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15 November 1976

North Polar Region of Mars: Imaging Results from Viking 2

Abstract. *During October 1976, the Viking 2 orbiter acquired approximately 700 high-resolution images of the north polar region of Mars. These images confirm the existence at the north pole of extensive layered deposits largely covered over with deposits of perennial ice. An unconformity within the layered deposits suggests a complex history of climate change during their time of deposition. A pole-girdling accumulation of dunes composed of very dark materials is revealed for the first time by the Viking cameras. The entire region is devoid of fresh impact craters. Rapid rates of erosion or deposition are implied. A scenario for polar geological evolution, involving two types of climate change, is proposed.*

On 30 September 1976, Viking 2 executed an orbital plane change maneuver modifying the inclination of the Viking 2 orbit from 52° to 75°. This maneuver made the entire north polar region of Mars visible to the Viking 2 spacecraft under favorable lighting conditions through an atmosphere of widely scattered clouds. This report presents some preliminary interpretations of the geological features in the north polar region gained from study of the orbital imaging data returned to Earth and processed by 1 November 1976.

Intense interest in observing the north polar region of Mars with the Viking orbiter cameras was stimulated in 1971–72 by high-resolution (200 m) Mariner 9 observations of the south polar region (*1–5*) as well as by moderate resolution (up to 600 m) observations of the north polar region (*6*). Briefly, these observations revealed a complex mass of eroded layered deposits near the martian south pole and strongly suggested the existence of a similar terrain near the north pole. The layered polar deposits provide the first persuasive geological evidence for cyclical climatic change on a planet other than Earth. Viking 2, with an improved imaging system relative to Mariner 9 (*7*) and a capability for extensive multiframe stereoscopic and colorimetric coverage, has provided an outstanding opportunity for examining this evidence in much more detail. This opportunity began at the time of the Viking 2 orbital plane change and will end, at latest, when the region passes over the terminator during the northern autumn (the fall equinox is 4 January 1977). It is quite possible, however, that the onset of the autumn-winter high latitude haze and cloud cover known as the polar "hood" may terminate surface visibility even earlier.

Geological framework. The polar terrains revealed so far by Viking 2 images can be conveniently classified into three types: layered deposits in the central polar region, a contiguous area covered by dunes, and a cratered plains surface that appears to underlie stratigraphically both of these units. A sketch map delineating the distribution of layered terrains, dunes, and cratered plains appears in Fig. 1, which also illustrates the areal extent of the photographic coverage available for study. The materials of the perennial ice cap, identified as water ice by Viking 2 temperature measurements (*8*), occur primarily within the perimeter of the layered terrains, although isolated patches or outliers occur in physical contact with both the cratered surface and the dunes. The mosaic of long-range oblique Viking 2 images (Fig. 2) obtained before the plane change illustrates the pinwheel pattern of frost-free areas within the predominantly frost-covered layered deposits.

Characteristics of layered deposits. The layered deposits contribute more than any other feature to the geological distinctiveness and significance of the polar regions of Mars. We suspect that these layered deposits are exposed at the surface in all areas mapped in Fig. 1 where frost is absent. They are manifested on slopes by a parallel striping of the surface (Fig. 3) (*9*); however, in only a fairly small number of locations can the topographic and geological nature of the exposures be clearly discerned. In one of these areas (Fig. 3b), selected so that shading and shadowing dominates locally over brightness variations caused by albedo, a terraced slope can be recognized.

With the use of arguments presented previously for features viewed in the south polar region (*2*), a strong case can be made that erosion of a layered deposit accounts for the origin of the terraced slope. The lateral continuity of terraces and their uniformity in height suggest that the individual layers that gave rise to the terraces extend as continuous thin sheets over areas of several thousand square kilometers. Moreover, these individual sheets are not only quite constant in thickness, but the thicknesses of different sheets are rather similar to one another. The apparently unique occurrence of layered deposits in the polar region implies meteorological control over their formation. Direct deposition of dust from the atmosphere, perhaps influenced by the distribution of polar ice and modulated by climatic change, remains the most probable mechanism of accumulation. These climatic changes may have resulted from periodic, perturbation-induced changes in the orbital elements of Mars and the direction of its rotation axis (*5*).

Another distinctive attribute of the layered deposits on a planet characterized by many ancient crater-pocked surfaces is the absence of fresh impact craters. In an area of 800,000 km², no fresh craters can be recognized. Much of this surface is so smooth and free of other forms of topographic relief that there should be no difficulty in detecting craters down to 300 m in diameter. Similar results for the south polar region were reported from the Mariner 9 data (*1, 2*). There are some circular structures in the size range of 2 to 8 km which may be the remnants of impact craters (Fig. 4). The production rate of impact craters this large on the planets is expected to be several orders of magnitude below the production rate of craters in the size range of 300 m to 1 km. Consequently, if these circular structures are impact craters, then the efficiency of crater obliteration in this part of Mars must vary dramatically with crater size.

Many of the frames taken by Viking merely confirm what was already known about the characteristics of layered deposits from Mariner 9 observations of the south polar region and what was strongly suspected about their characteristics in the north polar region. However, even from our preliminary analysis, we are able to report some significant new results regarding the erosional history of the layered deposits and their relationship to the formation of the present polar ice deposits.

Unconformable contact of buried landscape type. In Fig. 5, there appear several examples of unconformable contacts of the buried landscape type as evidenced by one set of terraces obliquely truncating another. The topography and stratigraphy of this relationship is illustrated by the block diagram and cross section in Fig. 6. Such relations indicate at least one major erosional interruption in the deposition of layered materials in the north polar region.

We propose that the unconformable contacts were brought about by the following series of events. First, a series of near-horizontal layers were deposited, obscuring all earlier topography and culminating in a flat or gently sloping surface. Then erosion set in, and differential erosion of the layers caused slopes to assume a terraced topographic form. The next event was another episode of deposition of layered materials which obscured the relatively small-scale terracing but otherwise conformed to the relief of the eroded slopes. Finally, another episode of erosion resulted in the formation of a set of terraces both in the most recent layered deposit and in the older deposit, perhaps by exhumation of an old buried terrace system. The two sets of terraces meet obliquely, thereby revealing the unconformable contact.

It is possible that all the unconformities of Fig. 5 were produced in the same erosional episode. If this is true, it implies a minimum of two erosional episodes in the north polar region: an earlier one associated with the unconformities and a later one responsible for the most recent development of terracing. The origin of these erosional episodes is quite uncertain.

Dune fields of the north polar region. A vast belt of dunes occupies much of the region around the permanent north polar cap (Fig. 1). Much of this belt consists of a continuous mantle of dune-forming materials (presumably sand) in which regularly spaced ridges with moderately sinuous crests are developed. Both longitudinal dunes, formed by winds directed parallel to the ridge orientation, and transverse dunes, formed by winds acting perpendicular to the ridge orientation, have been identified. In some areas (Fig. 7a), the ridge spacing and orientation are almost invariant over distances of more than 100 km; this suggests a similar consistency in the strength and direction of the wind. In other areas (Figs. 7b and 8), ridge spacing and orientation change rapidly from place to place, and the sinuosity and degree of branching and merging of the dune crests are enhanced. These characteristics indicate both greater variability in the direction of strong winds at any one place and also significant variations in the mean wind direction with location. Occasional strong winds from more than one direction are indicated by a secondary set of ridge alignments oriented obliquely to the primary ridge pattern (Fig. 7a).

On the periphery of the "sea" of transverse dunes is a transitional zone where separation and direction of ridges changes rapidly and the continuous mass of dune-forming materials breaks down into longitudinal dunes, barchans, and other approximately equant dunes whose detailed shape is not resolved (Fig. 8). Some of these dunes may be in the process of accreting to the main dune mass; others may be breaking away from it. Such a relationship is most striking within and near the mouth of Borealis Chasma (Fig. 9). A narrow stream of dune-forming materials appears to be migrating along a gently curving valley southward until it joins a large delta-shaped dune mass distinguished by highly sinuous ridge patterns. On the other

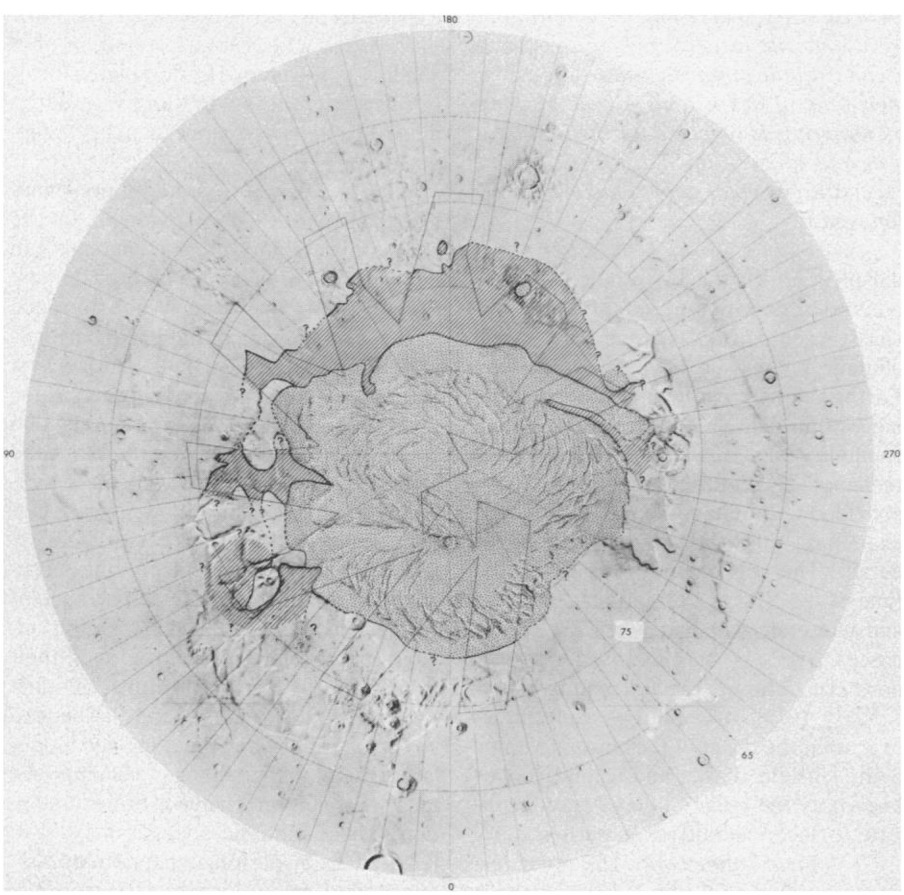


Fig. 1. High-resolution photographic coverage obtained by Viking 2, up to and including data returned and processed by 1 November 1976, is outlined by fine line. Terrains have been classified into three types: layered deposits (stipple), dunes (stripes), and cratered plains (these definitions are clarified in the text). The distribution of permanent polar ice deposits is not indicated.

side of this large reservoir of sand, the continuous pattern of dunes dissolves into a tenuous skein of linear dunes and isolated barchans. This assessment of the dynamic geological situation is preliminary; it is possible that the general pattern of migration is taking place in the opposite direction from the one contemplated above.

The north polar dune fields have a complex relationship with other topographic features and terrains. Moderate-sized craters can serve to partly anchor the dunes in a discontinuous pattern of ridges (Fig. 8a) that may only partially mantle the surface. Where the cover of dune-forming materials is continuous, buried crater rims may be expressed as subtle indentations in the otherwise smooth sinuosity of the dune crests (Fig. 8b). This can provide some indication of the depth of the dune mass if reasonable estimates of the crater rim relief can be derived. Dunes extend up and over the layered deposits in places (Fig. 10). There they clearly postdate both the deposition and erosion of layered materials.

What materials are these north polar dunes made of, from what source are the materials derived, and what accounts for their accumulation in this 80°N latitude belt as dunes of prodigious thickness and extent? A plausible model is that the source of dune-forming materials is the layered deposits. The morphology of these surfaces indicates that erosion has occurred, and it seems reasonable that a portion of the eroded material could have formed dunes. A difficulty with this idea is that the layered units are believed to have formed by the deposition of suspended dust particles. Dust, however, is much too fine to be mobilized by saltation, the transport process which is generally thought to be required for dune formation. There are ways around this objection. One could argue that dust in the polar regions has accreted to sizes large enough for saltation to operate by the process that is responsible for duricrust (*10*) formation. Alternatively, one might argue that the regimes of suspension and saltation are not so rigidly separated on the basis of particle size on Mars as they are on Earth.

Neither of these arguments appears too convincing; moreover, the circumpolar dunes display a substantial albedo contrast relative to the cratered plains and the layered deposits. Their darker appearance suggests a different composition, perhaps similar to the spectacular dark dune masses photographed elsewhere on Mars (*11*). It may be that these dune materials are derived directly from the soils of lower latitudes instead of indirectly after having first resided in the polar layered deposits. These materials may represent the missing compositional component inferred to exist from elemental deficiencies in the soils at the Viking

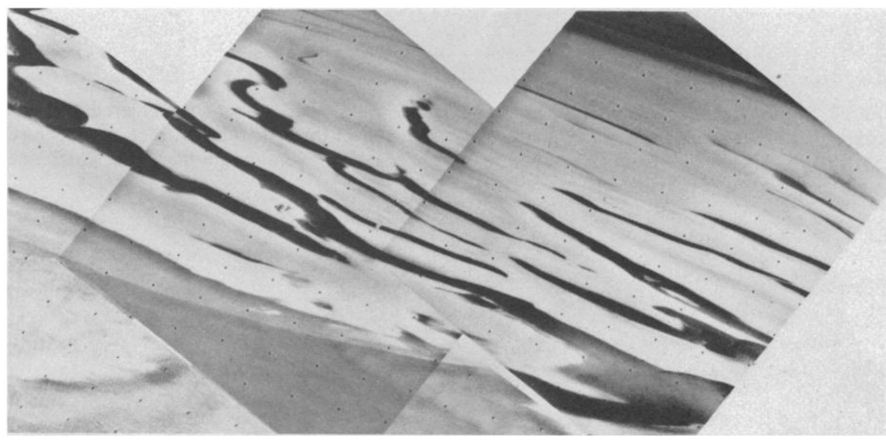


Fig. 2. An oblique view of the north polar cap of Mars, acquired before the Viking 2 orbital plane change, shows part of the spiral pattern of dark, frost-free bands, wherein slopes are locally steeper than the surroundings. Higher-resolution images show complex fine-scale parallel light and dark bands within these areas (Viking 2 frames 22B33 to 22B37). The region shown extends from about 80°N to 90°N (at the planet's limb). Each frame in the mosaic is 185 km wide.

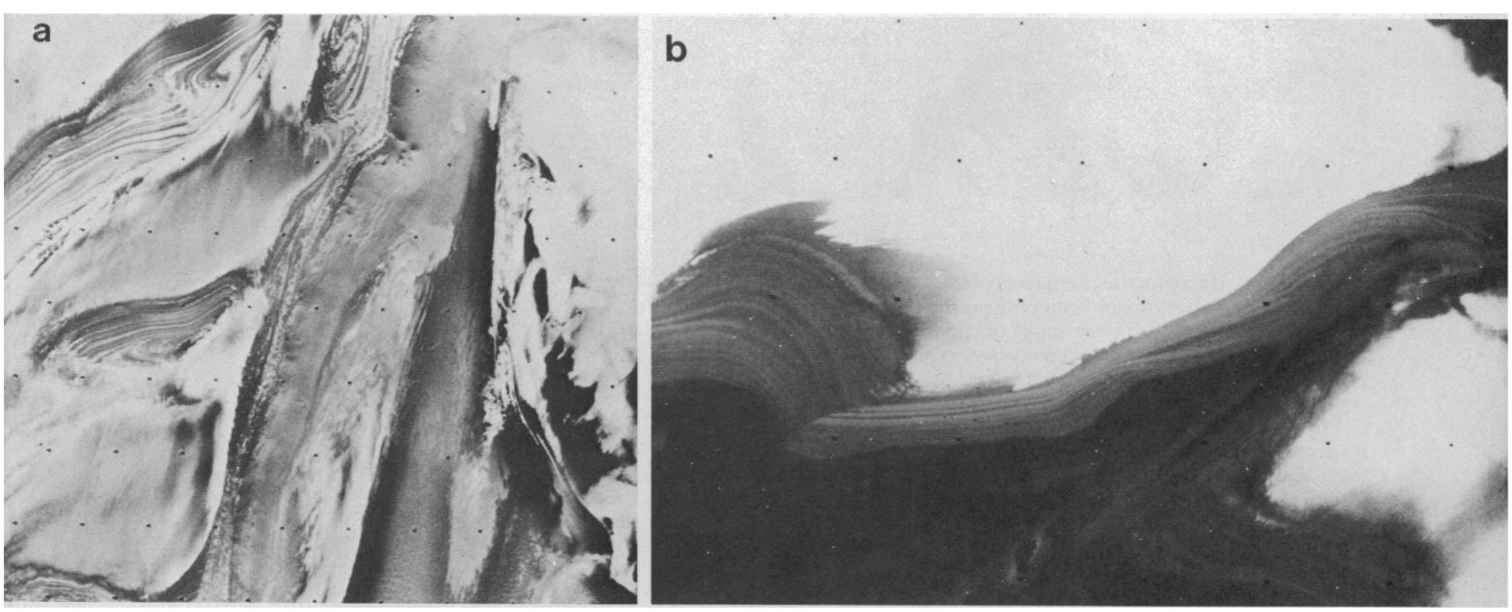


Fig. 3. Layered deposits in the north polar region of Mars. (a) Parallel banding indicative of layered deposits in the north polar region. Tonal contrasts due to albedo markings are difficult to separate from those due to differences in illumination. The topographic nature of this surface is still obscure (Viking 2 frame 59B77). The region shown is about 65 by 100 km. (b) The terraced character of some of the layered deposits is revealed in this image, in which the sun is illuminating the scene from the bottom (Viking 2 frame 57B32). The region shown measures 35 by 55 km. The frost-covered upland area at the top of the frame is separated from the dark frost-free lowland by terraced slopes, which are highlighted where they face the sun. This image has not been filtered, and different features in the scene appear in their true relative contrasts.

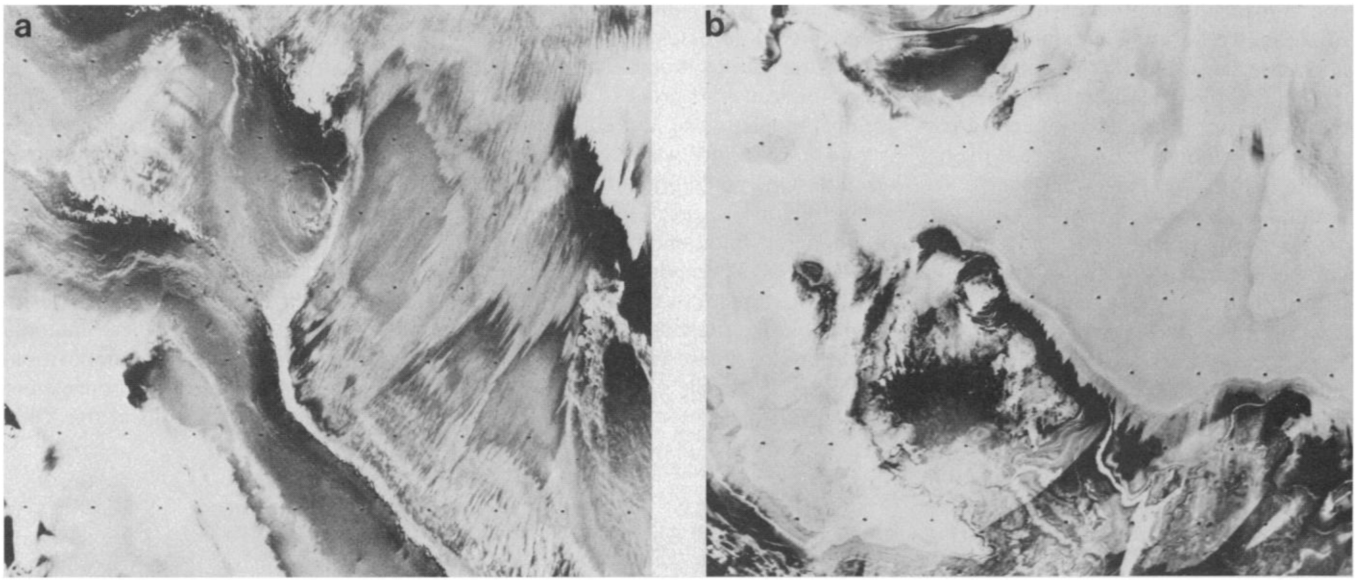
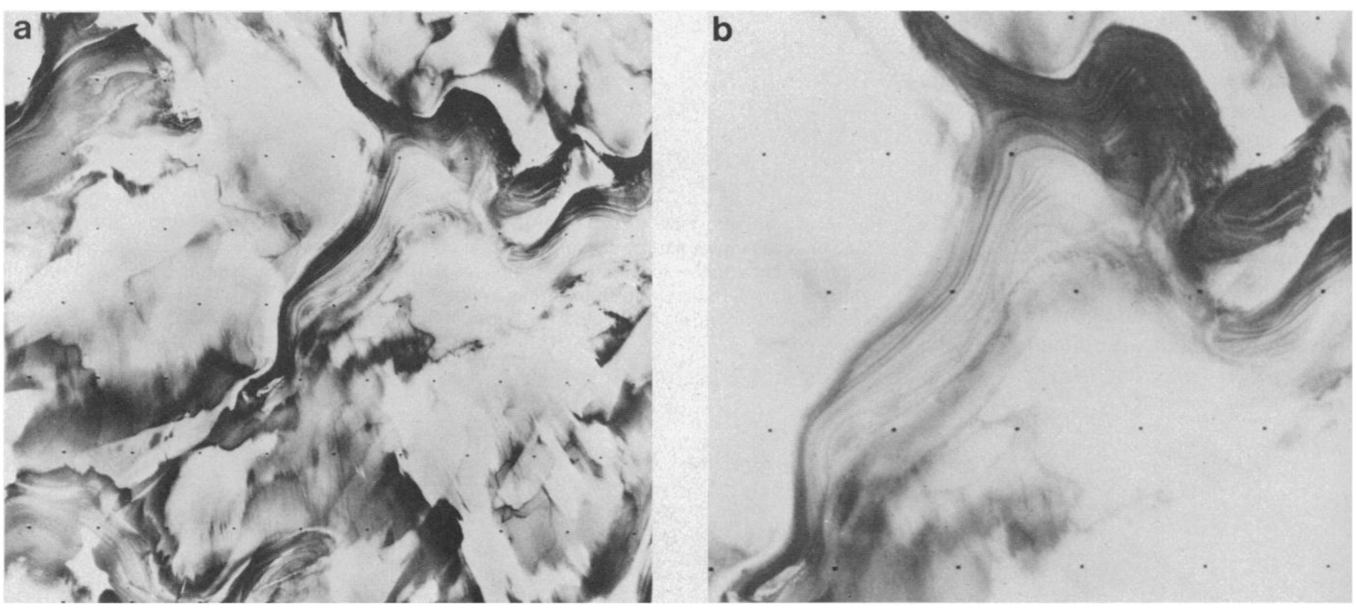


Fig. 4. These frames reveal no indication of small fresh impact craters on the layered deposits but the larger circular structures may be of impact origin. (a) The candidate impact structure is comprised of three or four distinct circular raised ridges visible just above center (Viking 2 frame 59B78). (b) The candidate impact structure is comprised of several bright markings which nearly form a closed subcircular form tangential to the edge of the ice cap (Viking 2 frame 56B79).



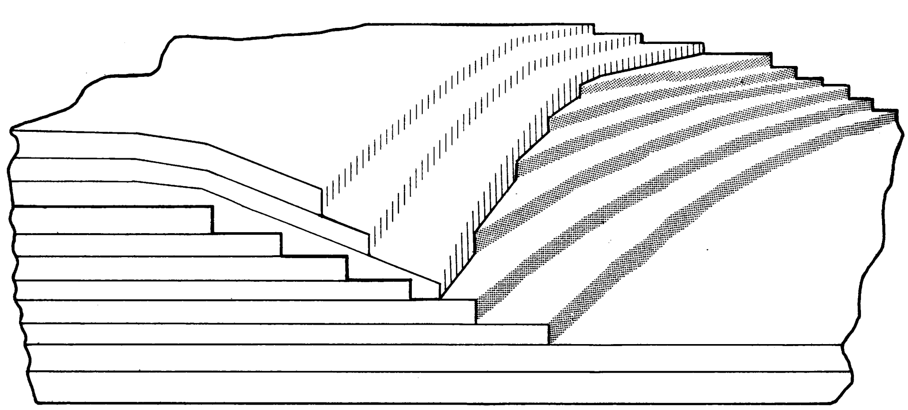


Fig. 5 (above). Unconformable contacts of the buried landscape type found within the north polar layered deposits. (a) One series of contacts is seen near the upper right center; another series, near the lower left edge of the frame. A replicating angular pattern of dark markings (see text) is located near the lower right corner. Bright searchlight patterns also appear in the frame and extend from the lower right corner toward the center of the frame. Most of the area in this frame is ice-covered (Viking 2 frame 56B84). (b) An enlarged view of the first series of unconformities. The clearest example is near the center of the frame, where the uppermost terraces, which have a rather irregular form at this point, obliquely truncate terraces at a lower level. This enlarged view has not been filtered, and different features in the scene appear in their true relative contrasts. Fig. 6 (right). A block diagram indicating the three-dimensional structure of the topography and sedimentary layering that appears near the center of Fig. 5b. The view is similar to the one that an observer located on the surface of Mars near the apex of the deposits at top center would obtain by looking in the direction of 6 o'clock. The cross section shows the sequence of layers from which the terrain is believed to be constructed.

landing sites (12). Dunes on the layered deposits within the polar cap may be quite different in composition from the circumpolar dunes; they may be largely composed of particles of water ice.

Cratered plains unit. The cratered plains unit provides the substrate upon which the layered deposits and dunes have formed. Portions of this terrain surface can be observed outside the area covered by layered deposits and dunes. An analogous unit in the south polar region—the pitted plains unit (1)—is characterized by extensive pitting and grooving, which has been attributed to early aeolian activity (1–3) preceding the formation of layered deposits. No clear evidence of comparable north polar aeolian activity has been recognized in Viking 2 pictures, but the imagery of the cratered plains is somewhat affected by haze and is very limited in areal coverage (Fig. 1).

Characteristics of permanent ice. The observations of the north polar region being reported here were obtained in the midsummer season on Mars when the areocentric longitude of the sun relative to vernal equinox ranged from 130° to 140°. Earth-based observations (13) indicate that the polar cap should have reached its minimum size 2 or 3 months previously. Consequently, we expected to observe a deposit of perennially frozen volatiles, and the Viking 2 infrared radiometer observations (8) suggest that water ice and not frozen carbon dioxide is the dominant if not the sole component.

Perennial ice is observed in isolated patches on the cratered plains and dunes but covers the major part of the layered deposits (Fig. 1). On the layered deposits the ice follows the spiraling pinwheel configuration of the terrain, covering the flat areas but shunning the slopes (Fig. 2). The calculated albedo of the ice (8) is much lower than expected, and it appears that the albedo of ice is reduced significantly below the value for pure ice as a consequence of admixture with dust.

Relationship between perennial ice and dunes. The dune pattern in the circumpolar belt displays two distinct kinds of relationships to perennial ice. In the first, the pattern of ridges is unmodified by the presence of ice (Fig. 7a), which has apparently formed after the dune ridges assumed their present configuration. This relationship suggests that water ice is either accumulating or being redistributed in the north polar region on a time scale that is short compared to the age of the dune ridges. In fact, we cannot exclude the possibility that some of these ice deposits sublime later in the summer season.

Near other frost patches, the pattern of the dune ridges is clearly altered near and within the frost. This could imply that the perennial ice in that area preceded the most recent change in the distribution of the dunes. Better definition of the relationship of frost patches to the dunes will be possible when color images of the dune fields are acquired.

Relationship between perennial ice and layered deposits. As judged from our analysis of monoscopic imagery only, perennial ice appears to occupy primarily the flat-lying areas between sinuous and curving terraced slopes. In many instances (for example, Fig. 4b), the perimeter of the frost is parallel to the margin of the uppermost layer on the slopes. It is tempting to speculate that the present distribution of frost is controlling the accretion of material that forms the layers. If this were the case, then the terraces formed at the same time as the layers with which they are associated. However, there is evidence to contradict this model. In Fig. 5b, for example, perennial ice covers the unconformity between the most recent series of layers and an older series. Consequently, the notion that the terraces on a given slope form during an erosional episode after the deposition of the series of corresponding layers was completed is the more probable explanation of the topography.

The surface of the perennial ice is devoid of craters and any other topographic forms over the major part of the interior of the ice cap. Locally, however, there are small areas of possible dune fields, and near the margins of the ice cover there are a variety of unusual patterns in, or on, the ice. One class of phenomenon is informally known as "searchlight patterns" (Fig. 5a). These bright elongate patches are bounded by abrupt margins that sustain a linear trend for 100 km or more, maintaining a parallel or slightly diverging aspect. Wind erosion or deposition seems an obvious ex-

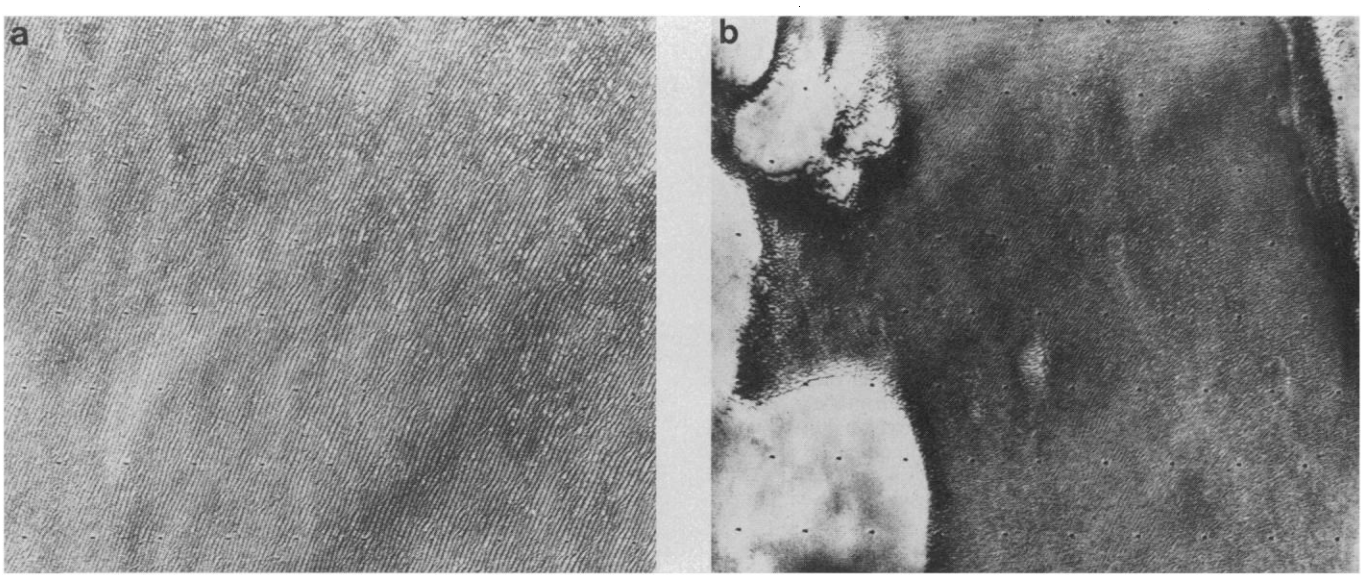


Fig. 7. Fields of transverse sand dunes from an area peripheral to the north polar ice cap. (a) Dunes here have a consistent trend (approximately north-south) with minor sinuosity, branching, and merging. Vague circular forms are probably buried craters. Bright spots within the ridges are ice deposits (Viking 2 frame 59B32). (b) Dunes with much more variation in direction also occur: a shorter wavelength and greater sinuosity appear in this dune field, which adjoins and in places appears to be mantled by frost deposits. Vague circular forms again are probably buried craters. The bright patches of ice near the upper left are associated with a distinct change in the dune pattern, possibly indicating that the deposits of ice preceded the development of the present dune pattern (Viking 2 frame 58B01).

planation for these features, although the exact mechanism is unknown. Linear dark markings also form angular patterns on the ice; Fig. 5a includes an example of two almost identical patterns separated by about 3 km. We have considered the possibility that lateral motion of the upper portion of a single feature caused this apparent replication, but insufficient information is known about the topography to pursue this idea in any detail. We expect that the higher-resolution pictures available after conjunction will help us elucidate the nature of features such as these.

Dynamics of the annual and perennial ice. No changes in the frost cover have been observed over the short time base of Viking observations. However, duplicate coverage has been very limited in areal extent. Model studies suggest no significant changes in frost cover in this season, and so the negative result is not surprising.

The recent elucidation of the water ice composition of the northern polar cap by Viking 2 temperature measurements now causes us to reexamine some earlier conclusions (*1*) about the annual behavior of polar frosts on Mars. A region near the edge of the permanent southern cap, known informally as "the fork," was monitored from near the beginning of the Mariner 9 mission, the first third of southern summer, to near the fall equinox (*13*). During this time the ice was observed to retreat continuously both at the edges and patchily within the ice mass. It is likely that both residual caps have the same water ice composition (*13*) and that the observations relate to the disappearance of seasonal water ice. If the water ice is laid down in the same proportion to CO_2 as the mixing ratio in the atmosphere, then about 10^{-2} g cm^{-2} would be deposited seasonally and would remain until all the seasonal CO_2 has sublimed. An upper limit for the amount of water ice that could be deposited at the residual cap would be the total water vapor in one hemisphere, assumed to average 20 precipitable micrometers: a total of 0.2 g cm^{-2} for a cap covering 1 percent of the hemispheric surface area. This seasonal accumulation of water ice is presumed to sublime gradually (since the air will rapidly saturate) during the summer. The conclusion may be reached that a very small amount of water ice is capable of providing the appearance of an unbroken ice sheet. Thus, the observation of regions within the residual caps where the cover is uniform does not necessarily imply great thickness. The thickness of water ice might be so small that it is transferred entirely from one pole to the other during the cyclic precession of the equinoxes (period, ~ 180,000 years). The southern summer solstice occurs near perihelion, so the southern cap presently experiences considerably more insolation during the summer than does the

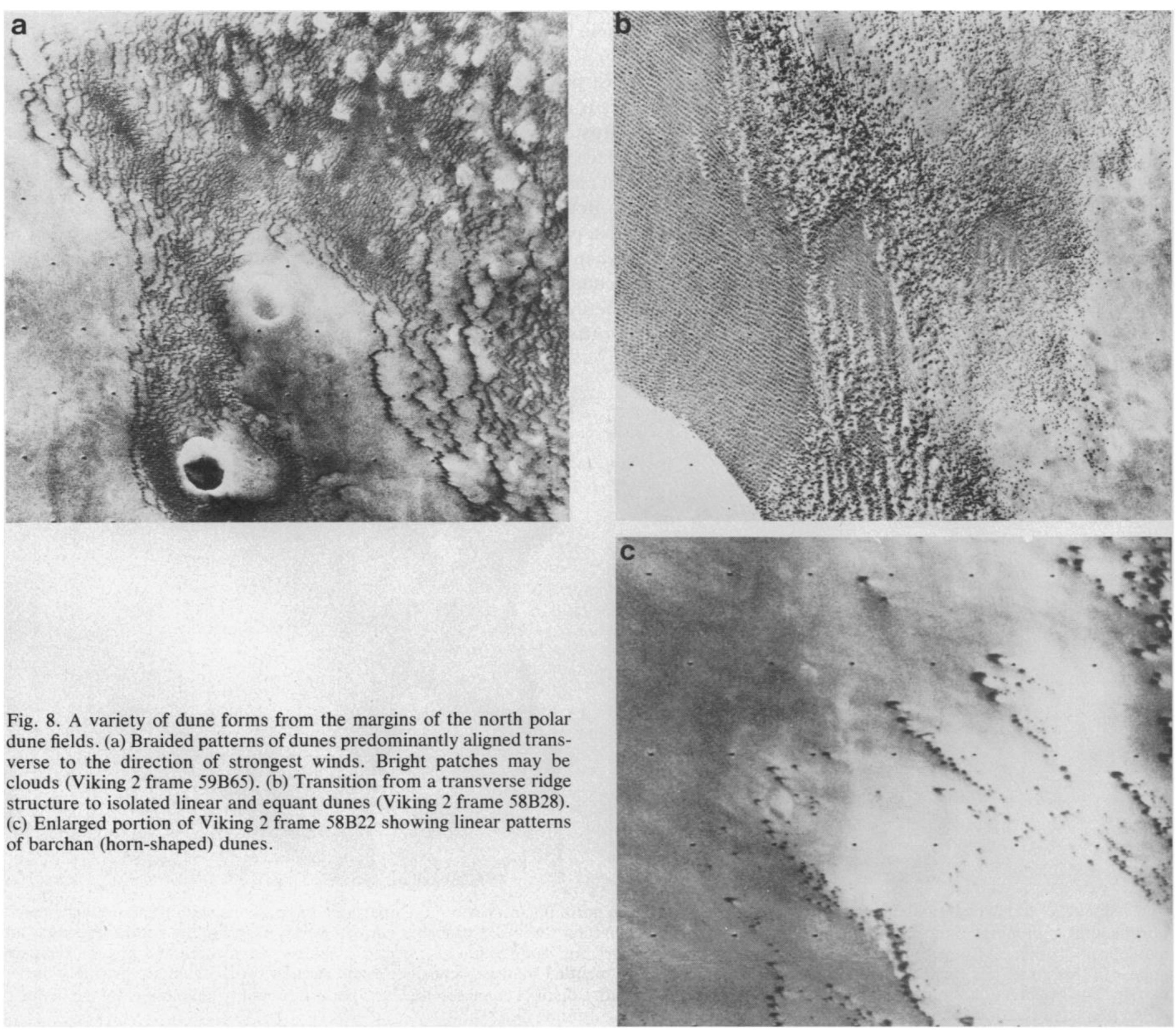


Fig. 8. A variety of dune forms from the margins of the north polar dune fields. (a) Braided patterns of dunes predominantly aligned transverse to the direction of strongest winds. Bright patches may be clouds (Viking 2 frame 59B65). (b) Transition from a transverse ridge structure to isolated linear and equant dunes (Viking 2 frame 58B28). (c) Enlarged portion of Viking 2 frame 58B22 showing linear patterns of barchan (horn-shaped) dunes.

northern cap. The relatively small size of the southern cap and its broken and patchy appearance at the end of summer may be due to the gradual transfer of water to the northern cap.

Huguenin (*14*) has discussed the photochemical weathering of surface materials by oxidation, in which atmospheric water vapor would be irreversibly lost. The rates of loss derived by Huguenin would have significant implications for the polar caps. Water released from the caps during the summer months would be used to replenish the atmospheric water lost to weathering, and the caps would thereby be diminished in thickness. Oxygen removal at a rate of 10^8 to 10^{11} atom cm^{-2} sec^{-1} (*14*) implies water vapor removal at 10^{-7} to 10^{-4} g cm^{-2} $year^{-1}$. If all this were supplied by the polar caps (areal extent, ~ 1 percent of the surface area of Mars), then the caps would be depleted at 10^{-5} to 10^{-2} g cm^{-2} year.$^{-1}$ A meter of ice could be lost in 10^4 to 10^7 years. If the caps are indeed thin enough to transfer between poles over the equinoctial cycle, then it is likely that they have a total lifetime that is very short in geological terms. In that event, the present residual caps may represent a relatively recent outgassing event (or even current outgassing at a rate only slightly greater than the weathering rate) or, less plausibly, a recent cometary impact. The Viking results are unlikely to resolve the question of ice cap thickness, however, and new remote sensing or in situ data will probably be required.

Crater retention ages in the layered deposits, dunes, and perennial ice. No fresh impact craters have been recognized on the circumpolar dune fields or the layered deposits on either ice-covered or ice-free areas. Approximately ten fresh craters with sizes large enough for detection (300 m) would be expected to form in an area this large (~ 10^6 km^2) every million years if one scales the present lunar cratering rate to Mars (*15*). These craters would be easier to recognize in some areas, the flat ice cap for ex-

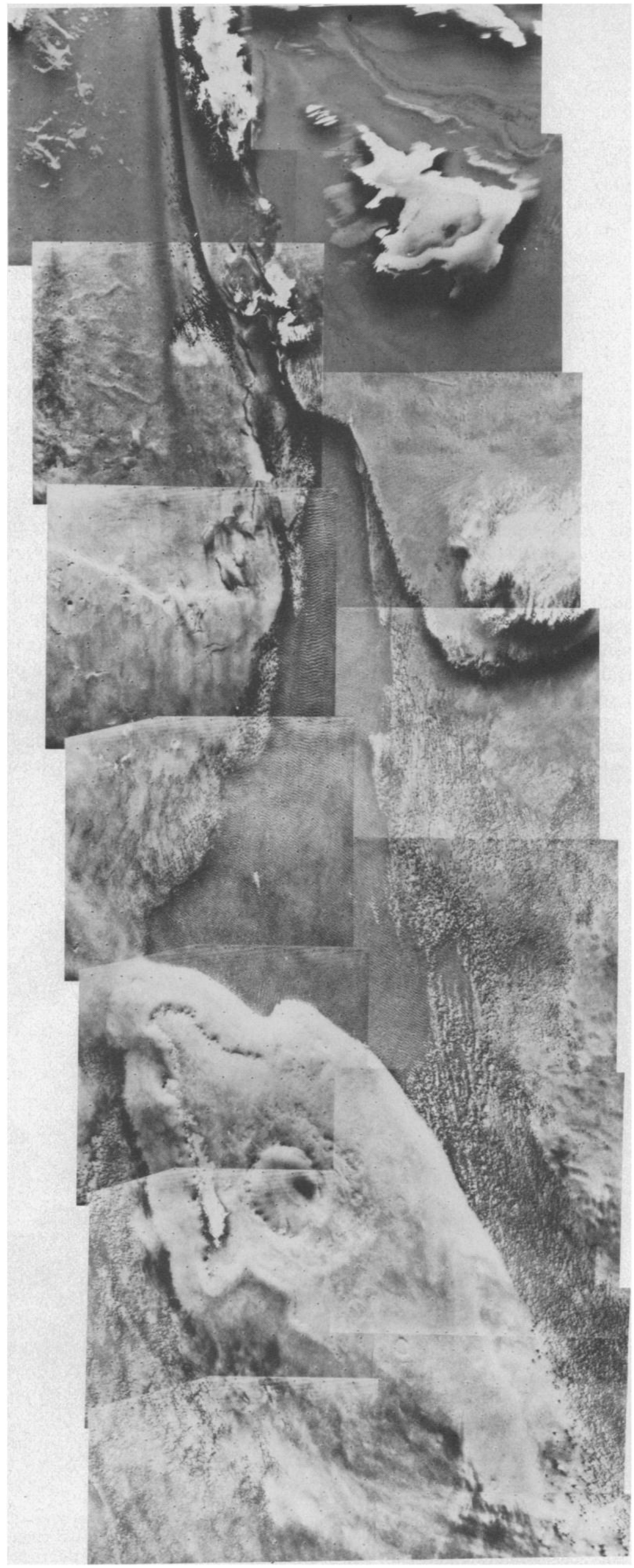


Fig. 9. A dune field in Borealis Chasma. Dark dune-forming materials have apparently been transported away from the pole in a curving stream extending from the top of the frame. They are accumulated in an approximately triangular dune mass that occupies the center of the mosaic. The average trend of the sinuous ridges in the dune mass rotates in a clockwise direction through an angle of approximately 45° from the northern to the southern margin. The discontinuous dark texture on the right side arises from partial dune cover. Perennial ice is visible near the top of the frame and associated with the crater near the bottom of the frame. The bright patch near center right may be cloud (mosaic of Viking 2 frames 58B21 to 58B34).

Table 1. Outline of geological evolution of north polar region of Mars.

Stage 1	Onset of polar activity Moderate aeolian modification of the ancient volcanic terrains
Stage 2	First depositional period Layered deposits of silicate dust and possibly interbedded ice accumulate to a thickness of several kilometers
Stage 3	First erosional period Erosional attack of layered deposits results in a landscape of gently curving scarps and channels with terraced slopes
Stage 4	Second depositional period More layered deposits accumulate unconformably on top of the units formed in the first depositional period
Stage 5	Second erosional period Further erosional attack of layered deposits results in exhumation of earlier formed landscapes and reveals unconformable contacts between the deposits of the first and second depositional period. Some of the eroded material reaccumulates as a girdle of sand dunes between 75°N and 80°N
Stage 6	Recent period Ice in the permanent polar cap assumes its present form and distribution

ample, than in others such as the dunes. However, the absence of a population of impact craters indicates that the lifetime of fresh craters in this part of Mars is very much shorter than a million years. One possible explanation is that the landscape as a whole is changing at the scale of several hundred meters to a kilometer in time periods of less than a million years. An alternative possibility is that processes exist in the polar region which selectively destroy impact craters. For example, cavities in ice created by impact may "heal" at a faster rate than the surrounding landscape changes by the erosion or accretion of ice and dust.

We can estimate the deposition and erosion rates that are needed in the area of the layered deposits, for example, to remove craters at the rates implied by the estimates given above. The layered deposits occupy an area of 800,000 km^2; for this exercise we will not distinguish between the area covered by ice and the

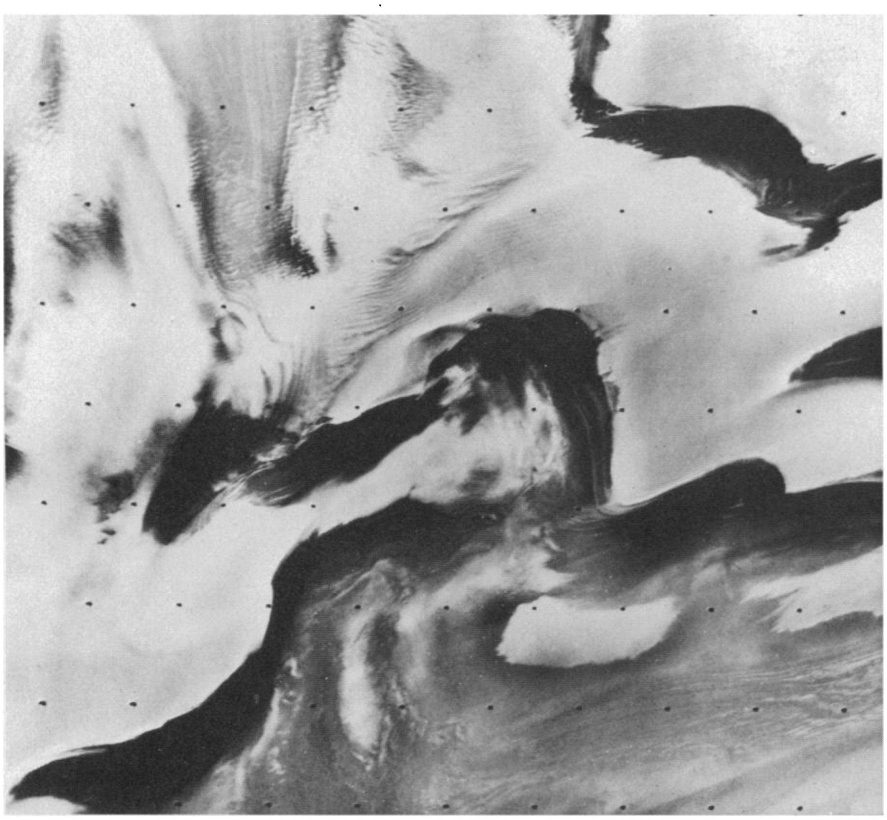


Fig. 10. Dunes overlying layered deposits near the edge of the ice cap. The dune ridges are formed almost perpendicular to the direction of the layering near the upper left center of the frame. The dune covering is apparently thin or discontinuous because the layering is not totally masked by the dunes (Viking 2 frame 56B57).

very much smaller area of frost-free ground. Using the observation that there is less than one fresh crater of 300 m or larger in an area of 800,000 km^2, one can compare this result with equilibrium populations $C_E(D)$ calculated on a variety of assumptions.

The equilibrium incremental population of craters of diameter D per 10^6 km^2 may be expressed as

$$N_E(D) = N(D) \cdot T_L(D) \qquad (1)$$

where $N(D)$ is the incremental crater production rate in craters of diameter D per 10^6 km^2 per million years, $T_L(D)$ is the crater lifetime measured in millions of years, and the cumulative equilibrium population, $C_E(D)$, is expressed as

$$C_E(D) = \int_D^\infty N(D')\,T_L(D')dD' \qquad (2)$$

If the crater lifetime is independent of diameter, then by using Eqs. 1 and 2 and the observed upper limit to the crater populations, the lifetime of craters 300 m and larger is calculated to be 0.12 million years if the lunar value for $N(D')$ is assumed.

A more realistic model for crater removal must incorporate a diameter dependence. With perhaps overly simplistic notions of crater obliteration by means of uniform removal of material from the surface or through uniform addition of material from the atmospheric suspension, the crater lifetime scales as the diameter D. Adopting incremental crater production rates proportional to D^{-4} below 1 km and D^{-3} above 1 km, one can calculate a rate of removal or addition of material to the surface based on the upper limit on crater populations. These rates are approximately 1 km per million years or 1 mm per year.

An alternative is that obliteration of craters may be caused by filling from a sheet of saltating material transported to and fro across the ice cap. There are indications of dune features on the ice cap which could imply pervasive saltation processes, perhaps involving mixtures of ice and silicate debris. In this case, crater lifetime varies as D^2 and rates of material transport are estimated to be 0.08 km^3 per kilometer of width per million years or 800 cm^3 per centimeter of width per year.

Although deposition and erosion rates calculated above are large, they are not implausibly large considering that materials have been observed to be redistributed over the surface on scales visible from orbiters in a matter of days or weeks (*16*). Perhaps, the only distinctions between polar regions and other parts of Mars where impact crater topography is more enduring are that in the polar regions the surface processes are well supplied with mobile material and are sustained for a much larger fraction of the time.

A scenario for the evolution of the north polar region. Our preliminary study of the north polar region geology leaves us with uncertainties and ambiguities concerning the events that have taken place there. Some of this confusion may well be resolved by future analyses of the imaging data. The scenario that is outlined in Table 1 is not a unique one—it may not even be the one that is most in harmony with the data—but it does offer a credible framework for the observations against which further observations and theoretical models may be tested.

Two distinct types of climate change are implied by this scenario. Climate changes of type 1 are associated with the fine-scale layering and are clearly cyclical with a relatively short and apparently regular period. They seem to involve fairly limited excursions in environmental conditions affecting, apparently, the rate of deposition. Climate changes of type 2, of which two episodes, at least, have been recognized so far, occur on a much longer time scale, perhaps two or even three orders of magnitude longer than that of type 1 changes. Type 2 climatic changes do not necessarily have a uniform duration or a regular period, and they seem to involve radical excursions in environmental conditions from a depositional regime to an erosional regime.

There is no evidence that changes in the polar climate have any connection with climatic changes postulated in connection with channel formation on Mars (*17*). The polar climatic changes indicated are probably much more subtle than the massive temperature and pressure changes required for fluvial activity in the equatorial regions. The martian channels are also reported to be extremely old (*18*) whereas erosion in the polar regions is clearly very recent. We cannot, however, exclude the possibility that accumulation of the layered deposits was contemporary with channel formation, but even if that were so, the erosion of the deposits postdated it. The layered deposits may nevertheless play an important role in the volatile history of Mars. Much of the water inferred to have been released from the planet's interior since its formation (*19*) could have been codeposited in the form of ice with dust in the polar regions.

Paradoxically, the events that are least certain in the history of the polar region are those that are closest to the present. The relationship of the layered units to the polar caps is not understood. Neither is the origin of the dune fields. The searchlight features that transect major topographic features without a change in direction are also a puzzle. We don't know whether the polar region is presently experiencing a depositional or erosional cycle. We cannot exclude the possibility that the evolution of the polar region is now controlled by a climatic regime quite distinct from those that have existed previously. If we are fortunate enough to recover higher-resolution imagery after the spacecraft passes the solar occultation period of superior conjunction, we may obtain insights into some of these tantalizing problems.

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7. The Viking visual imaging system consists (two high-resolution, slow-scan television fran ing cameras. Conceptually similar to the Mar ner camera systems used in previous Mars, Me cury, and Venus missions, the visual imagin system incorporates improvements designed t increase both spatial resolution and coverage Each camera employs a 475-mm diffraction-lir ited telescope and a 37-mm-diameter vidicon the central region of which is scanned with raster format of 1056 lines by 1182 samples an produces a 1.54° by 1.69° field of view. Th optical axes of the cameras are offset by 1.38° Cameras are shuttered alternately, which result in contiguous swaths of images 80 km wide, wit resolution better than 100 m near periapsis. Si color filters are available to restrict the imag spectral bandpass to limited portions of the cam eras' near-visual response characteristics. Th camera systems are described in detail by J. B Wellman, F. P. Landauer, D. D. Norris, and T E. Thorpe (*J. Spacecr. Rockets*, in press).
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9. All images published here are oriented with the north approximately toward the top of the frame and with the illumination directed from the bottom of the frame. Unless otherwise noted, the dimensions of individual frames lie in the range 60 to 100 km. Most images used have been filtered to display detail in both ice-covered and ice-free areas. Consequently, in many cases the brightness of an area in the processed image is not a reliable indicator of the presence or absence of ice cover.
10. The crustlike material observed by the Viking landers has recently been termed "duricrust," which avoids the implication of genesis that accompanied the earlier use of the term "caliche."
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20. The Viking 2 reconnaissance of the north polar region of Mars has benefitted from the dedicated efforts of large numbers of individuals. Among members of the orbiter imaging team and staff we thank especially K. Klaasen, T. E. Thorpe, R. Tyner, and J. B. Wellman for their untiring support of the polar photography effort. Financial support for the work of team members was provided by NASA through the Viking Project Office and the Office of Planetary Geology (R.G.).

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Mars Dynamics, Atmospheric and Surface Properties: Determination from Viking Tracking Data

Abstract. *Approximately 3 months of radio tracking data from the Viking landers have been analyzed to determine the lander locations, the orientation of the spin axis of Mars, and a first estimate from Viking data of the planet's spin rate. Preliminary results have also been obtained for atmospheric parameters and radii at occultation points and for properties of the surface in the vicinity of lander 1.*

The objectives of the Viking radio science investigations are to use the data from the tracking and communication systems on the orbiters and landers for scientific studies of Mars and its environment, to study properties of the solar system, and to perform tests of general relativity (*1*). Preliminary results from three of the investigations, lander tracking analyses, the occultation experiment, and the surface properties experiment, are reported here.

Lander tracking analyses. In a previous report (*2*), we presented preliminary results for the Viking lander 1 (VL1) position and for the orientation of