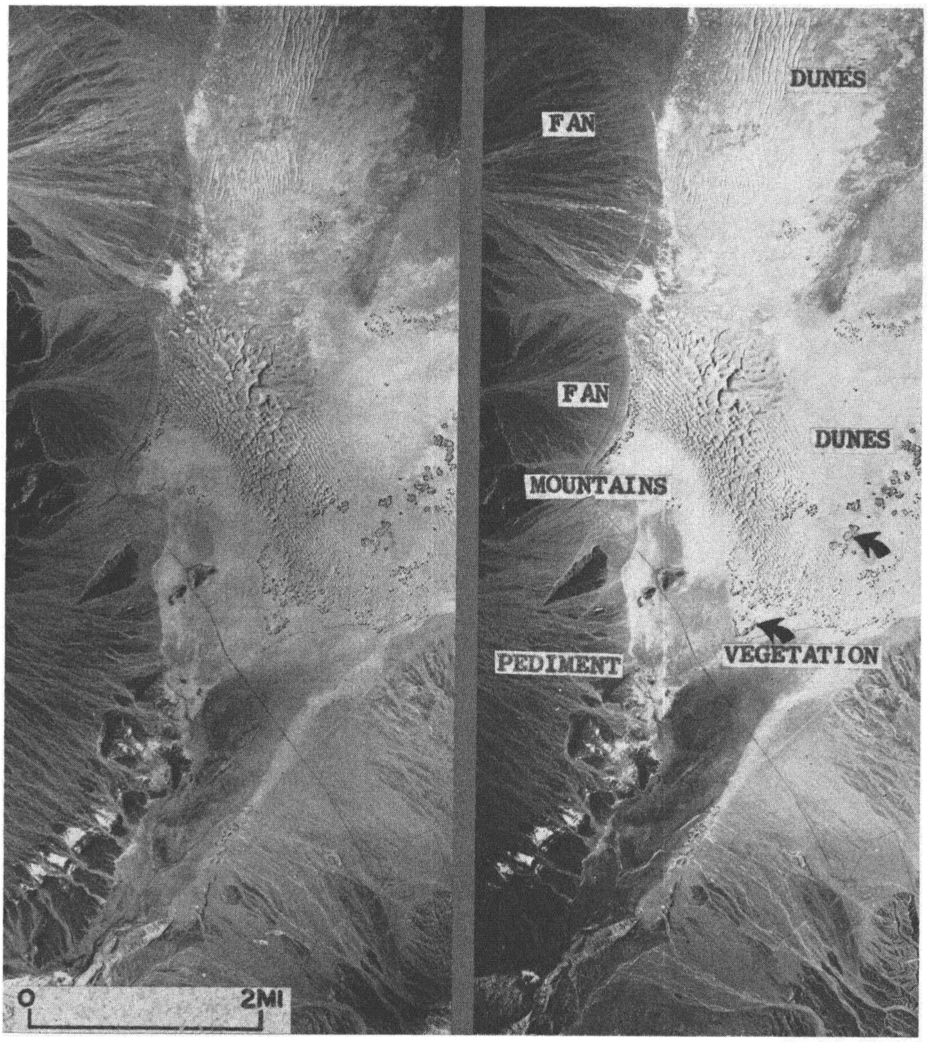


FIG. 11. Desert mountains, alluvial fans, and sand dunes, southern California. Nearby mountains of sedimentary rock are the source of granular material feeding these large fans. A band of variously oriented dunes rings the low center of this basin. Eddying winds have disrupted the striking linear pattern of the sand and have piled up the highest dunes. Scale 1:96,000.—USGS

wind. Dunes occur as long transverse ridges or seifs, crescentic hills or barchans, transverse dunes, sigmoidal dunes, and fishhook dunes (Figure 11). Dunes may change their shape as the wind shifts direction. Drifting sand also may pile in the lee of obstructions forming sand shadows. At times vegetation may stabilize dunes and prevent their movement. Water may be tapped by drilling at the base of a dune. Dunes may provide shelter for aircraft—a barchan resembles a huge revetment. The interdune floor may be swept clean of sand and so afford easy going for vehicles.

10. DRAINAGE

In the desert every line of drainage is apparent on aerial photography—each gully, each rill, each wadi, as well as springs and seepage zones. The patterns of drainage everywhere are obvious.

Gullies cut into the surface of the soil-mantle reflect the gross grain size present. The cross-section varies to indicate clay, silt, sand, and gravel. Vegetation frequently grows along the active water courses. In a wide-bottom wadi with several channels present, vegetation may help differentiate between active and abandoned channels. Wadis are sources of sand and gravel and may be tapped for water. Bars and terraces may be used by aircraft as emergency landing sites.

SUMMARY

Arid regions are particularly suited for air photo interpretation. Much accurate information about surface conditions may be obtained by identifying the desert landforms on standard black-and-white photography at such scales as 1:30,000 to 1:40,000. At these scales, however, some microrelief features of terrain such as low scarps, salt pinnacles, and large boulders important for engineering considerations cannot be seen. To determine if they are present there are needed either additional photography at larger scales or lenses and films capable of resolving microrelief at scales of 1:30,000 or 1:40,000.

Additional research is necessary not only to improve methods of acquiring information, but also to improve the ability to interpret the data. The Air Force Cambridge Research Laboratories are conducting inhouse research, and are sponsoring programs that ultimately should benefit studies of desert terrain. These research programs include:

1. REMOTE SENSING OF ENVIRONMENT

The use of radar, infrared, and other electromagnetic sensors is being studied in addition to air-droppable devices capable of yielding information on physical properties of the terrain. Soil samples are being studied under controlled conditions in the laboratory with infrared and radar sensors to determine whether a catalog of soil measurements can be obtained and used for eventual comparison with actual field data.

2. RESEARCH ON INDIVIDUAL TYPES OF TERRAIN FEATURES

Several field and laboratory investigations are in progress which ultimately may aid the photo interpreter in assessing surface conditions. These studies include mineralogy and soils, hydrology, sedimentation, and engineering properties. Landforms of current interest are desert flats and playas.

3. LANDFORM DISTRIBUTION MAPS

These maps are being prepared for the North African deserts. This research will provide further delineation of terrain variations which occur in the vast expanse of the Saharan, Nubian, and Arabian Deserts. Air photo analysis is an integral part of this investigation.

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