# The Movement of Barchan Dunes Measured by Aerial Photogrammetry

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On the southern coast of Peru, in the Pampa de La Joya, sand dunes of the barchan type occur extensively. The barchan is a crescent-shaped formation with a parabaloid plan. It has sharp cusps or horns pointing in the direction of the prevailing wind. The windward slope is gentle (about 10°), and the leeward slope is a concave surface standing at the angle of repose of the sand (about 32°). (See Figure 1.) These barchans are distributed by the hundreds over an area of about 50 kilometers length and 15 kilometers width. They are characteristic of an open, relatively flat desert which is absolutely free from moisture and vegetation, and which is swept by a relatively constant, unidirectional wind blowing from an unlimited source of sand. The barchans in this area vary in height from less than one meter to about seven meters. They are continually in motion in the direction of the wind, due to the rolling of sand up the windward slope and over the crest. This increases the angle of the leeward slope (or slip-face, as it is called) and causes an immediate shifting forward of the sand until the stable angle of repose is re-established. Thus the entire body of the dune moves forward over the hard, stony pavement of the desert as though it were an independent, living organism. The rate of forward displacement of the barchans is a function of the grain size and density of the sand, the velocity of the wind, and the dimensions of the barchan. This has been the subject of much theoretical study.[1]

The movement of these dunes is, however, of more than academic interest, since the Pampa de La Joya is the site of a projected irrigation scheme to convert 3,500 hectares of desert into agricultural land. Shifting dunes in this area represent a serious hazard to the water distribution canals, as well as an insurmountable obstacle to cultivation. Before undertaking the design of large-scale and expensive measures for the control of these dunes, either by stabilization or eradication, it was necessary to gather data on the physical behavior of the barchans.[2]

Fig. 1. Typical Barchan of the Pampa de La Joya, Peru.

Among the many factors studied, the forward rate of motion of the barchans was paramount. Since the area is desolate and completely uninhabited, there were few landmarks and no personal observations which could give any reliable indication of the change in position of even a single barchan over the years. It was only known that both the highway and railroad line which traverse this pampa have expensive maintenance problems in keeping their rights-of-way cleared from the continually encroaching sand. Under these conditions the use of photogrammetry seemed indicated.

The entire desert had been flown in 1955 by the Servicio Aerofotografico Nacional of the Peruvian Air Force (hereinafter referred

[1] See, for example, Bagnold, R. A., "The physics of blown sand and desert dunes." Methuen and Co., London, 1954.

[2] This work was carried out by the author under the auspices of the Food and Agriculture Organization of the United Nations, with the cooperation of the Peruvian government.

Ed. Note—The movement of dunes is also considered in a comprehensive paper that treats particularly of the geologic characteristics of barchans in southern Peru. See Finkel, H. J., 1959, *Jour. Geol.*, Vol. 67, No. 6, pp. 614–647.

to as SAN). This flight was at a very high altitude and the scale of the photographs was approximately 1:60,000, but due to the clean, dry, desert atmosphere, the pictures were very clear and each individual barchan was sharply outlined. Fortunately part of the same area was rephotographed by SAN in 1958 to the scale of 1:20,000 and with excellent results. (See Figure 2.) Ground control had been established and marked with large stone crosses which were identifiable in both sets of pictures.

By using a multiplex projector, SAN plotted the correct positions of over 100 barchans on a sheet of low-shrinkage acetate paper to a scale of 1:10,000. The entire planimetric outline of each dune was indicated. This was done for both flights on the same sheet using different colors to distinguish the 1955 from the 1958 positions. Part of this sheet is shown on Figure 3. It was immediately obvious that the barchans advanced at varying rates, with the smaller ones having a greater forward displacement. In the field, the complete dimensions of 45 barchans had been measured by use of stadia and a theodolite. These formations varied in height from one to almost seven meters. The width across the horns (measured at right-angles to the wind direction) varied from 10 to over 65 meters. This width, when plotted against the crest height for each barchan, was found to have a linear relationship expressed by the equation

$$W = 10.3\,H + 4.0 \qquad (1)$$

where W is width and H is crest height, in meters. This had a highly significant degree of correlation. By chance, however, of the 45 barchans which had been measured on the ground only 19 appeared on the planimetric map plotted by multiplex. The horizontal displacements of these 19 were measured by calipers to an accuracy of 0.1 millimeter, representing a distance of 1.0 meter on the ground. This displacement, when plotted against the crest heights of the dunes as actually measured in the field, gave a set of points to which a reciprocal function was fitted by the method of least squares, having a coefficient of curvilinear correlation of 0.71, which in this case was significant. This function when converted to units of *annual* displacement, resulted in Table 1.

It was believed, however, that the statistical sample of 19 dunes might not have been sufficiently large enough to support the conclusions. The remoteness and desolation

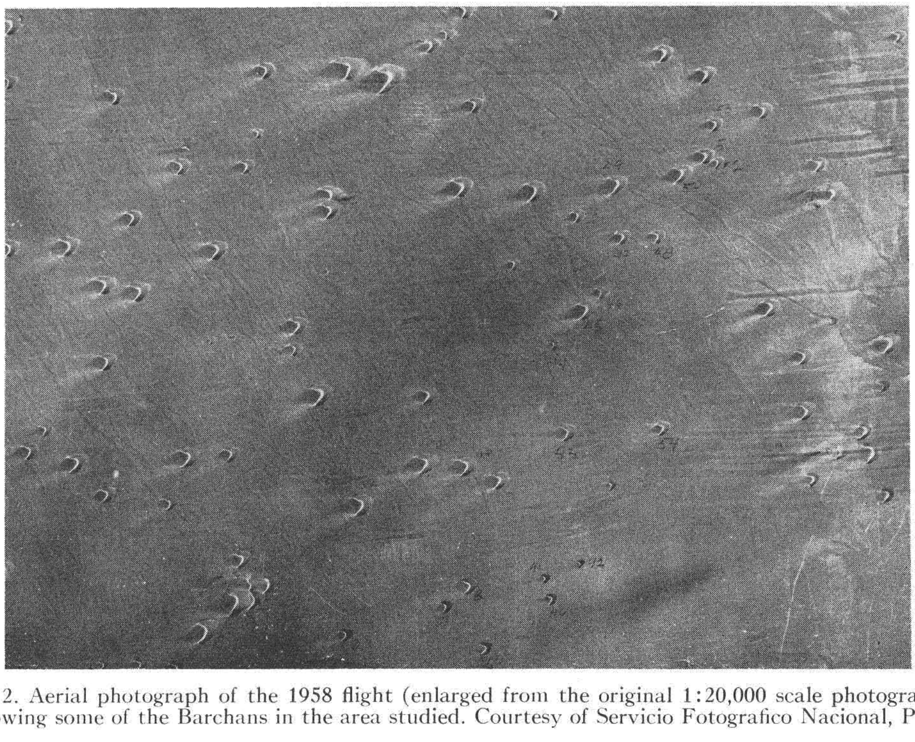

FIG. 2. Aerial photograph of the 1958 flight (enlarged from the original 1:20,000 scale photography), showing some of the Barchans in the area studied. Courtesy of Servicio Fotografico Nacional, Peru.

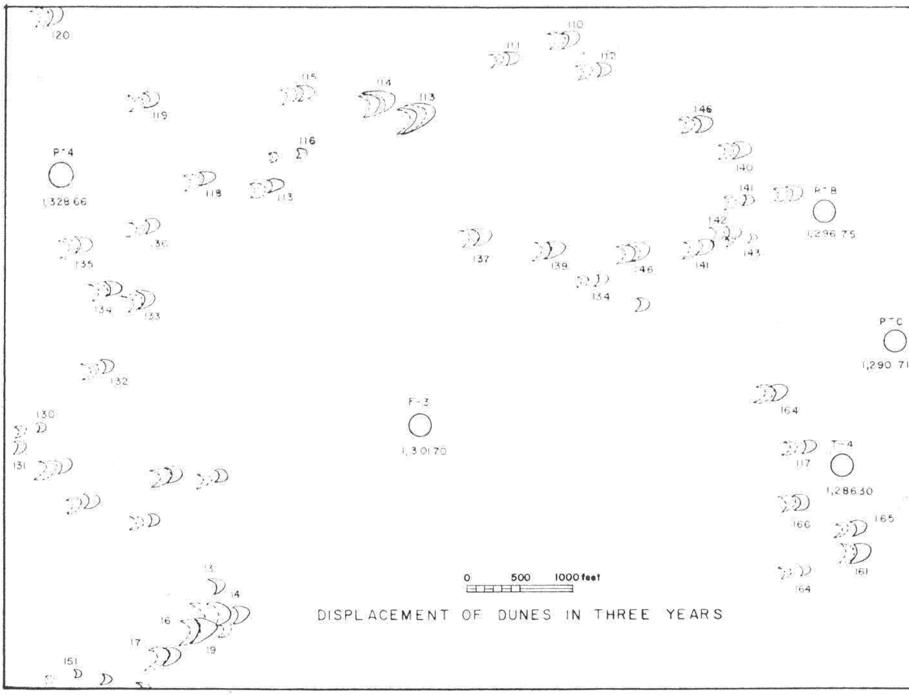


FIG. 3. Displacement of dunes in three years.

of the desert of La Joya, as well as the scarcity of field parties, made obtaining additional direct height measurements difficult and expensive. Consequently, it was decided to make additional use of photogrammetry.

On the composite plot shown partly in Figure 3, calipers were used in measuring the width across the horns of 75 additional barchans. Since the average width was about 37 meters an accuracy to one meter was considered sufficient. From these scaled widths the crest heights of the dunes were calculated by the tested relationship expressed in equation (1). These derived heights of dunes were plotted against the forward displacement in three years, as measured on the composite plot of Figure 3. The procedure previously used for the 19 barchans was then applied to data of these 75 dunes, and a reciprocal function was fitted; this finally led to the results presented in Table No. 2. It was encouraging to find that the forward displacement of the 75 barchans, whose height was calculated indirectly from the photographs, did not differ greatly from that of the 19 barchans whose height was actually measured in the field. The results for the sample of 19, however, proved to be statistically *significant*, whereas those for the sample of 75 proved to be *highly significant*.

A different technique might have been applied to this problem, namely, the determination of the crest heights of the 75 dunes by stereoscopic methods. This was not adopted, however, because the 1:20,000 scale of the 1958 pictures could, at best, have given an accuracy of only two meters for dune height determination by stereoscopic methods. Planimetric measurement on 1:10,000 scale enlargements, of the width across the horns, was, on the other hand, done to a ground-equivalent accuracy of one meter which rep-

TABLE 1

ANNUAL DISPLACEMENT OF 19 BARCHANS ACCORDING TO HEIGHT OF THE CREST

| *Crest Height (meters)* | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 |
|---|---|---|---|---|---|---|
| *Annual Displacement (meters)* | 30 | 22.6 | 18.1 | 15.0 | 13.0 | 11.3 |

TABLE 2

ANNUAL DISPLACEMENT OF 75 BARCHANS ACCORDING TO THE HEIGHT OF THE CREST

| *Crest Height (meters)* | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | *Average* 3.67 |
|---|---|---|---|---|---|---|---|---|
| *Annual Displacement (meters)* | 32.3 | 22.0 | 16.8 | 14.5 | 12.2 | 11.5 | 9.2 | 15.4 |

resented an accuracy of one-tenth meter in the calculated height of the dune crest.

The results of these determinations of the forward speed of the dunes as a function of the crest heights were compared with the theoretical speed as calculated from the average velocity of the prevailing wind and the sand grain size according to the formulae of Bagnold. The agreement between these theoretical rates and those determined by aerial photogrammetry was surprisingly close.

## MASS DISTRIBUTION OF THE BARCHANS

As there are hundreds of barchans scattered over the Pampa de La Joya, it was considered possible that their pattern of distribution might not be completely random, but instead was the orderly consequence of certain laws of dune movement. Here again, aerial photogrammetry was the key to solving this problem. That portion of the pampa which had been re-flown in 1958 was chosen for this phase of the investigation. Use was made of the flight index-sheet as a simple, uncontrolled aerial mosaic to the scale of approximately 1:30,000. This was sufficiently large to show clearly all of the barchans in the area, although of insufficient size for measuring their size. (See Figure 4.) The area of the mosaic was then ruled off into rectangular coordinates laid out on the azimuth of 152°, which was the direction of the prevailing wind as determined in the field by the orientation of 45 barchans. The rectangles represented 1,000 meters in the direction of the wind, and 200 meters at right angles to the wind. The number of dunes which fell within each of these coordinate rectangles was then counted, and this density (per area of 20 hectares) was taken as the parameter of barchan distribution over the area.

The results are shown, schematically in Figure 5. The average density of the dunes was computed for each row parallel to the wind direction (called $X_1$) and for each tier transverse to the wind direction ($X_2$), and recorded in the margins of Figure 5. When these average densities were plotted against $X_1$ (measured northward from an arbitrary starting point) and against $X_2$ (measured eastward from a point of greatest dune concentration, called the focus) a set of descending curves was obtained to which both parabolic and exponential regressions were fitted with very high degrees of curvilinear correlation.

The conclusions drawn from this statistical study of the barchan distribution were as follows:

1. The barchans seem to form a focus of high density at the south, or upwind end of the area studied.
2. From this focus, the average density decreases with the distance downwind.
3. The density also decreases in the crosswind direction, starting from the focus.
4. The lateral spread of the dunes over the desert also increases downwind from the focus, although asymmetrically. There are far more dunes to the right, or east of the focal-axis than to the west. (Subsequent analysis of the prevailing winds failed to provide an explanation for this distorted distribution).
5. The *total number* of dunes in any kilometer strip transverse to the wind direction remains approximately the same (within limits of statistical error). Consequently the decrease in dune density downwind appears to be the result, primarily, of the lateral spreading of the same number of barchans over a progressively wider area.

These conclusions, together with those recorded above in the tables of annual forward motion, aside from their general interest to geomorphologists, are of specific practical value to the engineer who is charged with designing a program of sand dune control in such an area.

## DISTORTION OF THE BARCHAN SHAPE

Close examination of the air photos reveals that in many of the barchans of the Pampa de La Joya, the west cusp is noticeably longer than the east. This has been confirmed by ground measurements on a large number of barchans, where the average length of the east horn was 0.85 of that of the west horn. This individual asymmetry might be explained by the fact that the ground has a gentle, but uniform slope to the west of about two per cent. One would naturally expect the

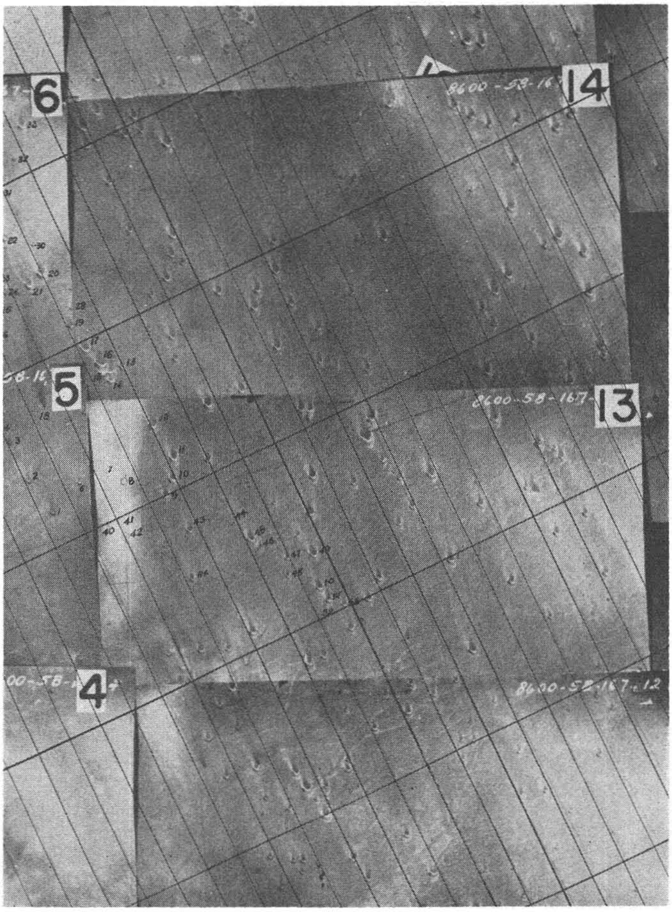


FIG. 4. Part of aerial flight index-sheet used as an uncontrolled mosaic, ruled off into rectangles with coordinates parallel to and perpendicular to wind direction, for study of mass distribution of the barchans.

moving sand to roll a bit farther on the lower side of the slope, and thus elongate the horn of the dune on that side. Accordingly it is more difficult to explain the general tendency of the barchans, *en masse*, to drift noticeably *toward the east*, or *up the slope*, as indicated in the distribution studies described above. Possibly the blowing action of the sand against slightly rising ground encourages rather than discourages the formation of more barchans, regardless of the relative length of the cusps. This apparently paradoxical behavior is worth further study.

## GEOLOGIC DATING BY BARCHAN DISTRIBUTION

Another aspect of the aerial study of barchans, namely the dating of climatic changes in post-Quaternary time, has suggested itself, but has so far, defied a simple solution. It is here mentioned to stimulate those readers who may be geologists and mathematicians. There was evidently a period of great uplifting of the entire southern coast of Peru dating from earlier than the Quaternary Period. (The present elevation of the Pampa de La Joya is about 1,260 meters above sea level.) After the uplift there was apparently a change in the climate, toward greater aridity, and the sand began to be blown northward from the Pampa de Clemisi; this is a large sand deposit near the coast, about 80 kilometers upwind from the first barchan, and lying at an elevation of about 1,000 meters. The barchans are first formed at a point known as Huagri and extend northward (the direction of the wind movement) until they crash against the steep slopes of a mountain range known as the Cerros de Caldera, over 50 kilometers from Huagri. The width of the barchan area in-

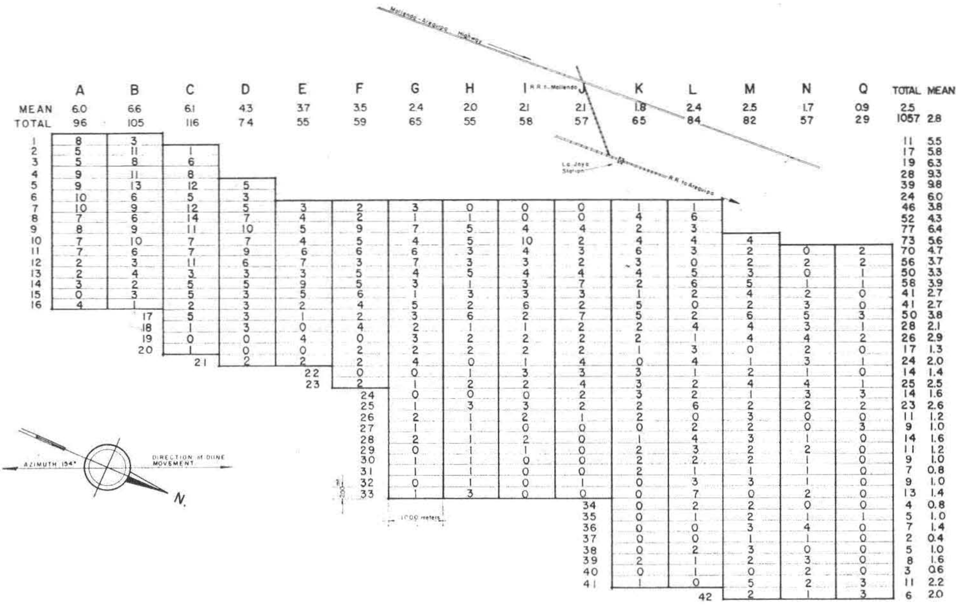


FIG. 5. Mass distribution of Barchans. The numbers represent the density of dunes in 20 Has.

creases somewhat irregularly to a maximum width of 10 to 15 kilometers.

The exact dating of the post-Quaternary period of climatic change has not been established with great certainty, and is the subject of some controversy among geologists. It is here suggested that if a mathematical analysis of the distribution of the barchans over the entire area be made with respect to their sizes. it may be possible to calculate the *minimum* period of time required for the achievement of the present configuration. These calculations would be based upon the known rate of advance of the barchans of varying crest heights as reported in the first part of this paper, and upon the assumption that the regime of wind velocities has remained essentially the same as that reported in recent studies by the author.[3] Furthermore, if the volume of the dune material, amorphously piled up at the foot of the Cerros de Caldera could be estimated, the known carrying capacity of the wind for this size of sand grain could be used to calculate the *maximum* period of time which might have elapsed since the climate turned arid and the sand began to blow. The author would be pleased to put his data at the disposal of any scientist who is willing to tackle this intriguing problem, although further field and photogrammetric data would probably have to be assembled. The first part of the problem outlined above is not unlike the problem of calculating the age of the universe from the known rates at which stars of different sizes are moving away from each other. This analogy may offer a possible approach to the problem of barchan distribution.

[3] Finkel, H. J. "The Barchans of Southern Peru" *Journal of Geology*, Vol. 67, No. 6, November 1959, pp. 614–647.