ICARUS 27, 215–228 (1976)

Martian Glaciation and the Flow of Solid CO_2

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Received April 10, 1975

The flow law determined experimentally for solid CO_2 establishes that a hypothesis of glacial flow of CO_2 at the Martian poles is not physically unrealistic. Compression experiments carried out under 1 atm pressure and constant strain rate demonstrate that the strength of CO_2 near its sublimation point is considerably less than the strength of water ice near its melting point. The data fit a power law "creep" equation of the form

$$\dot{\epsilon} = (4 \times 10^6)\sigma^{3.9} \exp(-12\,200/RT),$$

where $\dot{\epsilon}$ is compressive strain rate (sec^{-1}), σ is compressive stress (bars), R is the gas constant in calories per mole, and T is absolute temperature. The exponent of σ of 3.9 contrasts with a value near 3.1 for water ice, and indicates that the strain rate is somewhat more sensitive to stress for CO_2 than for water. Likewise, the low activation energy for creep, 12 200 cal $mole^{-1}$, illustrates that CO_2 is not highly sensitive to temperature and is thus likely to flow over a broad range of temperatures below its melting point. Strength values for CO_2 are of the order of one-tenth to one-third the strength of ice under equivalent conditions.

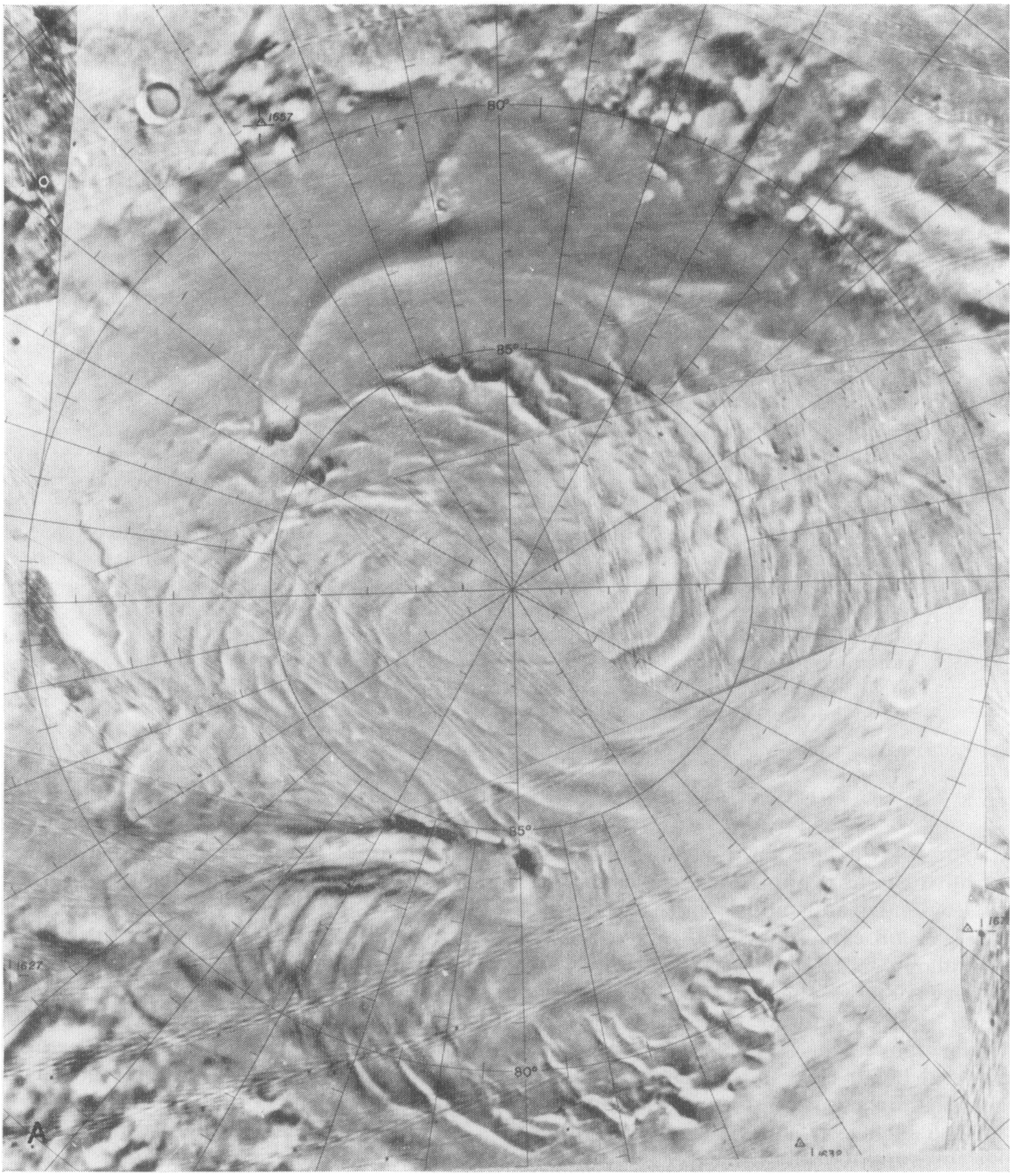
A plausible glacial model for the Martian polar caps can be constructed and is helpful in explaining the unique character of the polar regions. CO_2-rich layers deposited near the pole would have flowed outward laterally to relieve high internal shear stresses. The topography of the polar caps, the uniform layering of the layered deposits, and the general extent of the polar "sediments" could all be explained using this model. Flow of CO_2 rather than water ice greatly reduces the problems with Martian glaciation. Nevertheless, problems do remain, in particular the large amounts of CO_2 necessary, the need to increase vapor pressure and temperature with depth in the polar deposits, and the lack of good observational evidence of flow features. Within the limits of the present knowledge of surface conditions on Mars, CO_2 glaciation appears to be a realistic alternate working hypothesis for the origin of the polar features.

INTRODUCTION

Our knowledge of the surficial features at both the north and south poles of Mars has expanded enormously since the Mariner 9 television cameras were directed toward the planet in 1971. Descriptive reviews of observations at the south pole by Murray *et al.* (1972) and at the north pole by Soderblom *et al.* (1973b) have led to a general belief that both polar regions are mantled by a unique group of "sediments." At the surface is a thin cap of permanent ice, presumably mostly water ice, which is underlain by a deposit a few kilometers thick of sharply banded material of much greater areal extent than the permanent ice cap, and which in turn is underlain by a series of more nondescript deposits of even greater areal extent. In addition, the Mariner 9 cameras showed a variety of topographic features in the polar regions, including a lobate pattern of dark markings on the permanent ice cap, and terraced cliffs, channels, and pits on the other mantling deposits.

Two general hypotheses have been suggested for the origin of the polar features

(Murray and Malin, 1973a; Cutts, 1973a, 1973b). Murray and Malin interpreted the dark markings as cliffs that are roughly concentric about the center or thickest part of the permanent ice cap and become consistently lower in elevation toward the equator. They envisioned the deposits as a series of plates (or dishes) of decreasing radius stacked one on top of another. They also suggested that the plates are offset due to polar wandering. The plates themselves would be composed of the thin laminae of the underlying layered deposits. In Cutts' (1973a) view, the layered materials were deposited subaerially, under very stable atmospheric conditions, as flat sheets extending over the entire polar regions, then incised by winds blowing off the poles in a spiral pattern leaving channels in the permanent ice. Thus he interpreted the



dark markings as erosional valleys rather than cliffs. The distinction between cliffs and channels is not obvious in the Mariner 9 pictures.

Both hypotheses have their drawbacks. Although Murray and Malin (1973a) attribute the markings to offsets in the location of sediment deposition due to polar wandering, the markings in the permanent ice cap at the two poles are not symmetrical (Cutts, 1973b). In fact the cap is a few degrees away from the rotation axis at the

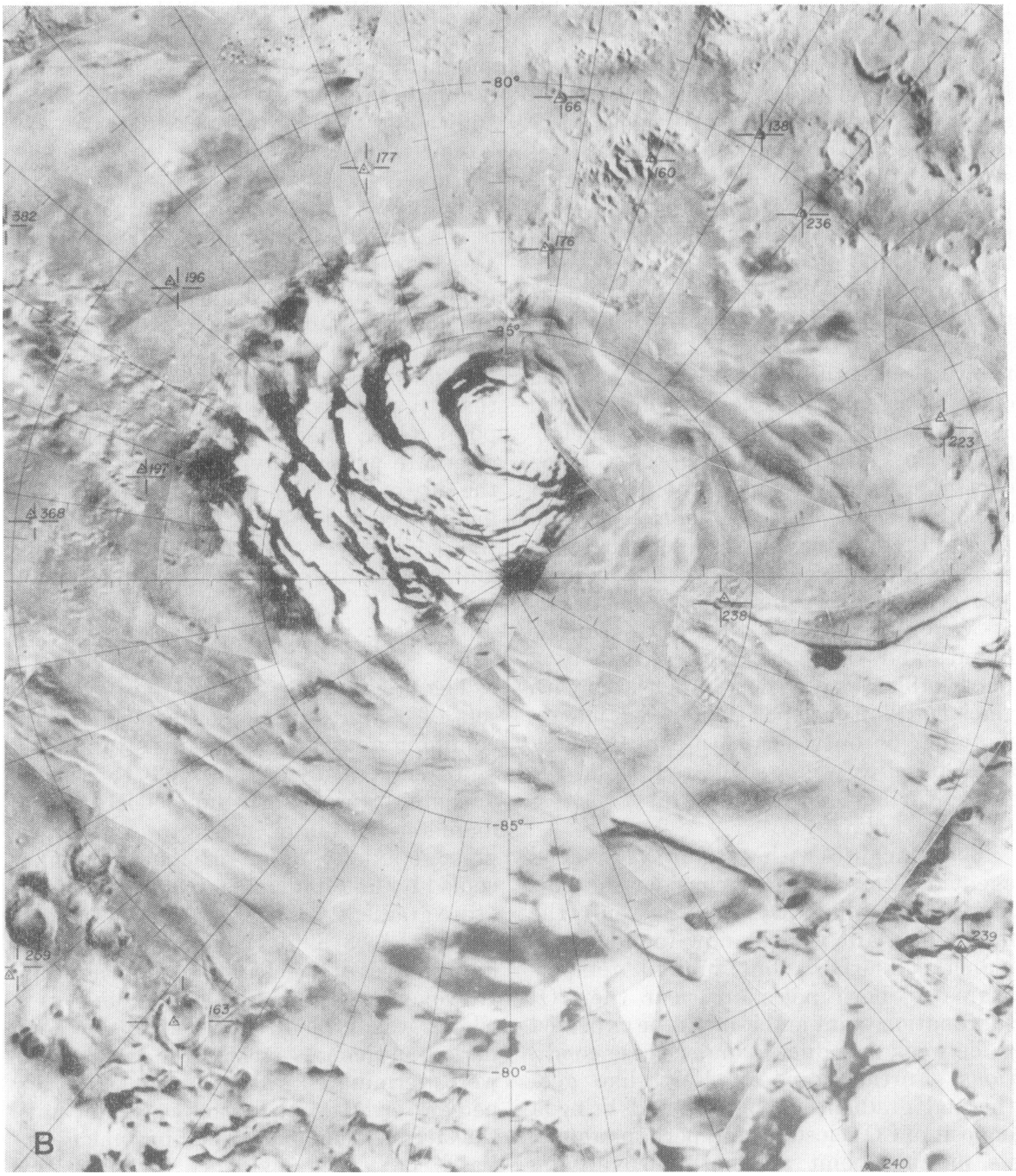


FIG. 1. Segments of the U.S. Geological Survey semi-controlled photomosaic of the north and south polar regions of Mars. (A) North polar region; high albedo of permanent cap has been reduced in preparation of photomosaic but permanent cap includes most of lobate pattern north of 80° latitude. (B) South polar region; showing offset of permanent cap from the pole of rotation.

south pole. Furthermore, Nash (1974) has shown that the planimetric regularity of the "cliff" edges (dark markings) is unrelated to their relative ages, suggesting that the edges are an erosional rather than a constructional feature. At the same time, Cutts' (1973a) interpretation of the markings as spiral features is at least disputable (for example, Dzurisin and Blasius, 1975). The markings clearly can be viewed as lobate and generally concentric about apparent centers of thick portions of the caps (Fig. 1). Although Cutts (1973a) cites strong evidence of erosion at work in the polar regions, the pattern of erosion need not be imprinted on the surface by a hypothetical wind pattern.

Observational features such as the dark markings and the generally concentric distribution of "sediments" at the poles, together with the unusually flat banding of the layered deposits, could be interpreted as evidence of lateral flow or "glacial" movements in the polar deposits. However, glaciers of water ice now or in the past on Mars seem unlikely indeed (Sharp, 1974). Present surface temperatures are far too low for ice to flow; the reduced Martian gravity requires great thicknesses of ice but almost no free water can be found; and the polar regions display a remarkable lack of features associated with glacial erosion or deposition on Earth (e.g., moraines or outwash features), although such features were suggested from the poorer-quality Mariners 6 and 7 photos (Belcher *et al.*, 1971).

The difficulties with water ice as a glacial agent on Mars led us to consider the flow behavior of solid CO_2. It is not only the most abundant volatile now found at the planetary surface, but present temperatures at both poles are near the CO_2 sublimation point and it might be expected to be weak and ductile under these conditions. Furthermore, an Earth-like geothermal gradient on Mars could bring a deposit of CO_2 close to, and perhaps above, its melting point at depth if overlying sediments raised the vapor pressure of buried CO_2 (Sagan, 1973).

Because flow properties of CO_2 had not previously been established, there was no physical basis for considering the possibility of CO_2 glaciation or the types of features which might be produced by movement of CO_2-rich materials. Sharp (1974) assumed that CO_2 could not flow appreciably under Martian polar conditions. Murray *et al.* (1972) assumed that features such as craters which were partly buried by the blanket of laminated terrain should appear eroded by movements in the laminated terrain. Might CO_2 behavior be sufficiently different from water ice behavior to produce different types of flow features?

To investigate these assumptions we have derived a flow law for solid CO_2 from a series of laboratory deformation experiments. The flow law can be used to predict its behavior under conditions thought reasonable for the Martian polar regions. The flow strength of CO_2 is so much less than that of water ice near its melting point (Glen, 1955), that we propose as an alternate working hypothesis a model for the history of the polar deposits which includes lateral flow of CO_2-rich layers near the poles. Finally, we discuss assumptions and constraints required by such a model.

EXPERIMENTAL PROCEDURE

The flow law for CO_2 was derived from sets of compression experiments at 1 atm confining pressure, constant strain rate, and temperatures from 163 to 193°K. Jacketed samples of solid CO_2, 19mm in diameter by 48mm in length, were compressed axially in an insulated chamber cooled by liquid nitrogen (Fig. 2). Temperature gradients along the sample were kept to less than 3°K by cooling the upper and lower halves of the chamber independently. However, thermal drift of the unit as a whole was difficult to control for long periods of time. As a result, the experiments were terminated after strain of a few percent or less, but in each case, not until the stress–strain curves had become essentially flat. The evidence from a few extended tests indicated that strain hardening did not affect the strength values greatly, within the temperature and strain rate ranges used here.

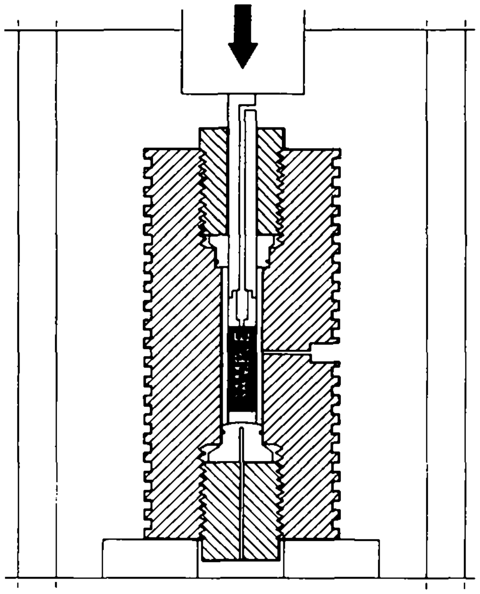


FIG. 2. Schematic drawing of sample chamber within hydraulic press. Although chamber is designed to test samples under high confining pressures, difficulties with sealing at very low temperatures have postponed those tests. Grooves on outside of chamber are pathways for liquid nitrogen coolant.

The CO_2 samples were cored from large blocks of commercially prepared solid CO_2. The blocks are formed by converting liquid CO_2 to snow at low temperature, then compacting the snow under pressures as high as 150bars. Minute amounts of propylene glycol (0.02%) and oil (0.001%) are added to the CO_2 snow to increase the adhesion between grains, but the only other measurable impurity is a trace of water. The starting material has a texture of interlocked equidimensional grains of very uniform grain size, approximately 0.3mm in diameter. Grain boundaries are smooth and simple. No pore spaces are visible even at magnifications of 40×.

The authors did not attempt to investigate any of the CO_2 clathrate compound suggested by Miller and Smythe (1970) as present in the Martian polar caps. Sharp (1974) assumes that only minor amounts of clathrate would be present, limited by an apparently severe shortage of available H_2O. The composition of volatile layers beneath the surface of the polar cap remains open for speculation.

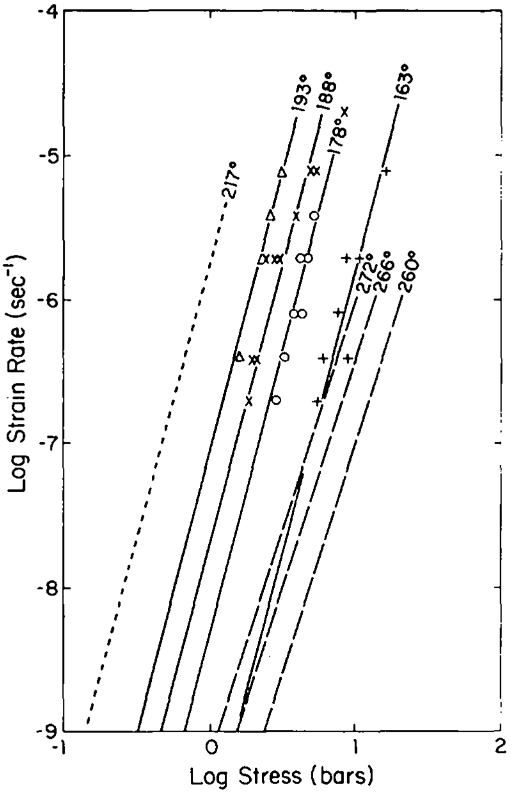


FIG. 3. Graph of CO_2 compressive strength vs strain rate. Solid lines are straight lines fitted to data for N = 3.9. Dotted line at left is extrapolated to melting point of CO_2. Dashed lines at right are data for water ice at temperatures given (from Glen, 1955).

The results of the deformation experiments are plotted in Fig. 3 as a graph of the log of strength σ vs the log of the strain rate $\dot{\epsilon}$ for a series of different temperatures. When plotted using these coordinates, the data for a single temperature appear to lie approximately along a straight line, although the range and accuracy of the points are not great enough to establish such a power-law relationship as the best-fitting law possible (see also Sherby and Burke, 1967). There is some suggestion from the 188° data that the straight-line relationship does not hold. However, at other temperatures the fit is quite good, and the assumption of a power-law fit seems justified for extrapolation over only two orders of magnitude to hypothetical glacial strain rates (10^{-9}sec^{-1}).

The fit of straight lines by least squares to all points for each temperature gives a relationship

$$\log \dot{\epsilon} \propto N \log \sigma,$$

where N varies between 3.0 and 4.9 with a mean value of 3.9. The scatter of N is not temperature dependent and should be reduced if an expanded range of strain rates were tested. This value contrasts with values of N for water ice found from creep tests (Glen, 1955) and from tunnel closure measurements (Nye, 1953) of 3.17 and 3.07, respectively. Thus the strength of CO_2 is somewhat less sensitive to strain rate than the strength of water ice.

The effect of temperature on CO_2 strength is assumed to be of the commonly used form (Sherby and Burke, 1967)

$$\dot{\epsilon} \propto \exp\,(-Qc/RT),$$

where Qc is the activation energy for creep. A plot of $\log \dot{\epsilon}$ vs $1000/T$ is shown in Fig. 4, in which the slope of the line has the value $Qc/(2.3 \times 10^3)R$. The value of Qc is found to be 12200 cal mole^{-1} from the experimental results. The activation energy for creep commonly can be correlated with activation energies for self-diffusion of atomic or molecular species, but to our knowledge no appropriate diffusion measurements have been made on solid CO_2. The creep activation energy for CO_2 is considerably smaller than that for water ice, given by Glen (1955) as 31 800 cal mole^{-1}. Therefore the strength of CO_2 is less affected by differences in temperature than the strength of water ice.

The flow law for solid CO_2 is thus found experimentally to be

$$\dot{\epsilon} = A\sigma^{3.9} \exp\,|12\,000/RT|,$$

from which strength at an appropriate strain rate and temperature can be predicted, and general comparisons with the behavior of water ice can be made (Fig. 3). An examination of the data in Fig. 3 shows that at temperatures within a few degrees of the respective melting/sublimation points, water ice is considerably stronger that solid CO_2. At a strain rate of 10^{-7} sec^{-1}, CO_2 is one-fifth as strong, and even with the steeper slopes of the CO_2 lines it would still be less than one-third as strong at a strain rate of 10^{-9}sec^{-1}.

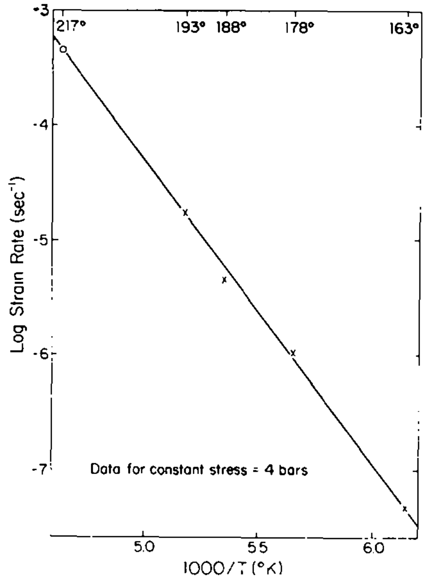


FIG. 4. Graph of strain rate vs $1000/T$ for a constant stress of 4 bars. Points marked with X are values determined from straight lines in Fig. 3. Point marked with o was used to extrapolate dotted line in Fig. 3.

If the pressure on buried CO_2 rises to 5.1 bars (depth of burial of < 100m), then the temperature is free to rise to 217°K before the solid becomes unstable (melts). Under those conditions the flow law would predict CO_2 strengths lying along the dotted line to the left of the solid lines in Fig. 3, giving a strength approximately one-tenth that of water ice near its melting point. As discussed below, such a situation can easily arise at depth at the Martian poles if pressures can rise above 5 bars, and temperatures follow a positive thermal gradient with depth.

Extrapolation of the flow law to buried conditions assumes that the flow law is independent of confining pressure. Rigsby (1958) showed that this was the case for water ice, and the flow laws for most other crystalline materials are also independent of confining pressures if brittle mechanisms are not active. No evidence of brittle mechanisms was observed in these experiments, either as drops in the stress values on the bulk stress–strain curves, or in the form of microfractures which could be observed in the binocular microscope. The latter might be expected to appear as either discrete breaks between or across grains or as a clouding of individual grains if fracturing were submicroscopic; however, at 40× magnification the grains appeared clear and unbroken. Nor was there any evidence, such as formation of visible porosity or opening of grain boundaries, that would indicate sliding had occurred along grain boundaries. Attempts to actually determine strengths under high confining pressures were postponed by difficulties with sealing the chamber at such low temperatures.

A second important assumption is that the proximity of the sublimation point to the experimental temperatures had no significant effect on the flow law. In other words, we presume that if we could raise the experimental temperature to the melting point (~ 217°K) without sublimation taking place, the flow law would still remain valid. Good evidence to support this assumption is found in the excellent fit of the points to the constant Qc line in Fig. 4. Even within 2°K of the sublimation point, there is no suggestion that the activation energy is changed. Thus the flow law is assumed to be valid up to the melting point if sublimation could be eliminated, as it would be at higher pressures.

One difficulty in evaluating these assumptions is our present lack of knowledge of deformation mechanisms in CO_2. The evidence that the material is deforming by intracrystalline mechanisms, probably translation gliding, is primarily the lack of features that appear to be due to cataclasis or brittle fracturing. Because of the face-centered cubic structure of CO_2, the logical glide planes would be $\{111\}$, the closest-packed planes, and the glide direction $\langle 1\bar{1}0 \rangle$, which gives the shortest displacements. However, the arrangement of the elongate CO_2 molecules in the structure results in complex interference between oxygen atoms during slip on these planes. This produces unknown effects on the Peierls energy, and we have as yet no optical evidence of that glide law.

DISCUSSION

The low resistance of solid CO_2 to shear stresses, as described by the laboratory flow law, adds an important constraint to speculation about the character and origin of the deposits of the Martian polar regions. If a convincing case can be made that the polar deposits have not flowed, then one of the following conclusions seems likely. (a) There has never been a large volume of solid CO_2 deposited at the poles; (b) a large volume of solid CO_2 may be present at the poles, but was deposited in the form of broad flat layers; (c) thick deposits of CO_2 may have been present but were laterally confined and thus unable to flow; or (d) thick deposits have been present in the past only when the mean annual temperature was so low (~ 160°K) that flow was prohibited. The present hypotheses generally conform to (a) or (b) above and we emphasize that the flow law does not seriously jeopardize those views. In fact, the CO_2 reservoir suggested by Murray and Malin (1973b) is restricted in shape to a broad thin sheet more effectively by the flow law than by atmospheric equilibrium considerations (which do not limit its downward extent).

If, on the other hand, the case against glaciation is not conclusive, then some type of glacial model might well account for the observations at the poles. Such an alternate working hypothesis should not be discounted until disproved. On the basis of the observations from Mariner 9 experiments, we contend that a glacial model, in which solid CO_2 is the glacial agent, is plausible. In the following discussion we present one model which seems to fit the present observations. We emphasize that there is no compelling evidence that this (or some other) CO_2 glacial hypothesis is correct. But strong arguments against water ice glaciers are not particularly valid for solid CO_2, and thus the model remains a tenable one.

Stratigraphy of the Polar Region

Detailed descriptions of observations from Mariner 9 photographs have been presented by Murray *et al.* (1972) for the south polar region and by Soderblom *et al.* (1973b) for the north polar region. The generally accepted view is that away from the equatorial region, especially at latitudes greater than 70°, the cratered terrain covering most of the planet is overlain by a mantle of sedimentary deposits whose surfaces are pitted, etched, rippled, or smooth (Soderblom *et al.*, 1973a). This mantle is in turn overlain by the layered deposits, which at the north pole cover most of the surface north of 80° latitude, and at the south pole are distributed somewhat more irregularly from −70° to the south pole. Overlying the layered deposits are regions of permanent ice, mostly north of 80° at the north pole, and offset somewhat from the pole but mostly south of −85° at the south pole (Fig. 1). The permanent ice cap is cut by dark markings in which ice is absent and underlying layered deposits are exposed. The markings are either outward-facing slopes, or actual channels (Dzurisin and Blasius, 1975), interpreted by Blasius (1973) to be on the order of 200m deep. Annual frost deposits a few meters thick or less cover most of the layered deposits and permanent ice during the winter at each pole, respectively.

This stratigraphy is compiled into a highly schematic cross section in Fig. 5A. The units of most interest in this paper, the permanent ice and layered deposits, are shown in the enlarged schematic cross section, Fig. 5B. The vertical scale has been greatly expanded to show more detail.

The permanent ice appears to form a thin deposit overlying the layered terrain at each pole. If Blasius' (1973) estimate of relief on the caps is correct, the permanent ice must be less than 200m thick, since in the topographic low regions the underlying layered deposits are exposed. Murray *et al.* (1972) and Soderblom *et al.* (1973b) interpret this deposit to be primarily water ice. If the winter frost is CO_2, then disappearance of the frost during the Martian spring requires that solar insolation be great enough for sublimation of CO_2. Yet during the summer months the shape of the permanent ice remains remarkably stable.

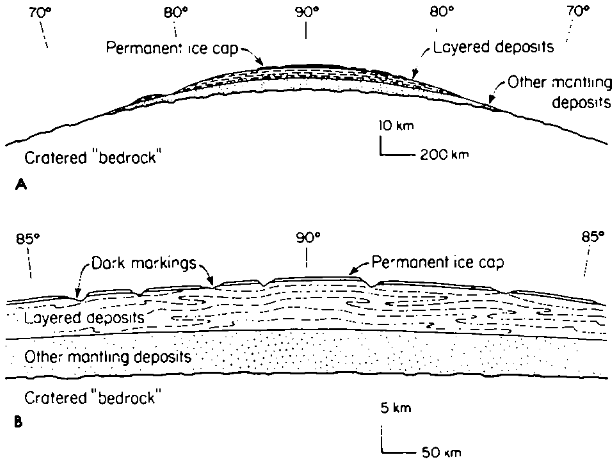


FIG. 5. Schematic cross sections depicting proposed stratigraphy and structure of Martian polar deposits. (A) General sequence of permanent ice, layered deposits, and other mantling deposits overlying highly cratered terrain. (B) Enlarged view of polar deposits showing a plausible flow pattern in the layered deposits, which could be responsible for breaks in the permanent ice cap, but would not be visible in Mariner 9 television pictures.

The permanent ice must then be a residual deposit, containing water deposited at various times at the poles, then left behind as the more volatile CO_2 sublimates.

The layered deposits were also observed in both south and north polar regions (Murray *et al.*, 1972; Soderblom *et al.*, 1973b). In both regions they are characterized by thin uniform layers that extend for hundreds of kilometers without disruption. The layers must be nearly horizontal and of the order of tens of meters thick. Good evidence is found in the Mariner 9 pictures that this deposit overlies the chaotic, pitted, or smooth plains of sediments that cover nearly all of the higher latitudes. Large outliers of the layered deposits in the form of buttes or tablelands are found at the edges of the deposits. It is difficult to imagine any history for these materials that does not end with an erosional stage to produce the present topographic relief. Cutts (1973a) makes a strong case for the importance of wind erosion in the polar region and this surely seems the most likely explanation for the present topography. But what of the origin of the deposits? A sequence a few kilometers thick and a thousand kilometers in diameter made up of a hundred regular layers each 20–30m thick is a monumental task for any subaerial depositional agent. Cutts (1973b) speculates that a period of 10^8yr of deposition of sediments from the atmosphere might be required to account for the layered deposits. Yet this requires a nearly complete absence of the wind conditions that lead to channeling and erosion at the poles today. In other words, dust storms such as the planet experienced in 1971 could not be responsible, since presumably the present atmosphere is far more effective at eroding the polar regions than building them up. In fact, it is difficult to conceive of such flat continuous layering in sediments that were not deposited under water. We suggest that it might be possible for much more irregular deposits to develop such flat regular banding during outward flow from the central polar regions before the present erosional stage. In this process the total thickness of deposits would decrease, the lateral extent would increase, and irregularities and discontinuities would be flattened until unrecognizable on the scale of the Mariner 9 pictures. The composition of the layered deposits is not known, but surface topographic features reported by Cutts (1974), as well as etch pit features described by Sharp (1973) from the other mantling deposits, indicate that volatiles may have been buried and then recently evaporated, leaving behind the strangely "eroded" topography.

Topographic features such as moraines and outwash plains are commonly associated with glaciers on Earth, but they appear to be virtually absent on Mars. The lack of outwash deposits might be expected from the high volatility of CO_2 under low atmospheric pressures; free-running liquid CO_2 on the Martian surface would require atmospheric pressures higher than 5 bars, a condition that would seem extremely unlikely. Consequently, little or no material could be moved by liquid CO_2 "stream action," even at the edges of the flowing deposits. Likewise, although moraines might be expected to build up locally at the edges of the flowing deposits, two factors can account for their lack of development. First, because the basal sliding mechanism, so important in water ice glacier flow, does not operate in CO_2 glaciers, there is little supply of excess material due to the gouging out of underlying material. Second, when small deposits of excess dust do form at the margins of the flowing material, wind action may be highly effective in removing the developing "moraine."

If CO_2 is able to flow under Martian polar conditions, then we should investigate the possibility that outward flow of CO_2-rich "ice sheets" from the poles may be responsible for (a) the dark markings in the permanent ice cap, (b) the very flat regular banding of the layered deposits, (c) the apparent ridge and channel topography on the layered deposits themselves away from the cap, (d) the general shape and location of the layered deposits, and (e) the lack of visible impact craters in the polar regions. In the following section we speculate on one type of CO_2 model which seems plausible and can account for these features.

Plausible CO_2 "Glacial" Model

A "glacial" model for the origin of Martian polar features is based on the hypothesis that a much thicker sequence of "sediments" than is now present, including both dust and substantial quantities of CO_2, was deposited at the very high latitudes at both poles. This weak pile of material began to settle under its own weight and flow laterally away from the poles until the internal shear stresses due to the great thickness of the deposit were reduced to a level that could be supported by the strength of the material. The thickness of the original pile might have been as much as 10–15km but has been reduced by lateral flow to a maximum thickness of 5km or less, with perhaps an average thickness of 2km, as estimated by Cutts (1973b). That CO_2 could remain stable throughout such a thick sequence requires the assumptions (see next section) that the vapor pressure increases with burial, allowing solid CO_2 to be stable to 217°K (triple point temperature); and that accumulation of the thick deposit would take place rapidly enough that the temperature would remain below 217°K even at depths of 10–15km on a planet where the thermal gradient was probably positive with depth.

The present extent and thickness of the layered deposits are in good agreement with a roughly "equilibrium shape" for CO_2-rich materials on Mars. The concept of an equilibrium shape is borrowed from the physics of water-ice glaciers and was derived in simplified form by Orowan (1949):

$$H = (2\tau L/\rho g)^{\frac{1}{2}},$$

where H is the thickness of the sheet at its center, τ is the shear strength, L is the half-width (nearly equivalent to the radius of a circular sheet), ρ is the density, and g the gravitational attraction. We can choose a conservatively large value of $\tau = 0.3$bars at a strain rate of $10^{-9}\mathrm{sec}^{-1}$ from the flow law, recognizing that

$$\tau = \sigma/\sqrt{3},$$

where σ is the compressive stress (Nye, 1953). For a sheet of 1000km radius on a flat base, the "equilibrium" thickness at the center would be 3.1km, in good agreement with estimates of present thicknesses. The sheet is not in true equilibrium of course, unless it could be shown that there is some fundamental strength to CO_2, below which no flow at all would occur. However, as the stresses decrease internally, the flow rate decreases to the level where the amount of flow becomes negligible.

A lateral flow mechanism thus explains the present thickness and areal extent of the layered deposits effectively. However, it could be argued that deposition could fortuitously produce the overall shape of the layered deposits, and this shape evidence is hardly diagnostic of a flow origin.

The dark markings of the present surface also might be a reflection of lateral flow. Irregularities of surface topography are a logical corollary of such flow, and the patterns we see are the predicted ones: lobate in planimetric form, and generally concentric about the center or thickest parts of the deposits (Fig. 1). The markings themselves might have arisen in the following way. As wavelike flow at depth produced the irregular topography at the surface, the slopes facing toward the equator received a greater solar flux than the pole-facing slopes and became areas of sublimation or nondeposition of the water or solid CO_2 that constitutes the permanent ice cap. As frost accumulated on other parts of the cap, the difference in temperature between frosted and frost-free areas was sufficient to control wind patterns over the polar cap, and selectively erode the frost-free areas. Erosion would be aided by local sublimation of volatiles in the dark regions heated by the higher solar flux. Thus the present topographic relief is an erosional feature as advocated by Cutts (1973b), but the planimetric pattern would be caused by the irregular topography left behind by flow within the underlying layered deposits. If the present erosional climate were to change, then the steep slopes and deep channels would close, assuming CO_2 is still present in the layered deposits. However, erosion appears to be rapid enough to more than offset any slow CO_2 flow.

There is also the possibility that the present dark markings are at least in part due to very recent movement of the deposits beneath the permanent ice cap, and that at least some of the dark markings are openings produced by pulling the superficial cap layer apart. This seems especially likely at the south pole where crevasse-like features appear toward the outer edges of the cap. Such an interpretation implies that the layered deposits still contain significant amounts of CO_2.

As Cutts (1973a) argued, some small surface features visible on the layered deposits beyond the permanent ice are likely to be due to wind action. He cited examples of apparent dunes, fine grooving and fluting, and evidence for local redistribution of surface materials. However, much larger markings that appear to be escarpments are so similar to the pattern of dark markings on the permanent cap, especially at the south pole, that we interpret this pattern to be a continuation of the dark markings and also due to flow.

Finally, we consider the possibility that the strong banding of the layered deposits is a type of flow banding which originated during lateral flow of the deposits and greatly modified the original bedding. In view of the difficulties associated with producing such perfect layering by subaerial deposition, it seems reasonable to consider the possibility that the present banding was produced by a flow-related mechanism. Here we suggest that during flattening of the polar deposits, the lateral flow was mostly laminar, and perhaps confined to layers of nearly pure CO_2. Alternate layers of dust were carried essentially passively with the CO_2. Where flow was not exactly parallel with initial layering, isoclinal folds and transposition structures might have resulted, although none has yet been observed at a scale visible in the Mariner 9 pictures. Irregularities in the original sediments, such as channel fillings or impact craters, would be greatly reduced in the process of spreading and thinning the deposit as a whole. In fact the present material may be capable of "healing" itself by flow after meteorites strike the surface.

A flow-banded deposit might differ from a sedimentary deposit either by containing progressively thinner layers toward its base, due to greater amounts of flattening in the deeper parts, or by becoming reasonably complex and distorted at the edges, while sediments might merely become thinner until they disappear. The photographic evidence is not diagnostic; the true outer limits of the layered deposits have apparently been removed by erosion (Cutts, 1973b), and the critical features may no longer be available for observation.

In summary, we maintain that a plausible model involving "glacial" flow of CO_2-rich layers in the Martian polar regions can be constructed and can provide an explanation of the overall shape, thickness, and extent of the layered deposits, of the presence of dark markings within the permanent ice caps and undulating topography beyond the edges of the ice caps, and of the persistent nearly horizontal uniform layering seen especially well in the layered deposits at the south pole. The observational evidence favoring such an interpretation is not strong from the Mariner 9 television pictures, but neither is the evidence against it. Perhaps the most effective arguments against CO_2 flow could be made about the physical assumptions of the model rather than our present level of observation.

Assumptions of a "Glacial" Model

A "glacial" interpretation of Martian polar features does require some critical assumptions with far-reaching consequences. Previously, the most important assumption has been that the flow strength of CO_2 is sufficiently high that it was unlikely to be a "glacial" agent. This has been shown to be incorrect. In this section we examine other important requirements the "glacial" model must satisfy.

First, it is necessary to postulate a sufficient amount of CO_2 present in the layered deposits to allow them to move. We assume that the deposit could move easily if composed of approximately 50%

CO_2. Most of the volatiles would be located in fairly pure layers alternating with layers of nearly pure dust or fine sediment. Following the experiments on water ice–sand mixtures of Hooke *et al.* (1972), we expect the effects on strength of mixing dust with the solid CO_2 to be minimal unless the dust makes up 20% or more of the layer. Using a bulk value of 50% CO_2 for the layered deposits as a whole, we estimate the CO_2 required as $2.5 \times 10^6 km^3$ or $2.5 \times 10^{21} cm^3$ (from rough calculations of layered deposit volume by Cutts, 1973b). The present atmosphere of Mars contains about $2 \times 10^{19} cm^3$ (Murray and Malin, 1973b), so approximately 100 times as as much solid CO_2 must be, or must have been, stored in the layered deposits. Leighton and Murray (1966) and Murray and Malin (1973b) make a strong argument that a solid phase is acting as a reservoir of CO_2 beneath the north polar cap, although this view has been challenged by Ingersoll (1974). They postulate a reservoir of $10^{20} cm^3$, indicating a total outgassing of CO_2 of $60 g cm^{-2}$ of the planet's surface area. Our estimate requires a CO_2 outgassing of approximately $1.5 kg cm^{-2}$, and for comparison the figure for the Earth is about $70 kg cm^{-2}$. While we see no violation of factual observations by this amount of outgassing, it clearly implies a different history of differentiation and devolatilization than the Murray and Malin model. It also suggests that the ratio of $H_2O:CO_2$ outgassed is lower on Mars than on Earth.

The second important assumption is that buried CO_2 deposits will be under vapor pressures far above 6mbars, and therefore much more stable than recent authors have accepted (Murray and Malin, 1973b; Ingersoll, 1974). Ingersoll argued that a buried CO_2 deposit is unstable because the average annual temperature at the surface above the deposit is higher than the CO_2 saturation temperature. This is true because the winter temperature, during which frost is deposited at the poles, is apparently the temperature corresponding to the 6mbar atmospheric pressure. Since summertime temperatures are higher, the average temperature is above the 6mbar temperature (148°K). If the surface temperature is high, then the buried deposit receives a net influx of heat and must begin to sublimate if it is in vapor contact with the atmosphere. Hence, such a buried deposit is not stable.

Such an argument does not apply to deposits of CO_2 which are effectively sealed from the atmosphere. Since dust and fine particles of water-ice frost are likely to form a blanket with very low permeability, we can expect buried CO_2 to build up appreciable vapor pressure before significant escape to the atmosphere begins. Given an average surface temperature of 180°K, only 200mbars pressure is required to stop sublimation. In fact, if vapor pressures equaled the overburden pressure, then the triple point pressure (5.1 bars) would be reached at a depth of less than 100m, and neither sublimation nor melting would occur until the temperature rose to 217°K.

Murray and Malin (1973b) consider the burial of solid CO_2 to be unlikely because of the warming effect of dust being deposited at the same time. It seems necessary to postulate a climate somewhat different from today's climate to allow such deposition, but in view of the fact that the polar deposits now appear to be eroding, a different (perhaps colder and cloudier) climate must have been present in the past just to explain the existence of the polar deposits at all. The changed conditions might have been due to obliquity oscillations, as suggested by Ward (1974), or to other unknown causes (e.g., periods of active volcanism which changed insolation).

Two bits of observational data suggest the possibility that CO_2 might be present in buried deposits at the pole. First, the ratio of mass of known CO_2 outgassed on Mars to the planet's weight, approximately 4×10^{-8}, is far less than that of Earth (including carbonates), or Venus, near 10^{-4} (Ingersoll, 1974). One effective way to account for a much larger amount of outgassed CO_2 is to postulate large quantities sealed in the polar deposits. Second, a plausible explanation for the unusual erosion features observed near the poles (Sharp, 1973; Cutts, 1974) is that wind erosion of overlying dust caused pressure reductions at depth and the consequent sublimation of buried CO_2.

A final assumption is that the temperature gradient with depth is sufficiently steep that most CO_2 layers below the first few hundred meters are considerably warmer than the 150°K winter temperature at the surface. The existence of reasonably young volcanic activity supports the contention of a positive gradient that might be quite steep. Sagan (1973) speculated that it might be equivalent to the Earth's gradient, $10–40°\mathrm{K\,km}^{-1}$. Even a 10° gradient would bring CO_2 near its melting point at the maximum 6km depths for the base of the present layered deposits postulated by Cutts (1973b). However, such a gradient would be slow enough in developing that it does not seriously jeopardize our earlier suggestion of a 10–15km thick pile of material at the pole before significant flow had occurred.

CONCLUSION

The concept of "glaciation" on Mars remains an alternate working hypothesis for explaining the unique features of the polar deposits of Mars. Observational evidence is not diagnostic. The unusual topography of the permanent ice caps at both poles strongly suggests flow in the underlying layered deposits. The fine layering of the layered deposits is compatible with a flow interpretation, but sedimentary interpretations are more conventional. The overall shape and thickness of the deposits are well explained by flattening of a thick CO_2-rich sheet, but they could also have been deposited fortuitously with similar dimensions. Good evidence of flow patterns in the layered deposits, large enough to be visible in the Mariner 9 television pictures, are lacking. However, considerations of the physics of such a mechanism are favorable. We have shown that CO_2 does indeed flow at low stresses, and further assumptions needed to construct a plausible model are indeed reasonable.

Because the flow hypothesis carries new and different implications from other hypotheses used to explain the history of the Martian polar regions, the constraints on the atmospheric history and devolatilization of the planet are not at all clear. Thus one should maintain caution when accepting specific constraints based on the polar history of Mars and building atmospheric or planetary differentiation models upon these constraints.

ACKNOWLEDGMENTS

The authors are grateful to C. Drexler, J. Baily, and D. Chapman for their help with experimental problems; to Dr. D. R. Peacor for discussions of mineralogical problems; and to Dr. C. I. Smith for encouragement in the early stages of the study. Drs. J. A. Cutts and R. P. Sharp contributed unsettling but appreciated discussions and reviews. The illustrations were prepared by D. Bell. Financial support was provided by the National Aeronautics and Space Administration, Grant No. NRG 23-005-563. Finally the authors thank the management of the Chemetron Corporation, Toledo, Ohio, for providing the information on the commercial preparation of the CO_2 used.

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