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Origin of the Stepped Topography of the Martian Poles

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The circumpolar stepped topography observed within the Martian polar regions can have originated from one of a limited number of processes, including (i) erosion of resistant layers, (ii) erosion rates inversely proportional to slope gradient, (iii) basal sapping, and (iv) bistable rates of erosion and deposition. The last mechanism appears most likely to operate on the polar escarpments, driven by ablation of volatiles on the dark scarps and deposition on the icy flats. Decreasing albedo and a corresponding increase in radiation input caused by dust accumulations on the ablating layered deposits on steeper slopes provides a metastable erosion rate model sufficient to produce a stepped topography. Wind erosion is presumed later to remove the loose excess residual dust which accumulated during ablation of the scarps. The ablation of the scarps contemporaneously with ice accumulation on the flats implies the layered deposits exposed on the scarps have formed beneath overlying flats, and the observed unconformities within these deposits can be due to the exposure of deposits laid down under more than one flat with different gradients. The linearity and mutual parallelism of the scarps is a result of scarp retreat on a regional slope or with a preferred direction of scarp retreat. The spiral arrangement of the scarps is probably due to more rapid retreat of scarps facing slightly west of the equatorward meridian, that is, in the direction of greatest solar and atmospheric warming. The model suggests, but does not prove, that the layered deposits are mostly water ice, with small amounts of codeposited silicate dust and volcanic ash.

INTRODUCTION

The Mariner and Viking probes have revealed many spectacular landforms, but most, including the channel systems, the shield volcanos, and equatorial troughs, appear to differ from terrestrial examples primarily in magnitude. But no terrestrial analog has so far been found for the layered and stepped terrain of the North and South Poles of Mars. Recent evidence, including the models presented here, suggest that the low polar temperatures account for the unique Martian features; rather than snowfall, bulk flow, and meltwater processes that dominate on Earth, the Martian polar landforms are sculpted by vapor-state volatile transfer, wind action, and mass-wasting.

The polar areas are underlain by thin, nearly horizontal layers which can be traced laterally over hundreds of kilometers (Cutts, 1973a; Murray *et al.*, 1972; Soderblom *et al.*, 1973; Cutts *et al.*, 1976). Individual layers are approximately 5 to 50 m thick (Dzurisin and Blasius, 1975), although they may be composed of even thinner bands below the level of photo resolution. These deposits have been sculpted into a series of stairlike escarpments, with volatile-covered, nearly level "flats" and darker, gently sloped (1–5°) "scarps," the latter being characteristically 100 to 1000 m high and 3 to 10 km in width (Dzurisin and Blasius, 1975). The scarps are apparently erosional, for many strata are exposed on each. The flats appear to be

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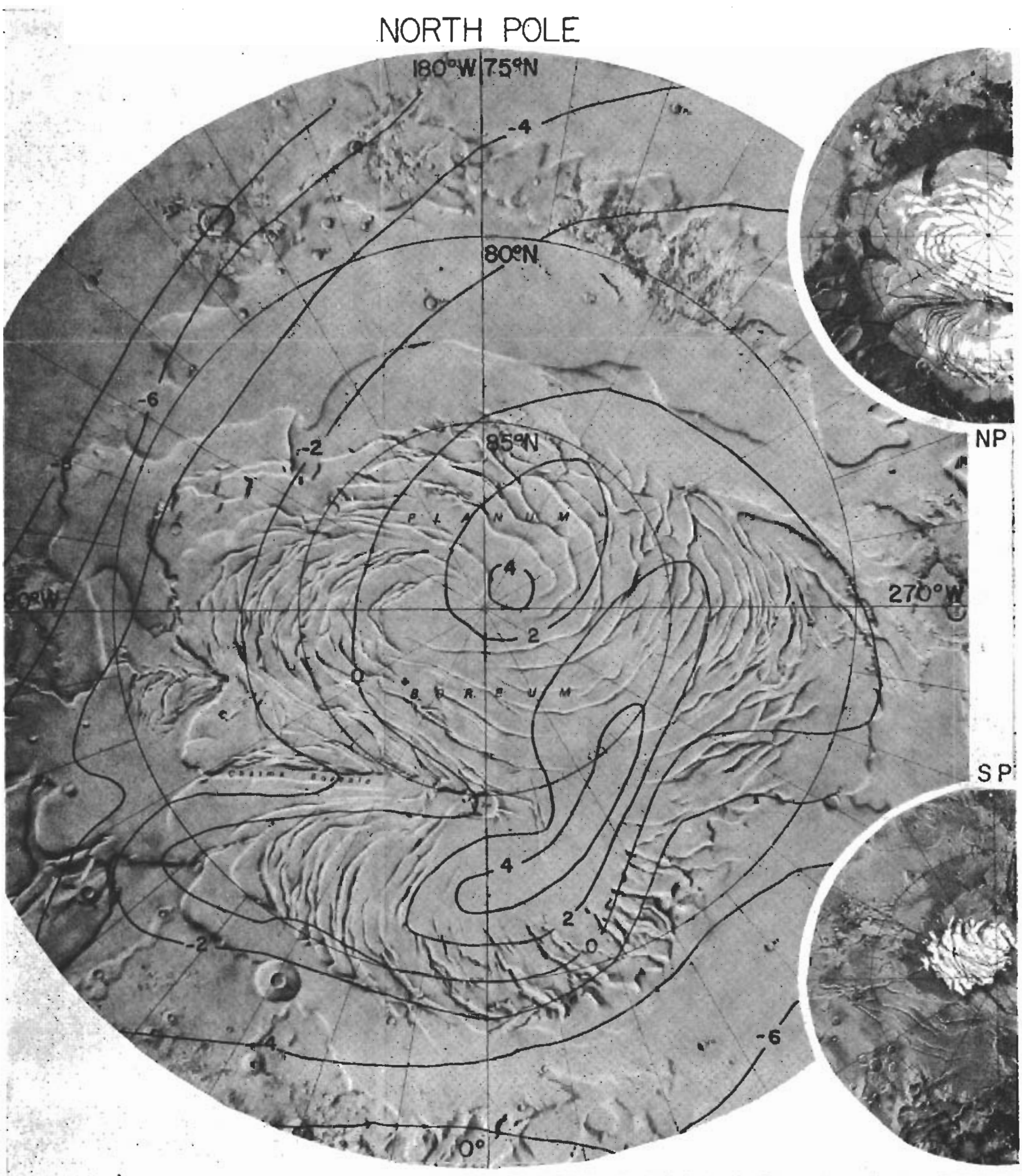
conformable to the layers. Although most of the polar dark bands (Fig. 1) are gentle escarpments, as described, a small proportion are shallow, linear depressions (Dzurisin and Blasius, 1975).

Near the poles the scarps contrast sharply in albedo with the flats. Kieffer *et al.* (1976, 1977) and Farmer *et al.* (1977) present evidence that the flats at the North Pole are covered with a permanent deposit consistent with "dirty water ice" ($A = 0.34$–0.45) whereas the albedo of the scarps is typical of Martian regolith ($A = 0.20$–0.25). Surrounding the permanent ice cap at the South Pole is a large zone of layered and stepped terrain, which



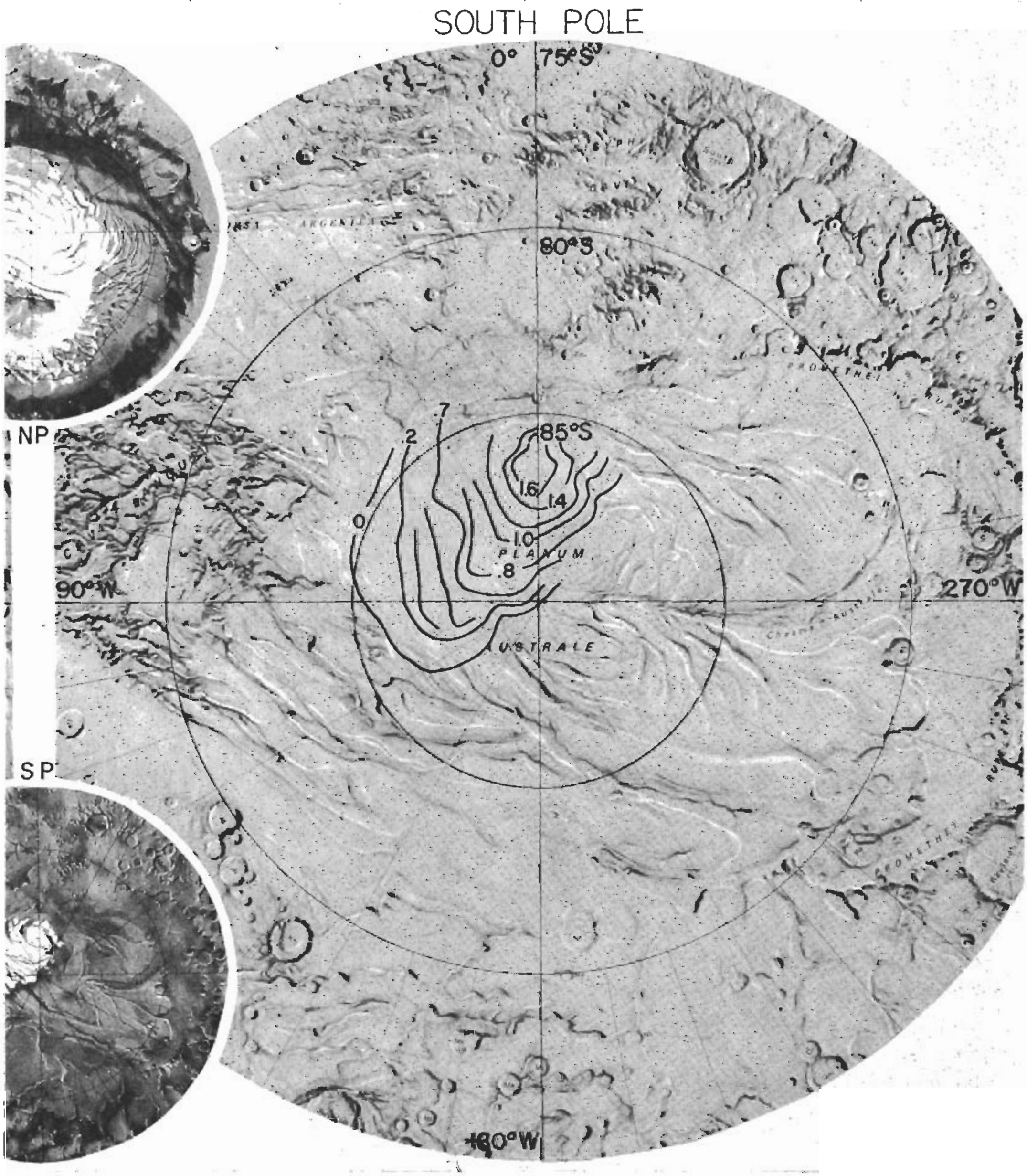


FIG. 1. Shaded relief maps of the Martian polar regions, with insets showing the extent of the residual ice caps. Approximate topographic contours from Dzurisin and Blasius (1975). Note irregular contour interval at the South Pole. Altitudes in kilometers.

lacks the albedo contrast between scarp and flat during the southern summer. By contrast, the perennial ice cap of the North Pole is much larger, and less of the layered terrain occurs outside its boundaries.

Most of the steps are laterally continuous over hundreds of kilometers, are nearly parallel, and are arranged in broad swirls which are more regular at the North than the South Pole (Fig. 1).

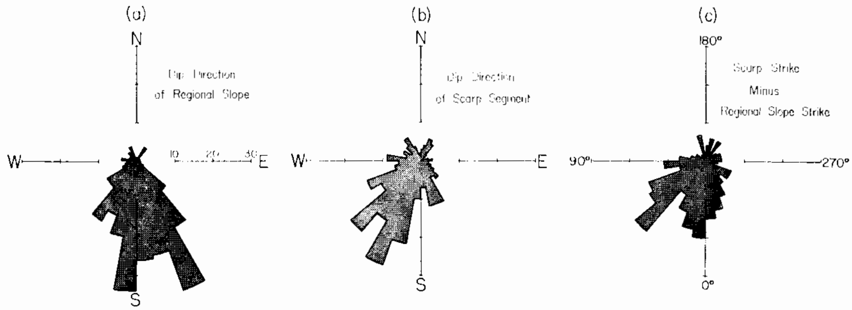


FIG. 2. Directional characteristics of North Polar scarps and slopes, based upon measurements of 262 scarp segments distributed fairly evenly over the stepped topography. The dip direction of the scarp in (b) is that of the landform, not that of the scarp slope (see Fig. 8).

The layers have been hypothesized to originate through the accumulation of variable quantities of volatiles together with silicious dust and volcanic ash deposited from atmospheric suspension (Cutts, 1973a; Murray *et al.*, 1972; Sharp, 1974). The volatiles in the layered deposits at the North Pole are almost certainly dominated by water ice; CO_2–ice and CO_2–H_2O clathrates, which earlier had been thought to dominate (Leighton and Murray, 1966; Murray and Malin, 1973b) have now been shown to be unstable because of high summer temperatures at the North Pole (Ingersoll, 1974; Kieffer *et al.*, 1976). The variation in physical state or composition producing the observed stratification is presumed to reflect climatic oscillations (Cutts, 1973a; Murray and Malin, 1973a). However, the origin of the superimposed stepped topography is still uncertain, although hypotheses have been proposed based upon polar wandering and associated depositional episodes (Murray and Malin, 1973a), wind erosion (Cutts, 1973b), mass-wasting (Cutts and Michalsky, 1974), glaciation (Clark and Mullin, 1976), and differential radiational control of volatile transfer (this paper). These processes are considered within the context of quantitative modeling of several types of erosion and depositional rate laws that can generate a stepped topography. Although these models are primarily framed about radiational processes, they are pertinent to most potential processes.

Any complete explanation of the stepped topography should account for its several features, including the slope dichotomy between scarps and flats, the linearity and parallelism of the scarps (although locally wavy and occasionally branching), and their circumpolar arrangement into spirals with southwestward dip at the North Pole and a less regular tendency toward a northwestward dip at the South Pole (Figs. 1 and 2). The models presented here provide adequate, quantitative explanations for these features, but they give limited insight into the factors controlling the scale of the topography (that is, the characteristic height, steepness, and separation of the scarps) and the rates and geologic history of the formative processes and resultant landforms.

Because of limited information on the composition and physical state of the polar terrains, the range of potential hypotheses is large, so that explanations should also be judged in part by their simplicity and the degree to which they involve only processes that can now be observed or inferred to be active, qualities which are inherent in the postulated radiational control.

REVIEW OF CURRENT HYPOTHESES

Sequential development during polar wandering. Murray and Malin (1973a, p. 997) noted that the steps are "roughly circular plates with outward sloping edges" and they hypothesize that ". . . the former position of Mars' spin axis may be recorded by the centers of curvature of the displaced circular topographic features of the laminated terrain." Presumably, each step marks a former equatorward limit of the depositional or erosional stability of the accumulation of the volatiles and included dust. Their hypothesis, while appealing in its simplicity, has never been quantitatively elaborated, and is not consistent with the geometry of the steps. In particular, the steps record only one segment of each envisioned polarcentric deposit, yet all of the steps appear to be of the same age (Nash, 1974). In addition, the steps and inferred paths of polar wandering are not hemispherically symmetrical (Nash, 1974; Dzurisin and Blasius, 1975), and are not represented by a well-defined circular structure around the present poles. In view of these shortcomings, this hypothesis will not be further considered.

Glaciation. Clark and Mullin (1976) proposed that the laminated deposits are dominated by CO_2 ice, which, during glacial outflow, had sheared depositional layers into the observed stratification. Their model cannot be considered seriously at present, for carbon dioxide is an unlikely major constituent of the layered deposits at the North Pole (Ingersol, 1974; Kieffer *et al.*, 1976), and water ice at polar temperatures is too stiff to flow at existing stresses (Sharp, 1974). In addition, the stratification is unlikely to be of deformational origin (Cutts and Michalsky, 1974).

Wind erosion. Cutts (1973b) suggests that the polar steps may be sculpted by wind erosion, although he does not detail any specific mechanisms. Convincing evidence has been found for polar erosion and deposition by the wind, including a concentric deposit of dunes beyond the present North Polar ice cap suggesting an outward transport of detritus eroded from the polar deposits (Cutts *et al.*, 1976). In addition, the layered deposits are eroded into yardang-like parallel grooves, and the major reentrant to each polar cap (chasma) may have been eroded by episodic concentrated outflow of the surface inversion layer over the poles (Cutts, 1973b).

However, a purely wind-erosional origin for the polar escarpments seems unlikely. The trend of erosional fluting on the polar caps is not of consistent orientation relative to the scarps, ranging from nearly perpendicular to nearly parallel (Cutts, 1973b). Wind erosion on Earth and Mars generally produce either irregular deflation hollows or streamlined yardangs which exhibit sharp intersections of sculpted facets (e.g., Grolier *et al.*, 1974; McCauley, 1973; Mutch *et al.*, 1976a), at variance with the gentle steps with their rounded contours (Murray *et al.*, 1972; Dzurisin and Blasius, 1975). If the steps lie parallel to an eroding wind, the secondary circulation patterns must be uncomfortably large and their spiraling is opposite to the sense of Coriolis deflections, but if they formed transverse to an eroding wind, then erosion would have to be concentrated on the lee face, which in terrestrial analogs of dunes and wind-eroded forms is a relatively protected location.

Nevertheless, wind erosion and transport plays an important supporting role in the models developed here, not determining the geometry of the steps, but removing dust loosened by radiation-controlled ablation.

Mass-wasting. Cutts and Michalsky (1974) found evidence that some of the south polar scarps are partially eroded by mass-wasting processes associated with differential decay of ground ice, producing stubby reentrant canyons. They feel that the mass-wasting is only locally important and that scarp and canyon sculpture requires wind erosion to remove the mass-wasted debris.

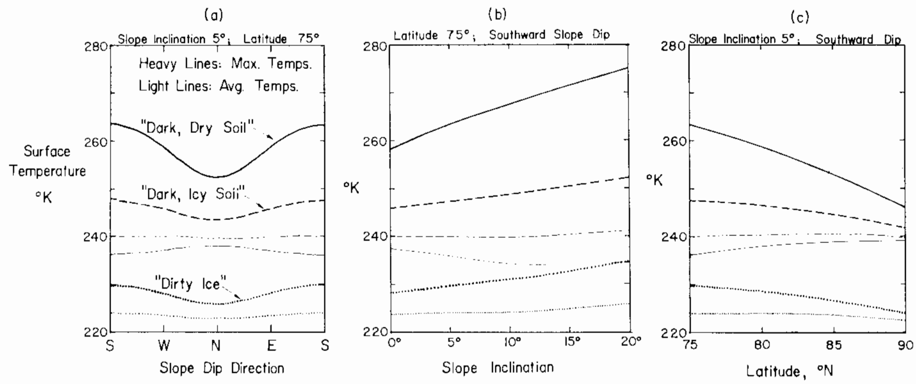


FIG. 3. Maximum and diurnal average surface temperatures during the Martian summer solstice as a function of slope orientation, slope gradient, and latitude. Calculation methods are similar to those of Leighton and Murray (1966), and ignore atmospheric interactions with surface heat flux. The dark, dry soil has an albedo of 0.24 and a thermal inertia of 0.007, the dark, icy soil has an albedo of 0.24 and a thermal inertia of 0.048, while the "dirty ice" has an albedo of 0.41 and a thermal inertia of 0.048. Slope effects calculated from formulas in Sellers (1965). Ablation and condensation are assumed to occur slowly enough that latent heats do not affect the surface temperature balance.

Differential ablation and deposition. Most investigators of the Martian polar landscape have felt that the stability of volatiles has controlled both accumulation of the layered deposits and the overall size of the polar cap. However, there has been no suggestion that the stepped topography specifically owes its origin to condensation and ablation of volatiles [although Murray and Malin (1973b) suggested that the steps owe their gentle rounding to ablation, and Cutts *et al.* (1976, p. 1333) hint that "the present distribution of frost is controlling the accretion of material that forms the layers"]. Recent analysis of Mariner 9 and Viking orbiter data strongly points toward ablation and condensation as processes directly sculpting the polar terrain.

The equatorward-facing scarps defrost during the Martian summer, while the flats retain a frozen water cap (Dzurisin and Blasius, 1975; Kieffer *et al.*, 1976). Once the seasonal frost is sublimed during the Martian spring and summer, the scarps become even warmer due to the lower albedo of the dust exposed in the layered deposits (Farmer *et al.*, 1976; Kieffer *et al.*, 1976). Recent analysis by Farmer *et al.* (1977) suggest that the highest water vapor concentrations on Mars occur over the dark polar bands. By contrast, the icy flats are cooler by virtue of lower slope and higher albedo, so that they may be stable, or may accumulate ice (although seasonal ablation is apparently responsible for a summer albedo characteristic of "dirty water ice"). The 30 to 40°C temperature contrast between the dark scarps and the light flats (Kieffer *et al.*, 1976; also see Fig. 3) may in fact promote a net vapor phase transfer of ice presumably present in the layered deposits to the flats (Kieffer *et al.*, 1976, p. 1343). This transfer could be self-maintaining because the net ablation on the scarps leads to surficial accumulation of dark dust particles, whereas net accumulation on the flats helps maintain the high albedo despite yearly deposition of atmospheric dust. An important feature of this process is a "threshold" effect (process thresholds in geomorphology are discussed by Howard, 1965; Chorley and Kennedy, 1971; Schumm, 1973).

As will be discussed subsequently, the differential ablation process requires the helping hand of wind erosion or mass wasting to remove accumulating dust from the scarps.

MODELS OF ESCARPMENT FORMATION

The development of a stepped topography requires complex slope processes involving, in general, thresholds or metastable states. The models developed in the following sections, although referenced primarily to the hypothesis of radiational control of landform evolution, are applicable to slope processes in general. The rate of erosion (or deposition) at a particular location may be a function of several variables, the most important of which, for a slope primarily eroded by surface attack, are (a) the resistance of the underlying material to weathering; (b) the influence of the size, depth, and cohesiveness of the weathered material upon its net rate of removal from the surface; (c) the nature and intensity of the surface processes; (d) the slope gradient; (e) the position on the slope; and (f) the elevation above some datum.

Depending upon whether the first or the second factor is the limiting control upon erosion rates, slope erosion may be either weathering limited or transport limited (Carson and Kirkby, 1972, p. 104 ff.). In the former case the transport processes are sufficiently active that debris is eroded from the slope shortly after weathering reduces the size and cohesion of parent material to transportable values. On the other hand, if the rate of removal of weathered detritus is slow, the accumulation of a "soil" reduces the efficiency of most surficial weathering processes, so that the rate of removal of debris becomes the limiting factor determining the rate of slope erosion. In most cases only one of the two factors, the rate of weathering (including entrainment and eolian grain plucking) or the rate of transport, controls the overall rate of slope erosion.

Erosion of the polar scarps is probably weathering limited, except locally. Transport-limited slopes generally are sculpted into morphologies reflecting the transporting agent. Terrestrial and Martian slopes which depend upon mass movement (for example, the walls of the Coprates canyon) generally present a smooth profile in which the differential resistance of the underlying bedrock is not expressed in surface morphology, whereas the small-scale terracing of the polar layers suggests such expression. This is characteristic of weathering-limited slopes (Howard, 1970). The small overall gradient of the risers also argues against mass-wasting as a dominant process, especially since liquid water is unlikely in near-surface materials. The local areas of polar scarp mass-wasting (transport-limited slopes) noted by Cutts and Michalsky (1974) are not covered by the models that follow; they will require separate treatment.

Modeling of weathering-limited slopes is simpler than transport-limited slopes, because in the latter case additions to and removal from the blanket of weathered material must be explicitly accounted for, whereas removal is implicit in the weathering-limited case. For weathering-limited slopes the rate of vertical erosion E (or $\partial z/\partial t$) is functionally related to the slope gradient S (or $\partial z/\partial x$) and the "weatherability" of the substrate K:

$$E = f(S; K), \tag{1}$$

where K may depend upon several factors, including the slope gradient, the intensity of the weathering and detachment processes, position on the slope, and elevation.

Stepped topography can be sculpted by only a few types of relationships between erosion rate and the controlling factors. Several potential mechanisms are discussed below. Others may be possible. All of the mechanisms discussed imply a threshold between erosion for slopes steeper than some critical gradient S_c and either deposition, stability, or modification of erosional resistance on slopes less than this value. The models considered involve rate laws

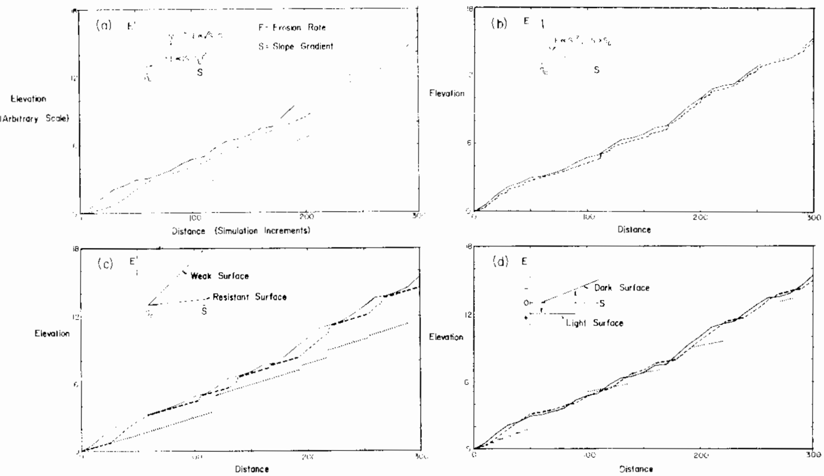


FIG. 4. Two-dimensional numerical simulation of slope evolution under various erosion and deposition rate laws (inserts). Initial topography (solid lines) generated by a constrained random walk. Successive stages of slope evolution shown by dashed and dotted lines.

that are very simple and thus are unlikely to be directly comparable to the actual circumstance, but which can serve to distinguish the relevance of various classes of rate laws. The numerical models discussed below assume a functional relationship of the form of (1), but they do not presuppose a particular erosional process nor do they attempt real-time simulation. For example, each temporal increment represents many years (or possibly thousands of years) of natural erosion and deposition. However, the discussion of each model focuses on the possible correspondences, if any, between the model and Martian polar processes.

Because of the nearly parallel and linear scarps, two-dimensional modeling is adequate to investigate the factor leading to a stepped topography. The reasons for the parallelism and linearity of the steps will be addressed separately in the context of limited three-dimensional modeling. Because of the necessity for thresholds in the erosion rate laws, analytical modeling is impractical, and digital simulation models using finite difference approximations to (1) were used to investigate slope evolution for various hypotheses. Computer modeling has been used extensively in slope studies (Scheidegger, 1970; Ahnert, 1971; Carson and Kirkby, 1972). The two-dimensional simulations were conducted with a slope 300 increments long. Erosion (or deposition) was simulated in small temporal steps according to the hypothesized rate law (shown as insets in Fig. 4). In all simulations the downslope terminus of the overall slope was fixed at a constant elevation. Forward differences were used in the two-dimensional models, and in the three-dimensional models the steepest gradient between the given point and the eight surrounding points was assumed to determine erosion rates. The initial slope is shown by solid lines in Fig. 4 (also Fig. 5a), and the dashed and dotted lines in Fig. 4 indicate successive stages of slope erosion after many iterations.

The computer simulations test whether the hypothesized rate law will sculpt an arbitrary initial topography (generated by a random walk process from an assumed population range of allowable gradients greater than zero) into a stepped topography; the simulations were not designed to model the steady-state morphology and scale of the natural steps. In the simulation models the size of the resulting steps is initially determined in part by the inherent scale of the initial topography (the number of spatial increments in each random walk segment) and in part by the rate laws. As the simulations progress the boundary conditions (particularly the fixed downslope terminus) become more important. The size of the spatial increments, which has no natural counterpart, may also affect ultimate step size.

Erosion proportional to slope gradient. One class of models tested assumes that the rate of erosion is solely a function of slope gradient and that no deposition occurs. However, if the rate of erosion is presumed to increase as the gradient becomes steeper, erosion tends to smooth the initial irregularities in the slope profile (Fig. 4a). This seems to be a general rule, for diverse rate laws of this class give the same result. L. Soderblom (personal communication) has pointed out that under this rate law Eq. (1) resembles a diffusion equation and would therefore tend to spatially average slope gradients through time. A partial exception occurs if the rate of erosion is a constant independent of slope gradient or if the rate is linearly dependent upon gradient, in which case the original slope elements are maintained during their subsequent erosion. However, maintenance of existing topography will not develop a stepped topography if it does not already exist.

If the rate law includes a decrease in erosion rate beyond some critical value, a stepped topography *is* produced (Fig. 4b), for gentle slopes become progressively

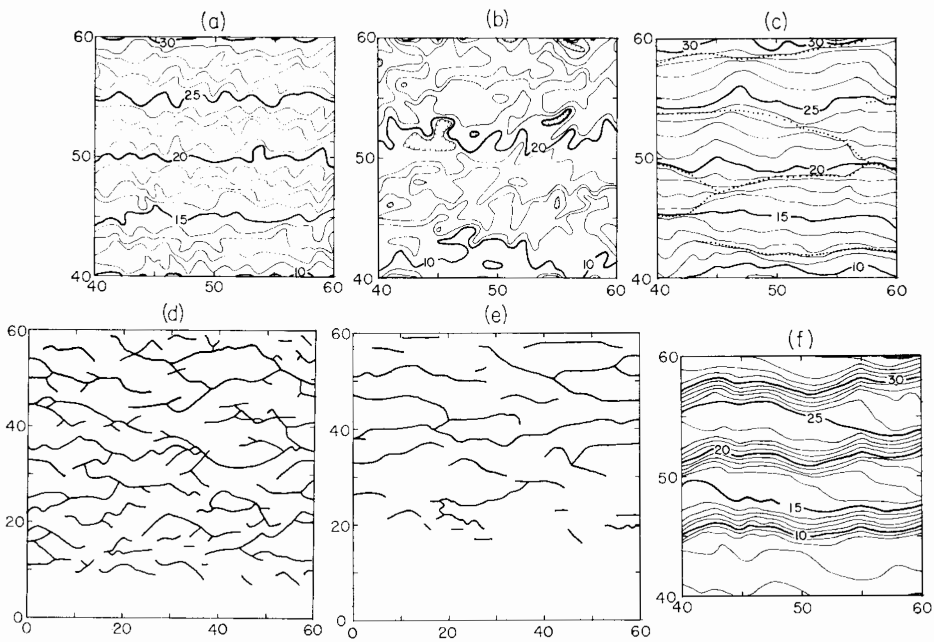


FIG. 5. Three-dimensional modeling of slope evolution under various rate laws: (a) Original topography of random fluctuations superimposed upon a regional slope dipping toward the bottom of the figure. Area shown is one-ninth of a 60 × 60 matrix. Arbitrary contour interval and datum; (b) Topography developed by the inverse rate law shown in Fig. 4b; (c) Topography formed by erosion with formation of resistant layers, as in Fig. 4c; (d) Scarps on a 60 × 60 matrix formed by erosion of resistant layers after 30 iterations. All scarps face in the general direction of the regional slope; (e) Scarps as in (d), but after 60 iterations. Absence of scarps at bottom of matrix due to low relief near the constant base level; (f) Topography formed by simultaneous erosion and deposition by a rate law as in Fig. 4d.

gentler, and steep slopes continuously steepen. However, this does not seem to be a realistic rate law for most slope processes, including radiation-controlled ablation, because maximum surface temperatures increase monotonically with increase in slope gradient (Fig. 3b). Furthermore, this inverse rate law produces escarpments that do not migrate (Fig. 4b). In the three-dimensional simulations this means that linear, parallel scarps are not produced (Fig. 5b), a point to be further discussed.

Development of resistant layers. The most typical terrestrial occurrence of stepped topography occurs when nearly horizontal resistant sediments are sandwiched between easily eroded layers, producing an escarpment and mesa topography that characterizes much of the Colorado Plateau and the midwestern United States. The resistant layers can only be eroded at a rate comparable to the weaker rocks if the gradient is steep, so that a stepped topography is produced by a combination of stripping of the overlying weaker unit from the top of the resistant unit and backwasting of the resistant layers by escarpment retreat.

A variation of such processes might apply to radiation-controlled or wind erosion in the polar regions, because low-gradient slopes are covered by a layer of water ice of undetermined thickness. The ice-covered flats are probably more resistant to ablation than the scarps simply by virtue of their higher albedo, and possibly also because of the greater quantity of ice that must be sublimated to cause a given amount of erosion as compared to the layered terrain. The icy flats might also be more resistant to wind erosion than more friable layers exposed in the scarps.

Development of stepped topography as a result of resistant ice layers might result from two processes, exhumation of volatile-rich or cemented strata within the layered deposits, and deposition of ice or cementation of the layered deposits whenever the slope gradient drops below some critical value, S_c. The later process was modeled in Fig. 4c by the development of a thin layer 10 times more resistant to erosion than steeper slopes on slopes gentler than S_c, and the layer is assumed to develop instantaneously on a one-time basis. For a given resistance, erosion was assumed to be proportional to slope gradient, although the exact rate law is unimportant. As would be expected, a stepped topography develops which eventually produces essentially parallel, linear escarpments (Figs. 5c, d, e). The model might more realistically include provisions for an increase in the resistance and/or thickness of the capping layer as a function of the time that the gradient remains at or below S_c.

Sapping of resistant layers in terrestrial and equatorial Martian environments usually produces a sharp break-in-slope at the top of the scarp and a blanket of wass-wasted debris covering an angle-of-repose lower scarp (although the latter feature is not a necessary consequence of resistant layer erosion). Despite their low scarp gradients, the polar escarpments and canyons described by Cutts and Michalsky (1974) may best be fit by the resistant layer model. However, the more typical Martian polar scarp topography, with gently rounded contours, is probably better fit by the simultaneous erosion and deposition model to be discussed.

The layered polar deposits may be more resistant than the underlying deposits. Cutts (1975) presents evidence that the marginal scarp bordering portions of the South and North Polar caps may be retreating more rapidly than the scarps in the layered deposits, and these marginal scarps appear to be more similar in morphology and steepness to normal escarpments of resistant rock than to the polar-layered scarps.

Basal sapping. If, instead of a decreased potential for erosion at the top of a slope caused by a resistant layer, the erosional potential is increased at the base of the slope, a stepped topography will likewise develop. For example, on terrestrial badland slopes runoff and lateral erosion cause a slope break at the foot of the slopes (Smith, 1958; Schumm, 1962). Emergence of groundwater or dry sapping at the base of slopes have been proposed for the origin of scarps elsewhere on Mars (Sharp, 1973a, b; Sharp and Malin, 1975; Carr and Shaber, 1977; Luchitta, 1974; Milton, 1973; Mutch *et al.*, 1976b). However, runoff and groundwater flow seem unlikely past or present processes at the Martian poles, due to the low temperature and atmospheric pressure (Cutts and Michalsky, 1974).

Bistable ablation and condensation rates. A stepped topography can also develop if erosion and deposition occur simultaneously on different parts of the same landscape. The bistable rate model, although somewhat more complex than the previous ones, appears to fit most conveniently with present knowledge of surface morphology, composition, and the inferred evolutionary history of the polar caps.

The model is similar to the previous ones in that, for slopes steeper than some critical value the rate of erosion increases with the slope gradient. The novel feature is the supposition that deposition occurs if the gradient is less than a smaller critical gradient. The model also requires an overlapping range of slope gradients for erosion and deposition. It is assumed that if the slope is presently eroding, it continues to erode until the gradient is reduced below a critical value, S_{c1}. Deposition then occurs until the slope increases to the second critical value, S_{c2} ($S_{c2} > S_{c1}$), whereupon erosion is reinitiated. The stepped topography will develop if the initial random topography includes gradients both larger than S_{c2} and smaller than S_{c1} (Fig. 4d). In this model the "switching" occurs at the top and base of the scarps.

This behavior seems plausible if erosion and deposition are controlled by the process of differential ablation and condensation outlined previously. Because of albedo differences between accreting slopes (high albedo) and ablating slopes (low albedo due to dust accumulation), there would exist a range of slope gradients at a given point such that erosion would occur if the albedo were low and deposition if the albedo were high.

An intriguing feature of the present model is the rich history implied by concomitant erosion and deposition. At some locations on the simulated slope (Fig. 4d) erosion occurred continuously, at others deposition was continuous. Other locations first eroded and then built up, or the reverse, and a few points underwent even more complex alternations of erosion and deposition.

Perhaps the most compelling feature of the model is that it can explain the development of nearly flat layers which are concordant with the overlying flat, for the layers would represent episodes of deposition on the superadjoining flat which subsequently become exposed as the scarps erode headward (Fig. 6). The angular unconformities observed in the layers exposed in the scarps (Cutts *et al.*, 1976) are likewise potentially explained, for if the scarps are not exactly equal in height (the Martian scarp heights vary from at least 100 to 1000 m in height), a tall scarp will exhume deposits laid down under more than one flat, and the unconformities will be angular if adjacent flats in the natural prototype are not parallel. However, noticeable unconformities appear to be rare, both because of the small angles of discordance and the need for a wavy pattern of scarp dissection to reveal the unconformities.

The model applies most simply if the bulk of the layered deposits is water ice. If sediment forms the bulk of the deposits, then deposition of new layers would have to involve an upward displacement of the water substance of the perennial ice deposit, implying either that it is very thin or that it is impermanent, perhaps disappearing

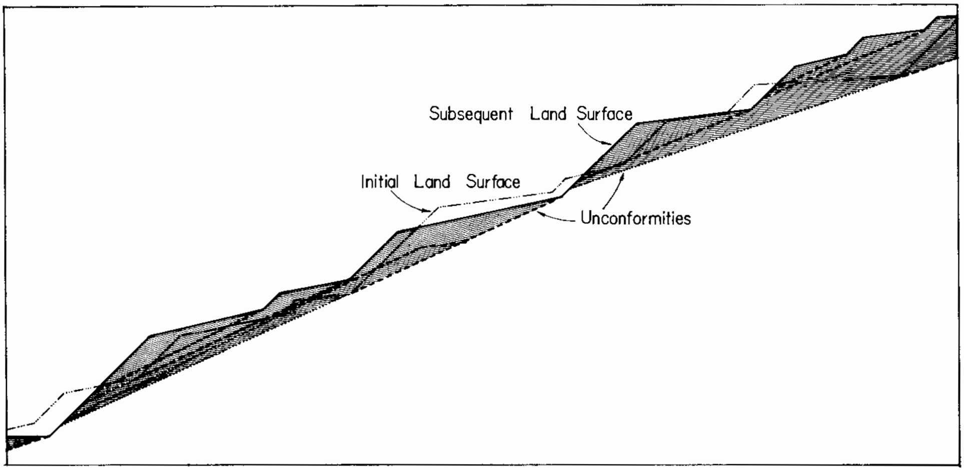


FIG. 6. Development of layered deposits with simultaneous ablation and condensation on a stepped topography. In this hypothetical example scarps have equal gradients but unequal heights, while both the width and gradients of the flats vary. Unconformities occur between layers deposited under different flats (dashed where formed between the initial and subsequent land surfaces and dotted where formed prior to the initial land surface). Uncolored areas formed earlier than the period considered. Notice that the tallest scarps expose the most unconformities and the oldest deposits, and that the layers above any unconformity are more steeply inclined than the underlying layers.

and reforming during climatic cycles. However, if the layered deposits are dominantly ice, then the flats differ from the scarps solely in the amount of surface dust accumulation.

The concomitant erosion and deposition model does not necessarily imply a long-term equilibrium of either total bulk of the layered deposits, of the ice, or of the contained sediment, although it can be consistent with any or all of these equilibria. All of the previous models imply net erosion in the polar areas, requiring a sink in more equatorial areas for water vapor released during ablation, for example, in weathering products or a deep permafrost layer. A net erosion of particulates probably explains the ring of dunes surrounding the North Polar cap (Cutts *et al.*, 1976). However, a rough cycle may occur, balancing net erosion and equatorward transport of sediment eroded from the scarps during the summer seasons with winter poleward migration and deposition of atmospheric dust eroded from equatorial areas. The dunes could be an equilibrium feature under these circumstances. However, a former episode of net particulate erosion seems indicated by the partially eroded debris blanket inferred to have been deposited over midlatitudes as a result of polar erosion (Soderblom *et al.*, 1973), which presumably requires long-term waxing and waning of the polar cap deposits.

OTHER FEATURES OF THE POLAR STEPS

These models also provide reasonable explanations for the linearity and parallelism of the steps, for the preferred orientation of the steps, and for the spiral structure of the banding.

Linearity and parallelism of the steps. Both of these qualities appear to be direct consequents of headward scarp erosion. This is illustrated by the three-dimensional version of the resistant layer model; an initial topography of random perturbations on an overall slope (Fig. 5a) develops rapidly into a series of nearly parallel, linear steps facing roughly downslope (Fig.

5c). Once the topography begins to segregate into a series of laterally continuous scarps separating gentle flats, the laterally uniform scarp retreat slowly straightens initial irregularities (compare Fig. 5d with the later stage illustrated in Fig. 5e). A process of uniform retreat ("uniform decresence") on an irregular surface produces pointed salients and rounded reentrants that gradually become more obtuse and shallower, respectively (Lange, 1959).

Similarly, any series of retreating scarps gradually develops parallel strikes with relatively few branches and mergers of adjacent scarps, due to overtaking and incorporation of scarps tending at an angle to the majority of the scarps. The directional bias of rapidity of scarp retreat (discussed below) enhances this effect, for scarps at an angle to the preferred direction move slowly, and are overrun by the more rapid scarps. Retreat of the scarps appears to be a prerequisite for development of parallel, linear scarps; they are also generated by the simultaneous erosion and deposition model (Fig. 5f), but the inverse-square erosion rate law (Fig. 4b) generates nonmigrating scarps and, in three dimensions, an irregular topography of plateaus, pinnacles, and flat-bottomed sinks (Fig. 5b).

The degrees of parallism exhibited by the Martian polar scarps is produced in the simulations only after the scarps retreat through a distance equal to several times their height, suggesting that the development of the stepped topography has required the erosion and, possibly, the concomitant deposition of a considerable volume of layered deposits.

Preferred orientation. Several factors have acted to create the south-to-southwestward dip of the majority of the scarps at the North Pole (Figs. 1, 2b) and the less regular northwestward bias of South Polar scarps (Fig. 1). Some of these factors act in general for models involving scarp retreat on a regional slope, and others are specific to the radiational control hypothesis. Examining the more general factors first, developing scarps will tend to face in the direction of the regional slope, where steeper gradients encourage scarp development. This occurs to some degree even for the nonmigrating scarps of the inverse rate law (Fig. 5b). Migrating scarps, however, are even more strongly influenced by the regional slope (Figs. 5c, d, e, f). The rapid development of downslope orientation of migrating scarps occurs because a scarp of given height and gradient will erode laterally (headward) most rapidly in the direction of the regional slope (assuming for the moment that the rate of erosion is not dependent upon scarp orientation), as is shown in Fig. 7.

Although the Martian polar scarps face in the general direction of the regional slope (the *regional*, or overall slope includes elevation changes across both the scarps and the gentler flats; regional contours strike at the angle α' in Fig. 8), there is a systematic bias such that the North Polar scarps are oriented about 30° clockwise of the regional slope on the average, giving a resultant SSW dip (Figs. 1, 2b, c). This orientation bias is probably due to a directional difference in scarp retreat rates.

The spiral structure of the North Polar scarps is a consequence of this orientation bias. If the scarp contours consistently face a direction (striking at the angle β in Fig. 8) which is different than that of the regional slope, then the scarp as a landform (striking at the angle γ in Fig. 8) faces in a direction different than the regional slope. Given that the erosional processes produce scarps that are nearly linear and parallel, a spiral banding will occur if the scarps retain a constant orientation relative to meridional lines (specifically, a loxodromic spiral).

Since scarp retreat without a directional bias in erosion rates produces scarps which parallel the regional slope, the consistent discordance between the strikes of the slope contours on the North Polar flats and

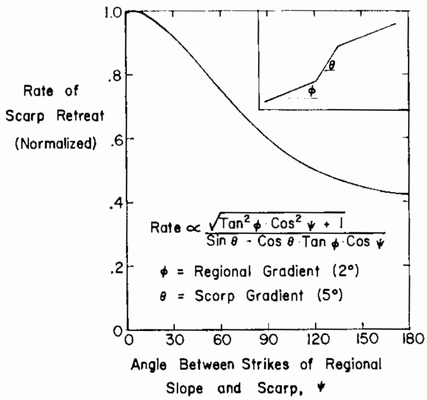


FIG. 7. Rate of scarp migration as a function of orientation of scarp relative to the regional slope. Shown for arbitrary values of the regional and scarp gradients.

those of the scarps is due either to a directional preference in scarp retreat rates or a directional bias in deposition on the flats. Unfortunately, the generalized contours of Dzurisin and Blasius (1975) do not permit the kind of decomposition of the slope strikes of the scarp-and-flat topography illustrated in Fig. 8. However, the most likely process producing the southwestward bias of scarp directions at the North Pole is a more rapid retreat of those scarps whose contours face toward the southwest. Note from Fig. 8 that any such southwestward bias upon a generally southward regional slope would be magnified in the spiraling.

It is uncertain whether the hypothesized mechanism of radiationally controlled ablation of the scarps is able to account for the directional bias of rates of scarp retreat. It might seem that the thermal interia of the soil would assure that a southwestward facing slope (in the Northern Hemisphere) would have the highest maximum temperatures, since for a horizontal or southward-facing slope the highest temperatures occur after noon. However, this is not the case, because slopes facing in other directions also have their temperature maxima after the insolation maxima, but the peak insolation is not at noon. In fact, the maximum temperatures are greatest on south-facing slopes in the northern latitudes (Fig. 3a), so that rates of ablation would presumably be greatest on such slopes. This directional effect, although helping to explain the generally southward dip of the steps, does not provide for the observed southwestward bias. On Earth in the Northern Hemisphere southwestward-facing slopes are generally warmer than southeastward-facing slopes, due to higher afternoon atmospheric temperatures. However, the low heat capacity and radiational transparency of the Martian atmosphere add little inertial effect to soil temperatures (Leighton and Murray, 1966; Neugebauer *et al.*, 1971; Kieffer *et al.*, 1973). On the other hand, the maximum temperatures fall off very slowly away from a southward orientation (Fig. 3a), so that even a slight atmospheric effect (not taken into account in the present calculations) might create a southwestward bias, especially in view of the recent measurements indicating near-saturation vapor pressures of water over the North Polar cap and in view of the surprisingly dusty atmosphere (Farmer *et al.*, 1976; Mutch *et al.*, 1976c).

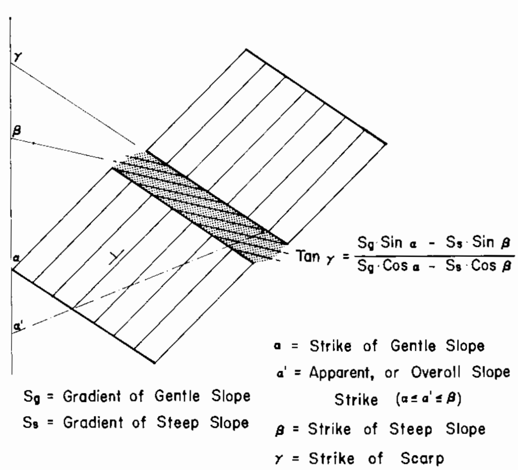


FIG. 8. Geometrical relationships for a scarp superimposed upon a gentler slope (plan view). Note that the strike of the scarp as a landform is not parallel to the strike of the contours on the scarp.

If radiationally controlled ablation does produce the southwestward scarp bias of the North Polar scarps, the same mechanism should produce a northwestward bias at the South Pole, leading to a clockwise-outward spiraling. The banding at the South Pole is less regular than the North Polar scarps, in part due to the offset of the cap from the pole. However, the steps farther equatorward than 87°S appear to show the required sense of spiraling (Fig. 1).

The scarps will have contradictory influences upon their orientation if the direction of maximum ablation and the dip of the flats are discordant. The relative influence of slope effects should increase with the flat gradients. As a possible example, along the steep margins of the Chasma Boreale the scarps follow the contours away from the general southwestward orientation. However, it is uncertain to what degree the regional slopes represent differences in flat gradients rather than differences in number, steepness, and width of scarps.

Scaling—slope gradients, scarp size, and process rates. Because of the limited correspondence between the numerical simulations and the natural polar processes, the models provide little insight into the process rates and the factors controlling the absolute size of the polar steps. However, the models *do* indicate the probable factors determining the gradients of the scarps and flats and their relative sizes. Of the several classes of models examined, two (the erosion of resistant layers and the simultaneous erosion and deposition model) appear most likely to correspond to processes at the Martian poles. These two are discussed separately.

If the flats are covered by resistant layers (Fig. 4c), then the gradient of the flats is close to the dip of the resistant icy cap, whereas the gradient of the scarps, and their width relative to the flats, is a function of (a) the dependence of erosion rates upon slope gradient, (b) the thickness and the relative difficulty of erosion of the resistant layer, and (c) the overall height of the scarp. If the icy flats are merely exhumed ice layers, then the absolute size of the scarps and flats is determined by the thickness and erosional resistance of the layers. However, if the resistant layers develop contemporaneously with scarp erosion (Fig. 4c), then the gradient of the flats will be close to the critical gradient above which net ice accumulation or cementation does not occur. In this case, the factors determining the absolute size of the steps are uncertain.

In the case of the model involving simultaneous ablation and deposition (Figs. 4d, 5f) the gradient of the flats is close to the critical gradient, S_{c1}, below which an ablating surface will revert to deposition (because of decreasing thermal loading), and the scarps have a gradient close to the transition from deposition to erosion (S_{c2}). If erosion and deposition are conservative of the total volatiles in the polar deposits, then the relative sizes of the scarps and flats at the steady state (Fig. 5f) depends upon the relative rates of ablation and deposition at the critical gradients, such that a slow rate of deposition on the flats coupled with a rapid rate of ablation on the scarps requires a large area of flat relative to scarp. However, the absolute size of the scarps and flats must be determined by processes other than those modeled here. One possibility is that there is no equilibrium size; the scarps may be gradually increasing in size. More likely, the size of the scarps is limited by the efficiency of lateral transport of atmospheric water vapor. For example, natural scales of atmospheric motion might rapidly decrease rates of backwasting for scarps wider than a certain size.

The models discussed here impose few limitations on the absolute rates of ablation, deposition, and associated scarp retreat, for they are framed in a relative time scale. The reported observations of near-equilibrium water vapor concentrations of about 100 precipitable microns over darker material in the polar regions (Farmer *et al.*, 1977) indicates what is probably an upper limit to scarp erosion rates, for if all of this water vapor has come from the dark scarps, if the layered scarps are dominantly water ice, and if all of this water is subsequently deposited on the flats, then the scarps are eroding vertically about 1 m in 10,000 yr or horizontally (for a 3° gradient) about 1 m in 500 yr. Since the scarps are spaced laterally at intervals of about 50 km, this implies a minimum time scale for reworking of the surface (scarp retreat through 50 km) of about 25 million yr.

CONCLUSIONS—SUMMARY, DIFFICULTIES, RESEARCH NEEDS

Several lines of circumstantial evidence point toward ablation and condensation of water vapor as dominant controls over the development of the stepped topography of the Martian polar caps. The scarps are frost-free during the summer, while the flats within the polar cap retain a remnant water ice covering. Summer temperatures on the dark scarps reaching at least 240°K should lead to rapid sublimation of ice incorporated in the laminated deposits (unless well insulated beneath a dust cover). Near-saturation water vapor pressures during the summer imply rapid exchange between the surface and atmosphere, but the degree of participation of the scarps is uncertain. The south-to-southwestward dip of the vast majority of the scarps in the North Polar region, and a less-regular northwesterly dip in the southern, that is, in the direction of the maximum solar heating, is consonant with rapid ablation of the scarps. Finally, the models presented in this paper indicate that ablational and condensational processes can lead to the dichotomous landscape of dark scarps and ice-capped flats.

The simplest model of the step-forming process assumes that the dark scarps are ablating as the flats accrete simultaneously by ice condensation. The albedo difference between the icy flats and the risers mantled with accumulated dust from ablation of the layered deposits provides the metastable process necessary to initiate and dynamically maintain a stepped topography. This model assumes that the layered deposits are the accretionary deposits laid down under the flats. If this model is accurate, the layered deposits are probably water ice with a small percentage of included dust, which accumulates on the scarp faces during ablation to produce the dark albedo. The laminated deposits could also be largely silicious dust and volcanic ash, but more complicated processes involving intrasoil ice migration or episodic ablation of the ice caps would be required to accumulate the dust. Since the layers are being deposited as the risers erode, a complex series of polarwide erosion and depositional events is not required to explain the angular unconformities in the layered deposits observed by Cutts *et al.* (1976), for they would result under continuous erosion and deposition, if scarp heights and the flat gradients are variable.

An alternate origin of the stepped topography as a result of the development or exhumation of resistant layers beneath the flats is also possible, with either the high albedo of the ice or cementation of the upper-layered deposits accounting for the resistance to ablation of the flats.

The primary difficulty with the models as so far presented is that both volatile transfer and wind erosion and transport must act in concert; neither could have sculpted the stepped terrain by their solitary action. The need for wind erosion lies in the accumulation of dust that would accompany ablation. A thin cover of dust enhances ablation because of its effect upon albedo, but a fine dust cover more than a few millimeters to a few centimeters thick would act as an insulating blanket because of its low thermal interia, reducing the penetration of daily and seasonal temperature variation and inhibiting outward vapor flow (Sharp, 1949; Hattersly-Smith, 1961; Bloch, 1964; McKenzie, 1969). Such a protecting mantle is a common feature at the terminus of ablating glaciers. Thus the accumulating dust must be eroded, presumably by the wind.

The weathering (ablation) rate on the scarps appears to be small enough that the wind strips the loosened debris soon after it is released from its ice cement, since the slopes are largely weathering limited. Thus only small concentrations of detritus are in transport at a given time, and most locations receive an occasional wind sufficient to strip-weathered detritus. Surface form is controlled largely by the ablational processes, although wind erosion locally modifies the stepped topography and dunes have accumulated near the edge of the North Polar cap, presumably consisting of dust released from the layered terrain (Cutts *et al.*, 1976).

The polar features may result from a more intimate interaction of wind with volatile and particulate transfer than is envisioned here, for as discussed by Cutts (1973b) and Cutts *et al.* (1976) the wind probably plays a dominant role in the creation of the polar chasma, the elongated channels of the South Polar region, the locally dissected margins of the polar caps, the "searchlite" patterns on the polar ice deposits, the locally wavy pattern of the scarps, and the dunal deposits. In addition to scour and deposition, local winds produced by albedo differences and slope gradients may affect ablation and condensation rates and rates of vapor transfer between the scarps and flats.

Although the polar topography is dominated by scarps and flats, some of the dark bands are broad, shallow, generally asymmetrical valleys. Although such valleys are not produced by the simple models reported here, the depressions are not necessarily incompatible with albedo-controlled ice ablation and deposition. Because of the thresholds and metastable states of erosion and deposition, a dark scarp might continue to ablate beyond a level surface, creating a slight depression before net yearly accumulation of ice triggers an accumulational regime. Other deeper valleys, or canyons, as discussed by Cutts and Michalsky (1974) require a localized erosional process, perhaps eolian.

Some polar areas may be sufficiently protected from wind action that dust accumulates, drastically reducing ablation rates and encouraging mass-wasting processes or the eolian redistribution of the dust into drifts and dunes, obscuring the layers or covering the flats. The area described by Cutts and Michalsky (1974) may be an example.

The model of simultaneous ice ablation and deposition presents consequences for landform evolution that may be testable with Mariner and Viking imagery of polar regions. Areas with thick residual dust cover due to inefficient wind erosion may develop the rolling topography characterized by episodic temporal inversion of relief and mass-wasting found on stagnant glaciers (Sharp, 1949; McKenzie, 1969; Clayton, 1964).

The circumpolar areas of layered deposits lacking perennial ice caps, prominant in the South Polar regions, do not have the summer albedo contrast necessary to maintain a stepped topography. The stepped topography presumably formerly present during the accumulation of the layers would become muted into more rounded forms during continued ablation. On the other hand, if the stepped topography is due to exhumation of cemented or volatile-rich layers, a stepped topography could be maintained without the albedo contrast.

The layered deposits should also afford evidence as to whether they form simultaneously with ablation of the scarps. If the topography has formed entirely by erosion of preexisting layered deposits, the terrace sequences on each scarp will be unique. However, if each sequence was individually formed beneath the flat forming the crest of the scarp, then each scarp will show a similar sequence of depositional events, and locations where scarps merge laterally should exhibit a pinching-out of duplicate beds.

If ice forms the bulk of the layered deposits, it constitutes a large reservoir that could be released to the atmosphere during global climatic changes or as a result of polar precession, polar wandering, or change of obliquity (Ward *et al.*, 1974; Hartman, 1977; Cutts *et al.*, 1976). Depending upon the configuration of the base of the layered deposits, the contained water could be of sufficient volume to cover the planetary surface with from 3 to 30 m of water, a volume which, together with presumed permafrost, could account for the apparent fluvial features of the Martian surface. However, because of the insulating effects of residual dust accumulation, the water would be released only if the mean annual polar temperatures exceed the freezing point (or at least are high enough so that the water vapor pressure is greater than the atmospheric pressure), or if the wind continuously strips the accumulated dust. However, the winds might be severely reduced by the lack of albedo contrast on an ablating pole.

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