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ICE ON MARS*

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Abstract. Ice unquestionably exists on Mars. Annual polar-region frost blankets are principally solid CO_2, and perennial residual ice caps near each pole are probably water ice, except for a part of the north polar cap which may consist of a 1 km thick mass of solid CO_2. Minor amounts of carbon-dioxide clathrate ($CO_2 \cdot \approx 6H_2O$) presumably accompany the solid CO_2. The annual frost blankets may have a concentric banding with an outermost very thin layer of water frost, an intermediate narrow zone of clathrate, and a major central core of solid CO_2.

Layered deposits and underlying homogeneous materials mantle large areas within both polar regions. These blankets are probably composed of dust, volcanic ash, or both, and possibly contain frozen volatiles. They may comprise the largest reservoir of water substance on the Martian surface.

Ground ice formed by the freezing of ascending de-gassed water substance may underlie the surface of Mars. Localized collapse of small areas may be due to ground-ice deterioration, and recession of steep slopes may have been caused by ground-ice sapping.

If liquid water ever existed in significant quantities on the Martian surface, intense frost shattering, widespread creep, and prolific development of patterned structures should have occurred because the thermal regimen of the surface is highly favorable to the freeze–thaw process. It is ineffective at present owing to the lack of liquid water.

No evidence suggests that the residual ice caps have ever acted like terrestrial glaciers in terms of erosion and deposition. Currently, they are too thin, too cold, and presumably frozen to their substrates. Their most important function is to buffer the atmosphere in terms of its H_2O and CO_2 content, thereby exerting a modifying influence on the surface environment of the entire planet.

Résumé. *Glace sur Mars.* L'existence de glace sur Mars ne fait pas de question. Les couvertures gelées annuelles des régions polaires sont essentiellement de la glace carbonique, et les calottes résiduelles pérennes près de chaque pôle sont probablement de la glace d'eau, excepté pour une partie de la calotte nord qui peut consister en une masse d'un kilomètre d'épaisseur de glace carbonique. Des quantités moindres de dioxide clathrate ($CO_2 \cdot \approx 6H_2O$) sont présumées accompagner la glace carbonique. Les couvertures gelées annuelles peuvent présenter des bandes concentriques avec à l'extérieur un très mince niveau d'eau gelée, une zone intermédiaire étroite de clathrate, et un noyau central principal de glace carbonique.

Des dépôts stratifiés et des matériaux sous-jacents homogènes recouvrent de larges surfaces à l'intérieur des deux régions polaires. Ces couvertures sont probablement composées de poussières, de cendres volcaniques ou des deux, et contiennent peut-être des produits volatiles gelés. Ils peuvent contenir la plus grande réserve d'eau à la surface de Mars.

De la glace de sol, formée par le gel de substances aqueuses montant sous forme gazeuse, peut recouvrir la surface de Mars. Des effondrements localisés de petites surfaces peuvent être dues à la dislocation par le gel du sol, et la réduction de pentes fortes peuvent avoir été causées par le travail de sape du gel du sol.

Si l'eau liquide a autrefois existé en quantités significatives à la surface de Mars, il a dû se produire une intense gélifraction des glissements généralisés, et un développement abondant des formes caractéristiques en raison du régime thermique de surface, hautement favorable au processus gel–fusion. Ce processus est actuellement inopérant par défaut d'eau liquide.

Il n'y a pas de preuves suggérant que les calottes résiduelles aient jamais travaillés comme les glaciers terrestres par érosion et dépôt. Normalement, ils sont trop peu épais, trop froids et probablement gelés jusqu'au sous-sol. Leur fonction la plus importante est de réguler l'atmosphère du point de vue de son contenu en eau et en gaz carbonique, exerçant par là une influence, modifiant l'environnement de la surface de la planète tout entière.

Zusammenfassung. *Eis auf dem Mars.* Zweifellos gibt es auf dem Mars Eis. Die jährlichen Frostdecken der Polarregionen sind hauptsächlich festes CO_2; die ständigen Resteiskalotten in der Nähe jedes Pols hingegen enthalten wahrscheinlich Wassereis, mit Ausnahme eines Teils der nördlichen Polkappe, der aus einer 1 Kilometer dicken Masse von festem CO_2 bestehen dürfte. In Verbindung mit dem festen CO_2 treten vermutlich geringere Mengen von Kohlendioxydklathrat ($CO_2 \cdot \approx 6H_2O$) auf. Die jährlichen Frostdecken dürften konzentrisch geschichtet sein mit einer äussersten, sehr dünnen Lage aus Wassereis, einer schmalen Zwischenschicht aus Klathrat und einem grösseren Kern aus festem CO_2.

Geschichtete Ablagerungen sowie darunterliegende homogene Materialien bedecken grosse Bereiche innerhalf beider Polarregionen. Diese Decken sind wahrscheinlich aus Staub und vulkanischer Asche, eventuell kombiniert, zusammengesetzt und enthalten möglicherweise flüchtige Stoffe in gefrorenem Zustand. Sie dürften das grösste Wasserreservoir auf der Marsoberfläche darstellen.

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Unter der Oberfläche des Mars könnte sich Bodeneis befinden, das sich durch Gefrieren von aufsteigenden, entgasten Wassermengen gebildet hat. Lokal begrenzte Einbrüche kleiner Gebiete dürften durch Zerfall des Bodeneises, die Rezession steiler Hänge durch Unterwanderung mit Bodeneis verursacht sein.

Falls jemals flüssiges Wasser in nennenswerten Mengen auf der Marsoberfläche existierte, dann sind sicherlich starke Frostspengungen, weiträumige Kriecherscheinungen und reich entwickelte Strukturböden aufgetreten, da der Wärmehaushalt der Oberfläche den Prozess des Gefrierens und Tauens sehr begünstigt. Er ist derzeit infolge des Mangels an flüssigem Wasser unwirksam.

Es gibt keine Anzeichen dafür, dass die verbliebenen Eiskappen hinsichtlich Erosion und Ablagerung sich jemals wie Gletscher auf der Erde verhalten hätten. Gegenwärtig sind sie zu dünn, zu kalt und wahrscheinlich an ihren Untergrund festgefroren. Ihre wichtigste Funktion besteht darin, die H_2O- und CO_2-Anteile der Atmosphäre zu steuern und dadurch die Oberflächenverhältnisse des gesamten Planeten mässigend zu beeinflussen.

Introduction

Mars is cold. The mean annual planet-wide surface temperature is roughly −80° C., and even at the equator it is near or below −60° C. Night-time temperatures are everywhere sub-zero at all seasons. If volatiles were abundant at the Martian surface, considerable ice would be expected. The evidence for ice on or near the Martian surface is thus of much interest as an indicator of environment and a measure of planetary degassing. Ice on Earth

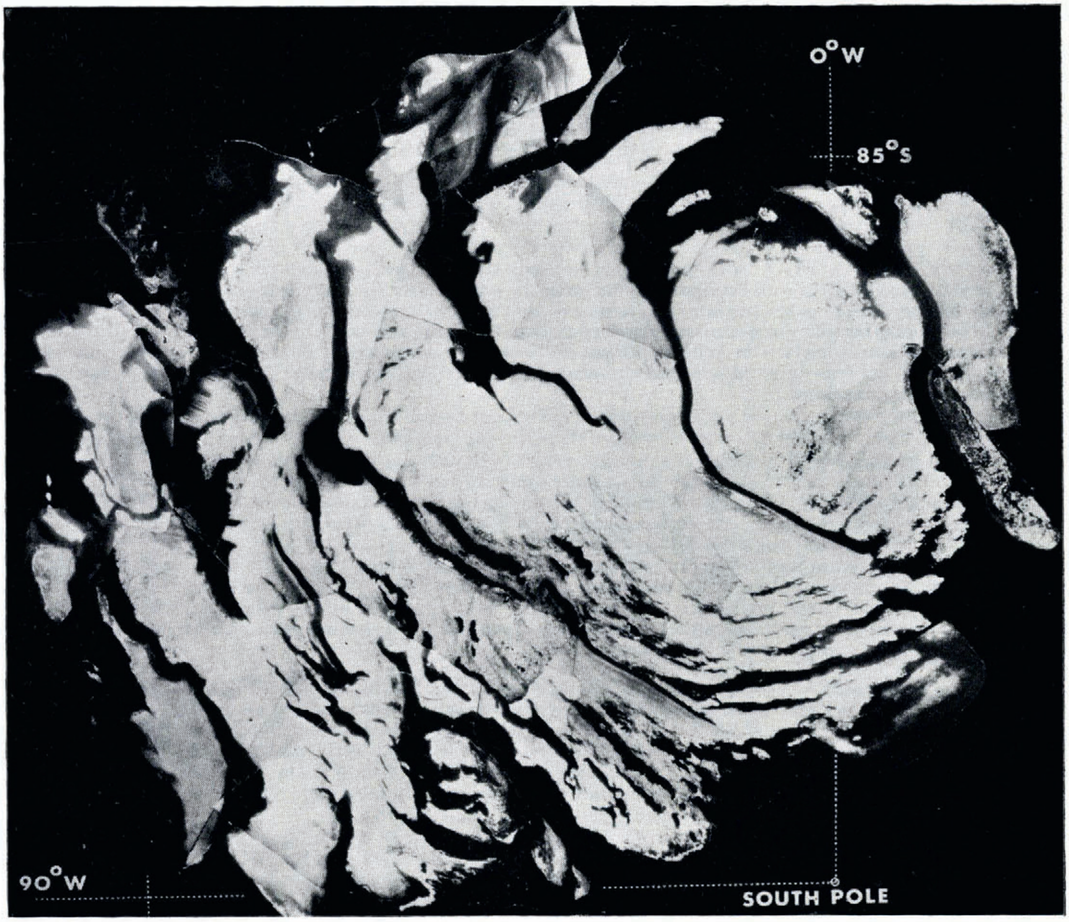

Fig. 1. Photo-mosaic of residual south polar cap on Mars near end of ablation season. Maximum diameter approximately 400 km. (Courtesy of M. C. Malin and J. J. van der Woude.)

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has been and continues to be an effective modifier of surface topography. Does it now, or has it ever exercised a similar role on Mars?

For at least 200 years astronomers have observed the annual expansion and shrinkage of white cappings at both Martian poles (Slipher, 1962). Initially, these masses were regarded as comparable to a terrestrial polar ice sheet, but it was eventually realized that they could be little more than thin frost coverings. This frost was first thought to be composed of water, but recognition of the extreme paucity of water substance at the Martian surface, the relative abundance of CO_2 in its atmosphere, and the presumed low polar temperatures suggested the alternative possibility of CO_2 frost. This speculation was confirmed by Mariner 7 instrumental observations in 1969 (Herr and Pimentel, 1969; Neugebauer and others, 1971).

Astronomers have long observed that shrinkage of the north polar cap ceased at roughly 10° radius suggesting the existence of a perennial body of that size. The situation was less clear at the south pole owing to unfavorable orientation for observation at the close of the ablation season, but gradually it was established that the south polar area also harbors a small perennial cap (Vaucouleurs, 1972). Mariner 9 has dramatically confirmed the existence of residual ice bodies in the vicinity of both poles (Figs. 1 and 2). The principal concerns now are the thickness, composition, and history of these bodies and the peculiar structural pattern each displays.

The existence of significant masses of ice on the surface of Mars in non-polar areas is unlikely under current conditions. Some topographic features of Mars attain prodigious heights, the volcano Mix Olympica rising more than 20 km above its surroundings, but unlike conditions on Earth, this does not result in perennial accumulation of ice, snow, or frost because of planet-wide low temperatures, paucity of available volatiles, an extremely thin atmosphere, and strong solar radiation. That large masses of ice may lie beneath the Martian

Fig. 2. Residual north polar cap of Mars. Central meridian passes vertically through center of photograph, and dark dot one-third from top is approximate location of north pole. Maximum diameter about 1 000 km.

surface has been considered likely (Morgenthaler, 1963; Salisbury, 1966) and features recorded on the Martian surface by Mariners 6 and 9 support this speculation.

Besides being extremely cold, Mars has a highly attenuated atmosphere. The mean surface pressure is about 6 mbar, or roughly 0.005 that of Earth. The principal constituent of this atmosphere is carbon dioxide with traces of water vapor and carbon monoxide. A denser atmosphere in the past is strongly championed by some (Sagan, 1971; Sagan and others, 1973) and discounted by others (Murray, 1973; Murray and Malin, 1973[a]). The thought is appealing because a denser atmosphere with moister conditions would help explain a number of enigmatic Martian landforms. It merits careful consideration, the principal objection being the difficulty of producing such an atmosphere and then largely dissipating it, perhaps not just once but several times. Nonetheless, any discussion of ice on Mars must consider the implications of a possibly different environment sometime in the past.

Ice in the atmosphere

Earth-based telescopic observers have long reported clouds, other than dust, over parts of Mars (Slipher, 1962), but the 1965 Mariner 4 fly-by failed to record any clouds and even Mariners 6 and 7 provided only dubious evidence of them in 1969 (Leovy and others, 1971). However, Mariner 9 in its nearly year-long orbiting of Mars has yielded unequivocal evidence of the formation, movement, and dispersal of clouds in the Martian atmosphere (Leovy and others, 1972; Leovy and others, 1973).

Temperature conditions are such that these clouds are judged to consist of water ice in the lower atmosphere (Smith and Smith, 1972, p. 520; Curran and others, 1973), and largely of solid CO_2 above 25–50 km (Fjeldbo and others, 1966; Herr and Pimentel, 1970). Clouds of solid CO_2 may form at lower altitudes over polar areas in winter (Leovy and others, 1972).

The amount of water ice currently in the Martian atmosphere can never be very large, equivalent perhaps to a few micrometers of water per cm^2 (Hanel and others, 1972; Conrath and others, 1973). The possibility that water snow falls onto the Martian surface, even in polar regions, is unlikely (Cutts, 1973[a]). Water is delivered to the Martian surface principally by direct condensation as frost.

The Martian atmosphere is rich enough in carbon dioxide so that CO_2 snowfall might be expected in the polar areas. This has been proposed as a mechanism for removing suspended particulate material from the atmosphere (Cutts, 1973[a]). However, direct condensation as frost is probably the principal means by which CO_2 solid accumulates on the Martian surface. Conditions are thus considerably different from those on Earth where most land-borne ice results from snowfall.

Ground ice

The existence of ground ice on Mars is wholly a speculation, supported largely by theoretical deductions (Smoluchowski, 1968) and interpretations of certain Martian landforms and landscapes (Sharp and others, 1971, p. 335; Maxwell and others, 1973). The surface temperature regime is currently everywhere favorable to the formation and preservation of ground ice, but the supply of water at the Martian surface is not adequate to sustain any significant amount of ground ice. From considerations based on a computer model, Leighton and Murray (1966) conclude that a small amount of ice, nourished by water vapor in the atmosphere, might accumulate under current conditions to a depth of a few tens of meters beneath the surface poleward of 40° to 50° latitude. If larger masses of ground ice exist, they must be fossil in the sense of having originated under different earlier conditions, or they may have developed from internal sources of juvenile water.

Ground ice on Earth is usually regarded as frozen meteoric water which has percolated into the ground. However, the Martian environment is frigid enough that significant amounts of ground ice may have been developed within the crust by freezing of juvenile liquid water and vapor ascending from the interior during de-gassing of the planet. This ice might lie deep enough within the crust to be sealed off from free contact with the atmosphere.

Differences of opinion exist as to the degree of de-gassing experienced by Mars, compared with Earth, but for the most part it is judged to have been considerably less (Fanale, 1971; McElroy, 1972; Murray and Malin, 1973[a]). The Martian atmosphere is currently over-endowed with CO_2 compared to H_2O. This can, perhaps, be accounted for by the dissociation of H_2O and the escape of H and O from the outer atmosphere (McElroy, 1972) or by adsorption onto the Martian regolith (Fanale and Cannon, 1971), but another contributing factor might be the preferential capture of ascending water substance as ground ice beneath the surface. Conditions are not cold enough to capture CO_2 in a similar manner, except possibly in limited parts of the polar regions.

The thermal regimen of the Martian crust could perhaps allow ground ice development to a depth of 1–3 km (Öpik, 1966; Soderblom and Wenner, unpublished), but probably not to 10 km (Sharp, 1973[a]). With a depth of freezing to 2 km and a porosity of 10%, the amount of ground ice could be significant. Porosities as high as 10% are not unreasonable owing to fragmentation of surface materials by meteoroidal impact and to the volcanic nature of much of the surface rock. If the ground ice occurred in segregated bodies, as on Earth, the amount could be much larger.

The Martian surface currently displays landforms and landscapes which appear to have evolved through extensive cliff or slope recession, or to have formed through subsidence and collapse. If ground ice were exposed in the face of an open fracture, steep slope or cliff, it would evaporate. This could lead to disaggregation of already fragmented materials, resulting in an undermining of the slope causing recession. Such a process has been termed ground-ice sapping (Sharp, 1973[a]). Internal geothermal changes related to incipient volcanism might melt masses of segregated ground ice producing subsidence or collapse of the ground surface. Some local areas of subsidence on the Martian surface may be of this origin, but most of the subsidence creating chaotic terrain is on a scale too large to be satisfactorily explained by ground-ice deterioration (Sharp, 1973[a]).

It is a matter of speculation as to when in Martian history ground ice development may have occurred. Mars has probably experienced some degree of de-gassing throughout much of its history (Fanale, 1971), but the intensity may have varied in phase with episodes of volcanism. However, trapping of volatiles by sub-surface freezing is probably more a function of the Martian thermal regime than the degree of de-gassing. Currently, the Martian surface regime is favorable, but it is not possible to say how far back in time this has been true. Volcanism may have been active through a long expanse of Martian history (Carr, 1973), but it was clearly intense within the last few hundred million years (Hartmann, 1973; Carr, 1973).* The formation of some Martian ground ice may have been related to early phases of this volcanism, and its subsequent local deterioration may have been caused by later associated geothermal changes.

Although speculative, the possibility of ground ice beneath the Martian surface has considerable significance with respect to the origin and evolution of several types of Martian landforms and landscapes, particularly if this ground ice existed in segregated bodies and to depths between 1 and 3 km. Subsequent meteoroidal impacts (Maxwell and others, 1973) or climatic or internal geothermal changes could have liberated some of the water locked up in such ground ice with significant results in terms of surface processes and features (Milton, 1973, unpublished). Mars may currently have important resources of water "in the bank", as it were, in the form of ground ice.

* *Note added in proof:* Interpretations of impact cratering flux on Mars, recently advanced, suggest the possibility of a greater age for even the youngest volcanism.

Polar ice

Annual frost blankets

By far the largest and most significant masses of ice seen on the Martian surface are in the polar regions. A distinction needs to be made between the annual frost covering of those regions and the more limited bodies of perennial ice residing near the poles. It has long been known, from Earth-based telescopic observations, that the frost covering in both polar areas annually expands and contracts, in opposite phases. The continuous frost sheet of both hemispheres occasionally extends to within 40° of the equator (Fischbacher and others, 1969). These thin annual blankets are composed principally of solid CO_2 (Herr and Pimentel, 1969; Leighton, 1970; Michaux and Newburn, 1970). Cross (1971, p. 112) calculates that at maximum development, the annual frost amounts to 132 g cm^{-2} of solid CO_2 at the north pole and 164 g cm^{-2} at the south pole. Assuming a frost density of 0.2 Mg m^{-3}, the respective thicknesses would be roughly 650 and 800 cm. The average thickness of the entire frost blanket must be much less, although it probably exceeds the few centimeters earlier estimated (Vaucouleurs, 1950; Firsoff, 1969).

In constitution, these annual frost blankets must have some vertical and radial variability. As autumnal chilling begins in a polar region the initial deposit should be water frost. Owing to the extremely low water-vapor content of the atmosphere only a few micrometers of precipitation would be expected, and the low-density, water-frost layer would be only a small fraction of a millimeter thick. As the falling temperature approached 150 K, this frost would react with CO_2 gas to form the carbon-dioxide clathrate (Miller and Smythe, 1970). This clathrate consists of an open cubic ice lattice with holes in which molecules of CO_2 gas reside (Cotton and Wilkinson, 1962, p. 148). Reaction times are such that conversion should be complete by the time solid CO_2 began to accumulate at about 148 K (Miller and Smythe, 1970). In its central part, the annual frost cover should eventually have a vertical stratification consisting of a very thin basal layer of carbon-dioxide clathrate and a much thicker overlying layer of solid CO_2 frost, with possibly traces of clathrate if any further water vapor could be wrung from the severely chilled air.

At maximum development the frost blanket should display a concentric planimetric structure consisting of an outermost modestly wide but very thin band of water frost. Inside that should be a much narrower very thin band of carbon-dioxide clathrate. Finally, the central and much the largest surface of the blanket should be CO_2 frost. As the frost cover shrinks under rising temperatures the concentric banding should also shrink as the clathrate is converted to water ice. Ultimately, water ice would be the last remaining component, but as long as any CO_2 frost remains, the concentric banding would exist.

Residual ice caps

The residual ice caps (Figs. 1 and 2) visible near the poles after recession of the frost blankets may be largely water ice (Murray, 1973), although it is speculated that one part of the north polar cap contains a significant body of solid CO_2 (Murray and Malin, 1973[a]). If so, at least a little carbon-dioxide clathrate must be present.

The northern residual cap is the larger, spanning a diameter of roughly 1 000 km. It is approximately centered on the north geographical pole. The southern cap is 300 to 400 km in diameter, and its center is offset from the pole by nearly 170 km along the 45° meridian. The north cap has an indented kidney shape, the south cap is more nearly circular, and their borders, although sharp, are irregular and strongly indented. Both display an unusual pattern of internal dark bands, irregularly concentric in the south and spiraling outward in the north. The center of concentricity in the southern cap is neither in the center of the cap nor at the pole but lies about 170 km from the pole along the principal meridian. Thickness

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of ice is not known, but with exception of one part of the northern cap, it cannot be great, averaging perhaps a few tens of meters and probably not exceeding 100 m. This is judged to be so because the ice does not generally blot out the relief of the underlying terrain, which under a part of the south polar cap, at least, probably averages around 225 m (Blasius, 1973, p. 4418). However, the banded pattern appears to be locally obscured in the northern cap within a region centered on the principal meridian about 300 km from the pole. The hypothesis is offered by Murray and Malin (1973[a]) that here the underlying topography is submerged beneath a mass of solid CO_2, averaging perhaps 1 km thickness, which in turn underlies a protective carapace of water ice.

Layered deposits

Strata within these deposits are remarkably regular, displaying uniformity in character and thickness over extended exposures and only modest differences in thickness between individual beds (Fig. 3). Their attitude appears to be essentially horizontal, although primary dips of a few degrees might be expected in places where they are known to mantle a rough underlying surface. The south polar blanket covers an area of roughly 1.5×10^6 km^2 with a maximum diameter of 1 500 km, corresponding dimensions for the north polar blanket are 1.1×10^6 km^2 and 1 000 km (Cutts, 1973[a]). The layered deposits are of particular interest because of their possible relationship to the dark banding visible within the residual ice caps and because they may contain frozen volatiles. Along with an underlying massive blanket of still greater areal extent and possibly comparable thickness, they could contain the most significant reserve of frozen volatiles on the Martian surface.

The nature and origin of the topographic surface of the layered deposits is of concern because of its relationship to the pattern of dark streaks seen in the residual ice caps. Owing to better photographs, this relationship is most clearly seen in the south polar cap where special processing has revealed that the intra-cap dark streaks consist of exposures of the layered deposits in which the outcropping strata have a configuration conformable with the outline of the nearby ice edge. In other words, both are determined by the topography of the surface on the layered deposits.

That this surface is at least partly of erosional origin is indicated by isolated outliers of the layered deposits, by areas from which they and the underlying massive blanket have clearly been stripped, by the local complex topographic configuration of the surface itself, and by the fact that it truncates the layering within the deposits (Fig. 3). However, within both polar regions, and especially within the area covered by the residual ice caps, is a larger topographic pattern of curved outward facing escarpments, especially well seen in the north (Fig. 2), which Murray (1973) interprets as being primarily of depositional origin. He draws an analogy to a stack of poker chips which has fallen over sideways, and invokes a speculation of polar wandering to explain the arrangement (Murray and Malin, 1973[b]). On the other hand, Cutts (1973[b]) and Soderblom and others (1973) regard the escarpments at least as partly erosional because they locally constitute the walls of long curving grooves. Whatever their origin, these escarpments form the dark bands within the residual ice caps. They are slopes facing outward in such a way that they receive enough insolation to be denuded of any perennial cover of frost or ice.

A consideration of still greater interest here is the constitution of the layered deposits and of the underlying massive blanket. The layered accumulation is clearly sedimentary and has probably formed by deposition from the atmosphere (Cutts, 1973[a]). The contrast in albedo of the layers and their variations in surface texture suggest that they are composed of different materials or different admixtures of the same materials, as a gradation of albedos is seen, not just two sharply contrasting shades. The darker component is thought to be largely dust, volcanic ash, or both, and the lighter component may be frozen volatile materials condensed

Fig. 3. Photograph of layered deposits in south polar region at lat. 74.6° S., long. 229.8° W. Evenly spaced dark dots are riseau marks on vidicon. Grooving in lower left is attributed to eolian erosion. Width of photograph roughly 55 km.

from the atmosphere (Murray and Malin, 1973[b]). The alternative of dusts or volcanic ashes of different colors must also be entertained. There is, at present, no direct proof of frozen volatiles in the layered deposits, but the possibility merits consideration. If they exist, the prime questions are which volatiles and how much?

If the layered deposits accumulated under environmental conditions like those currently existing, the included volatile would almost certainly be predominantly water ice for reasons earlier stated (Murray and Malin, 1973[a]). If the deposits accumulated under conditions of colder temperatures, reduced solar radiation, or denser atmosphere, then either solid CO_2, CO_2 clathrate, or both might conceivably be present (Sagan, 1973). Even so, solid CO_2 and the clathrate would probably be restricted to the immediate vicinity of the poles, and, since the layered deposits extend for at least 20° from the poles, the principal included volatile would probably still be water ice. Indeed, there might be a concentric zoning of volatiles in the layered deposits with a wide outer zone of water ice, an intermediate very narrow zone of CO_2 clathrate, and a small central core of solid CO_2. It seems unlikely that the layered deposits harbor as great a supply of CO_2 as Sagan and others (1973) would wish, unless the environment of their origin was very different from the present.

Although an explanation of the platy structure and of the stratification within the layered deposits has been made on the basis of variations in the obliquity of the spin axis of Mars (Murray and others, 1973; Ward, 1973), such variations cannot be the basic cause for initiating deposition of these materials or causing their subsequent erosion. An episodic event such as volcanism or a change in solar radiation are more likely basic causes.

Could the possibly included volatile be of significant volume? The volume of the layered deposits can only be approximated. Their areal extent is determined with reasonable accuracy, but the thickness has to be estimated. A simple calculation shows that the individual layers visible on Mariner 9 narrow-angle photos must have an outcrop on a 5° slope equal to that provided by a horizontal layer roughly 20 m thick. Many layers are clearly several times thicker and Cutts (1973[a]) uses a mean thickness of 30 m. It is possible to count 30 to 40 of these layers in some exposed sections, indicating a cumulative thickness possibly approaching 1 km. The impression is gained that there are other similar overlying and underlying sequences. On this basis, estimates of maximum thickness for the layered accumulations range from several kilometers (Sagan, 1973) to an extreme of 6 km (Masursky, 1973). Cutts' (1973[a]) estimate of an average 2 km, although possibly conservative, looks reasonable. Radio-occultation measurements (Kliore and others, 1973) suggesting that the old basement surface exposed at the outer edge of the layered accumulation in the north is about 3.5 km lower than in the south, support the conclusion of Soderblom and others (1973) that the deposits may be thickest in the north.

Using an average thickness of 2 km, Cutts (1973[a]) calculates the volume of layered deposits in both hemispheres to be 5×10^6 km³. If these deposits were composed 10% of water ice, that would represent 2.25×10^{17} kg of water. This exceeds by an order of magnitude the amount of water possibly present in the residual polar caps and in the atmosphere. Could such an amount have been supplied by the de-gassing of Mars? The following argument says possibly yes.

The Martian atmosphere currently contains 2.2×10^{16} kg of CO_2 (Cross, 1971, p. 113). Murray and Malin (1973[a]) postulate that up to five times that much CO_2 may be locked up in the north residual polar cap, giving a possible total of roughly 1×10^{17} kg of CO_2 currently on the surface of Mars and in its atmosphere. McElroy (1972) calculates that about half of the de-gassed carbon may have escaped from Mars during the life of the planet; if so, this would double the amount of CO_2 de-gassed to 2×10^{17} kg. The molecular de-gassing ratio of H_2O/CO_2 for Mars is thought to be about 45 (McElroy, 1972), but the weight ratio is closer to 20. Thus, the amount of water de-gassed from Mars could have been around 4×10^{18} kg. The amount of de-gassed water would be greater than this in proportion to any carbon in deposits, weathered compounds, or adsorbed on the Martian regolith (Fanale and Cannon, 1971).

Water in the amount of 10^{18} kg is more than adequate to supply a possible 10^{17} kg trapped in layered deposits and to provide for ice in the residual caps and water vapor in the atmosphere. However, the escape rate of hydrogen is on the order of 10^3 greater than the escape rate of carbon (McElroy, 1972), so this water cannot have been freely circulating in the atmosphere for any great fraction of the 4 to 5×10^9 years of planetary history. It has either been previously trapped in some subsurface situation sealed off from the atmosphere, or it has only recently arrived at the surface of Mars, as for example via relatively recent volcanic activity (Carr, 1973).

The nature of the particulate material in the layered deposits remains unknown. In spite of Cutts' (1973[a], p. 4 237–41) feelings to the contrary, the possibilities that much of it is volcanic ash merits continued consideration, partly because of the wide variations in albedo, surface texture, and erodibility displayed by the different layers. If there is a significant, or even predominant, component of volcanic ash in the layered deposits, then the possibility of entrapment of water ice is enhanced because of the large amount of gas presumably emitted during volcanism. There may be more water ice in the layered deposits of the polar regions than anywhere else on the surface of Mars.

Glaciation on Mars?

Returning to the residual ice caps on Mars, one may ask if they, or preceding and possibly larger thicker bodies, ever behaved like terrestrial glaciers in terms of flow, erosion, and deposition? Such behavior seems most unlikely at present because of the intense cold. Water ice at -90° C and CO_2 ice at roughly -125° C do not deform easily owing to a drastic drop in plasticity with lowering temperature (Glen, 1955). The present residual caps are hardly thick enough to generate much internal flowage, and even a postulated 10% ice in the much thicker layered deposits is unlikely to endow them with any degree of plasticity at prevailing temperatures. The residual ice caps are so thin that they must be frozen to their floors, preventing basal slip and basal erosion. The possibility of liquid CO_2 (Sagan, 1973) at the base of the thicker CO_2 mass in the northern cap, hypothecated by Murray and Malin (1973[a]), is discounted. If the ice caps do not effect erosion, they do not produce deposits. Features of the polar region earlier regarded as glacial moraines (Belcher and others, 1971) are now known to be escarpments within the layered deposits.

These are the conditions of the present, what about the past? If Mars once had a significantly warmer, moister environment what would the polar caps have done? Both warmth and greater moisture would have benefited the caps. They would have been much more richly nourished, larger, thicker, and possibly somewhat more mobile internally. It seems highly unlikely, however, that the climatic amelioration could ever have been great enough to keep them unfrozen at the base, thus permitting basal slip and significant erosion and deposition like that accomplished by continental Pleistocene glaciers on Earth. The evidence for such activity is certainly not seen on Mariner 9 narrow-angle photos which, with a resolution of 200–300 m, could be expected to reveal it. The erosional topography of the layered deposits is not a typical glacial morphology, it looks more like the product of eolian erosion pole and 164 g cm^{-2} at the south pole. Assuming a frost density of 0.2 Mg m^{-3}, the respective (Cutts, 1973[b]; Cutts and Smith, 1973, p. 4150). The pitted terrain (Sharp, 1973[b]) of the underlying massive blanket is even less glacial in aspect. The layered deposits are estimated to range in age from 100 million (Murray, 1973) to possibly 500 million years (Cutts, 1973[a]), so that evidence of possibly still older polar glaciation could be buried by this mantle.

Thus, although there are probably significant masses of water ice and possibly also of solid CO_2 with a little carbon dioxide clathrate in the polar caps of Mars, they currently do not and probably have not in the past, acted like large terrestrial ice sheets in terms of scour and deposition. They are principally significant as depositories of much of the planet's supply of water and possibly CO_2. They exert considerable control upon the present atmosphere and, thus, are an important influence on the surface environment of Mars.

Freeze and thaw

Ice, acting through the freeze–thaw process, could have played a major role in shaping details of Martian topography if significant quantities of liquid water ever existed on the Martian surface. Temperature regimes over much of the surface are highly favorable to the freeze–thaw process, and even under more amenable conditions associated with liquid water they would probably still have been adequate.

Using data derived from model calculations by Leighton and Murray (1966), which are reasonably consistent with Earth-based and space-borne instrumental observations, the Martian surface in areas poleward of 60° N. and 80° S. appears always to be below 0° C. However, within the 80° S. to 60° N. latitudinal belt, diurnal fluctuations across the freezing point of water occur for 1 to 12 months of the Martian year (Fig. 4). The belt between 10° S. and 30° N., with daily freezing point fluctuations for all Martian months, has a potential freeze–thaw flux far surpassing any area of comparable size on Earth. These data are somewhat different from those earlier reported (Sharp, 1968, p. 474).

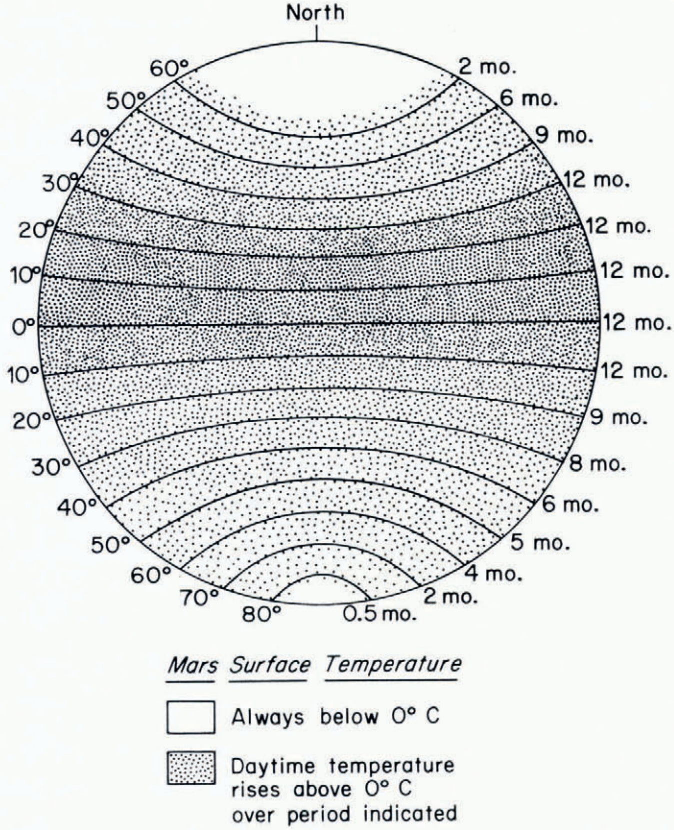

Fig. 4. Map showing Martian months per Martian year during which temperature fluctuates daily across freezing point of water (12 mo. = 12 Martian months = 1 Martian year).

If liquid water were currently freely available on Mars, frost shattering would be intense, creep would be widespread, and patterned structures (Washburn, 1956) might be prolific (Otterman and Bronner, 1966; Wade and deWys, 1968). Currently, such activities are prohibited by the lack of liquid water (Ingersoll, 1970) but they may have occurred in the past. Products, other than those of creep, which can also be caused by other agents, are too small to be seen on Mariner 9 photos. Surface pictures taken by Russian or U.S. landing vehicles may record such features. As indicators of the possible earlier existence of significant amounts of liquid water on the Martian surface, their occurrence would be of greatest interest.

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