38. The density of CO_2 ice is 1589 kg m^{-3} at 180 K (53). By correcting for expected compaction given martian gravity, the density of deposited CO_2 could in principle be calculated (54) if the depth distribution of the crystal sizes is known. However, the distribution of CO_2 crystal sizes on Mars is not well known (39). On Earth, powdery snow has a density of 30 to 100 kg m^{-3}, whereas a typical winter snowpack has a density of 300 kg m^{-3}.
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56. We acknowledge contributions from the MOLA instrument team, the MGS Radio Science Team, and the MGS spacecraft and operation teams at the Jet Propulsion Laboratory and Lockheed-Martin Astronautics. We thank R. Haberle, D. Paige, and J. Wahr for detailed reviews; F. Lemoine, D. Rowlands, and S. Fricke for orbit analysis; M. Torrence, P. Dunn, and J. McCarthy for gravity analysis; O. Aharonson for altimetry analysis; and P. Christensen, J. Foster, D. Hinson, H. Kieffer, J. Pearl, M. Smith, and L. Tyler for helpful discussions. The MGS MOLA and Radio Science investigations are supported by NASA's Mars Exploration Program.

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Observational Evidence for an Active Surface Reservoir of Solid Carbon Dioxide on Mars

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High-resolution images of the south polar residual cap of Mars acquired in 1999 and 2001 show changes in the configuration of pits, intervening ridges, and isolated mounds. Escarpments have retreated 1 to 3 meters in 1 martian year, changes that are an order of magnitude larger than can be explained by the sublimation of water ice, but close to what is expected for sublimation of carbon dioxide ice. These observations support a 35-year-old conjecture that Mars has a large surface reservoir of solid carbon dioxide. The erosion implies that this reservoir is not in equilibrium with the present environment and that global climate change is occurring on Mars.

In their seminal 1966 paper on the behavior of CO_2 and other volatiles on Mars, Leighton and Murray (*1*) deduced from a numerical thermal model that the polar caps are composed of frozen CO_2. They drew three other important conclusions from this analysis: (i) The year-round presence of solid CO_2 regulates the pressure of the atmosphere. (ii) The atmospheric pressure changes cyclically on a semiannual basis because of formation and retreat of the seasonal frost caps. (iii) The total amount of CO_2 on Mars could greatly exceed that presently in the atmosphere and form a large surface reservoir. In the past 35 years, many of Leighton and Murray's predictions have been verified and demonstrated by measurements taken on Mars (*2*). However, the existence of a surface reservoir of CO_2 large enough to have important implications for long-term climate and climate stability has yet to be demonstrated (*3, 4*). Here we report observations, made with the Mars Global Surveyor (MGS)/Mars Orbiter Camera (MOC), of interannual morphologic changes in the south polar residual cap that support the argument for a climatologically important CO_2 reservoir.

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The south polar residual cap exhibits morphologies unique to that location, characterized by irregular to circular pits, remnant mesas, and other landforms, interpreted to have formed by collapse and erosion (*5*). These features range from a few tens of meters to a few hundreds of meters in scale but display only a few meters of relief (*5*).

The erosion appears confined to, and highlights the layered nature of, the uppermost materials that make up the cap. The layers are relatively uniform in thickness but display a range in surface expression that appears related to their ability to erode (*6*). As few as one to as many as six layers crop out at various locations within the cap; not all layers are seen at all locales. On the basis of shadow measurements made during this investigation, each layer is about 3 m thick.

MOC was first used to observe the south polar region at high resolution in July 1999 (*7*). To search for changes, specific locations within the residual cap were reimaged at the same season and time of day beginning in late July 2001 [starting around heliocentric longitude (L_s) 223°±4° and continuing since then]. In each case, a 2.2 to 3.7 m/pixel image covering a portion of an earlier image was acquired (*8*). Upon receipt, both the original and new images were processed for analysis (*9*).

Figure 1 shows good examples of pits, intervening ridges, and isolated mounds that have changed. Diametric measurements, made on 100 features on each of four image pairs, indicate that these pits enlarged or their intervening ridges shrank by about 6 ± 2 m and features smaller than ~6 m across disappeared. In other words, in these examples, nonhorizontal surfaces appear to have retreated by ~3 m. Other areas within the residual cap display different morphologies, and some of these show no detectable change. Preliminary statistics suggest that between 25 and 50% of the escarpments have retreated between 1 and 3 m.

As part of the input to an estimate of the total amount of scarp retreat that occurred during the past martian year, the total perimeter in a variety of settings was determined by image processing techniques (*10*) and divided by the area viewed. Measurements were made on images representative of the range in areal density of various forms of escarpments within the residual south polar cap. The average scarp perimeter per area was 2.4×10^{-2} m/m^{-2}.

We determined that the amount of retreat was consistent with the subliming of a volatile ice by calculating the annual solar insolation using software based on spacecraft navigation routines, and we compared our results with the results of previous models of polar cap behavior (*1, 11–13, 14*). We used the order of magnitude greater volatility of CO_2 relative to water ice to differentiate between these two candidates. Table 1 summarizes the results of our calculations of the insolation and the equivalent areal mass density for H_2O and CO_2 ice for horizontal surfaces at various latitudes from the equator to near the south pole.

A variety of factors affect the translation of the maximum equivalent areal mass loss (Table

1) to a comparable effective scarp retreat (Table 2), and the result is sensitive to the values assumed for each of these factors. We explored some of these factors and a range of possible values for them (albedos between 0.5 and 0.75 and densities between 1 and 3 g/cm^3). Atmospheric contributions (which can act to enhance or diminish sublimation, depending on seasonal factors), conduction into the surface, and other physical processes that would reduce the amount of energy available for sublimation were represented by an efficiency factor of arbitrary value. We also assumed that slopes of between 30° and 50° (typical of the slopes measured by shadow techniques) facing the equator at 85°S latitude receive roughly the same insolation (with the same efficiency) as horizontal surfaces at 35° to 55°S (this simplification encompasses variations resulting from slope azimuth and season).

We first compared our calculations for horizontal surfaces with the areal mass density of CO_2 frost computed using thermal models of the seasonal polar cap near the south pole. From these models, we calculated that between 100 and 150 g/cm^2 is deposited at 80°S latitude each winter and is removed by sublimation each spring and summer (*1, 14, 11, 12*). When we use parameters similar to those used in these models (albedo = 0.65, density = 1.0 g/cm^3), efficiencies between 35 and 50% reproduce their results; an efficiency of less than 35% permits net accumulation at 80°S, whereas a greater efficiency permits net erosion or the heating of the nonvolatile surface.

For the same assumptions, our calculations suggest that efficiencies between 40 and 80% will lead to 1 to 3 m of retreat of 30° to 50° escarpments in CO_2. More importantly, they show that scarps in water ice could, at most, retreat only a few decimeters. Only extreme combinations of our three parameters (albedo < 0.5, density < 0.5 g/cm^3, and "efficiency" > 80%), which are generally unrealistic, could reproduce in water ice the magnitude of scarp retreat actually observed. We conclude that the erosion is occurring in one or more layers of moderately dense CO_2 ice.

We estimated the amount of material lost from the south polar cap over the past year by mapping the extent of the pitted, layered material (*5*) on a south polar stereographic map projection of a Mars digital image mosaic, based on close inspection of 144 pre- and immediately postsunrise, 12 to 15 m/pixel survey images acquired during July and August 1999. The map was then transferred to a comparably projected late summer view of the south polar region acquired by the MOC wide angle camera. The extremely strong correlation of the mapped contacts with the albedo of the late summer residual cap in the wide angle image permitted the use of image processing techniques to determine the area of the cap and its pitted surface (~87,000 km^2). The calculated amount of scarp perimeter is $\sim 2 \times 10^9$ m, and the volume of material lost between 1999 and 2001 is ~ 2 to 10×10^9 m^3 (2 to 10×10^{15} cm^3) for the ranges in retreat distance (1 to 3 m) and fraction of escarpments experiencing retreat (25 to 50%). For densities of CO_2 ice of 1 to 2 g/cm^3, this is 2 to 20×10^{15} g, or about 0.008% to 0.08% of the mass of the atmosphere.

A 3 m thick layer of pure CO_2 ice with a density between 1 and 2 g/cm^3 covering the entire residual cap would have a mass of 2 to 4×10^{17} g (1 to 2% of the present mass of the martian atmosphere). At a linear recession

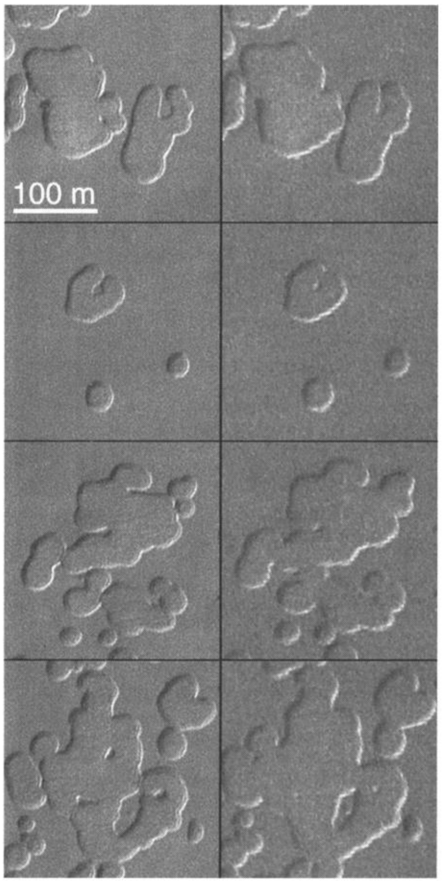

Fig. 1. Pits, intervening ridges, and mounds in south polar residual ice cap. Extracted from orthographically projected, 1 m/pixel versions of M08-04516 (left; 10/19/1999, $L_s \sim 227°$) and E07-01565 (right; 8/23/2001, $L_s \sim 219°$). Pit walls and other escarpments have retreated ~ 3 m in one Mars year. Illumination from upper left.

Table 1. Calculated solar insolation and maximum equivalent ice mass erosion for H_2O ice (column 6) and CO_2 ice (column 7) for one martian year on horizontal surfaces at different latitudes (column 1). Columns 2, 3, 4, and 5 give computed solar insolation in energy areal density per Mars year, or its equivalent power density, in several different representative physical units. All four columns present the same information—the solar energy input into the surface, independent of surface material—but in different units. Column 6 was computed using 652 cal/g for the latent heat of H_2O at 145 K. Column 7 was computed using 143 cal/g for the latent heat of CO_2 at 145 K. Values from columns 6 and 7 are used as input to the calculations summarized in Table 2.

	Parameter				Maximum	
					H_2O	CO_2
Latitude	(joules m^{-2} year^{-1})	(W m^{-2})	(cal m^{-2} year^{-1})	(cal cm^{-2} year^{-1})	(g cm^{-2} year^{-1})	(g cm^{-2} year^{-1})
−85°	4.79×10^9	80.7	1.14×10^9	1.14×10^5	175	798
−80°	4.89×10^9	82.3	1.16×10^9	1.16×10^5	178	814
−75°	5.06×10^9	85.2	1.20×10^9	1.20×10^5	185	842
−70°	5.30×10^9	89.4	1.26×10^9	1.26×10^5	194	883
−45°	7.93×10^9	133.6	1.89×10^9	1.89×10^5	289	1320
0°	1.07×10^{10}	179.6	2.54×10^9	2.54×10^5	389	1775

Table 2. Calculated amount of ice mass erosion per Mars year for H_2O and CO_2 ice as a function of latitude (column 1) and energy transfer. Columns 2 and 3 show the amount of mass loss per unit area for an albedo of 0.65. Columns 4 through 9 show the equivalent amount of surface retreat for material with a density of 1.5 g/cm and three different efficiencies of energy transfer (100, 50, and 80%). Calculations are for horizontal surfaces; escarpment retreat can be estimated by subtracting the slope declivity for the "actual" latitude to derive an "effective" latitude and reading across the row of that latitude.

	Parameter		Efficiency = 100%		Efficiency = 50%		Efficiency = 80%	
	H_2O	CO_2	H_2O	CO_2	H_2O	CO_2	H_2O	CO_2
Latitude	(g cm^{-2} year^{-1})	(g cm^{-2} year^{-1})	(cm year^{-1})	(cm year^{-1})	(cm year^{-1})	(cm year^{-1})	(cm year^{-1})	(cm year^{-1})
−85°	61	279	41	186	20	93	33	149
−80°	62	285	42	190	21	95	33	152
−75°	65	295	43	196	22	98	34	157
−70°	68	309	45	206	23	103	36	165
−45°	101	462	68	308	34	154	54	246
0°	136	621	91	414	45	207	73	331

rate, retreat of the present escarpments would consume a layer in 30 to 150 martian years. However, measurements of the enlargement of different sized pits show that the retreat of escarpments is independent of the size of the pit, so the rate of pit growth and hence release of additional CO_2 into the atmosphere is not linear but will increase with time. For example, the perimeter of a 10-m-diameter pit would double in 2 martian years at a 3 m/year recession rate and at that point would experience twice as much erosion and contribute twice as much gas to the atmosphere as it did 2 years earlier. The size-frequency and areal density relationships for depressions within the polar cap have not been fully quantified, but preliminary values suggest that the erosion of a layer may take only one-third as long as the linear estimate.

Thus, without accounting for deposition elsewhere, this erosion rate implies a secular and increasing contribution of CO_2 into the atmosphere, augmenting its mass by as much as 1% per martian decade. Were sufficient layers of CO_2 available, it would only take a few martian centuries to double the present atmosphere.

We do not know where the CO_2 is going (*15*). As previously noted (*3*), thermodynamics favor precipitation of CO_2 in the north polar region, but CO_2 frost is not seen to persist on the northern cap through the summer. The recently released CO_2 probably participates in the formation and retreat of the seasonal frost caps. Where it goes from there is uncertain; as the atmospheric pressure rises, regolith adsorption may increase (*16, 17*) or CO_2 may be precipitated at locations somewhere in the polar regions not presently detected.

The large, cyclic, and potentially chaotic obliquity and orbital eccentricity variations that Mars is believed to experience as a result of gravitational interactions between the planets may play a role in how, where, and when the surface reservoir forms, but calculations (*18–22*) show that values for these attributes have not changed substantially over the past 10,000 to 20,000 years. Given the high rates of destruction of the CO_2 layer(s), it is not clear that any of them could be surviving from the last period of dramatically low obliquity (when the polar regions would have been substantially colder) or dramatically high obliquity (when the higher polar temperatures might have been offset by higher atmospheric pressures to permit polar deposition) or from the last period when the polar temperatures were changing rapidly.

Repeated MOC observations indicate that a surface reservoir of solid CO_2 persists year-round on Mars and that this deposit is not in equilibrium with the present polar environment (it is being eroded). The rate and amount of erosion are phenomenal—the amount of scarp retreat, although small on a planetary scale, is substantially greater than any change previously identified on Mars at meter scale (*7*). It is unlikely that this rate can be sustained indefinitely, because the entire relief beneath the visible portion of the south polar residual cap, were it CO_2, could be sublimed to vapor in a few thousand Mars years. These and other observations (*7, 23*) suggest that the present martian environment is neither stable nor typical of the past.

References and Notes

1. R. L. Leighton, B. C. Murray, *Science* **153**, 136 (1966).
2. The predicted composition of the seasonal cap was confirmed to be CO_2 by infrared measurement of its temperature in 1969 (*24*). The predicted pressure variation cycle was confirmed by in situ measurement by the Viking 1 and Viking 2 landers between 1976 and 1982 (*25–27*).
3. Leighton and Murray (*1*) posited that the permanent deposit of CO_2 would be found in the north, but this view was shown to arise from an oversimplification in the inputs to their thermal model (*28*). Other studies (*29, 30*) suggested that the remnant, nonseasonal frost caps were both water ice, although Murray and Malin (*28*) argued that the north polar region was favored over the south for retention of CO_2 because at more than a 3 km lower altitude (*31*) (now known to be more than 6 km) (*32*) (and hence higher pressure), the CO_2 frost point was at an appreciably higher temperature (almost 6 K higher) (*33*). Calculations show that deposits of CO_2 arbitrarily introduced at the south pole migrate north rapidly (*14*). Viking orbiter infrared observations demonstrated that the north polar residual cap was indeed water ice but that the south polar residual cap was CO_2 (*34–36*). The presence of the CO_2 cap in the south, despite the argument raised by Murray and Malin (*14, 28, 33*), was explained by the extreme sensitivity of the equilibrium temperature to albedo; the south polar cap is more than 30% brighter in the spring than is the comparable northern cap (*37*), an effect attributed to northern winter deposition of dust raised each year during the period of most intense dust storm activity (southern summer) (*38*), which leads to "dirtier" frost and hence lower albedo in the north.
4. Although there is broad consensus that the southern residual cap is CO_2, the general impression from the literature is that the material is thin and occasionally may completely sublime. The only evidence put forth for this variability is the ground-based detection of abundant water vapor during the 1969 southern summer (*39*), an observation that would be at odds with the presence of CO_2 ice upon which the atmospheric water vapor would tend to deposit. The Viking orbiters observed only trace amounts of water vapor in 1977 (*40*), as would be expected in the presence of year-round CO_2 ice, and an analysis of Mariner 9 infrared measurements indicated that the southern residual cap in 1971 and 1972 also retained CO_2 frost throughout the summer (*41*). These inconsistent observations have been taken as evidence of an interannual instability (*42*) and have been used to argue that Leighton and Murray's prediction of a large surface reservoir is wrong (*42*) or that as yet unknown feedback processes between the other CO_2 reservoirs (atmosphere, polar cap, carbonate rocks, and gas adsorbed onto fine-grained regolith materials) maintain the near-zero mass of the surface frost (*41*).
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8. MOC is a line-scan camera that acquires images one line at a time (similar to a flatbed scanner or facsimile machine) (*43, 44*). With about 80 Mbits of buffer space, a losslessly compressed, full-resolution (~ 1.5 m/pixel) image 3 km across can be at most only 12 km in length. Positional uncertainties predicted several days in advance (the length of time it takes to acquire and process tracking data, examine the predicted orbit ground tracks for targets, and generate and transmit commands to the instrument to image those targets) vary from 3 to 9 km. By summing images by two, MOC images can cover these uncertainties for more than one polar image per orbit, at the expense of resolution (3 m/pixel).
9. Images were first radiometrically calibrated to remove instrument signature. They were then digitally warped to an orthographic projection with a common pole on the International Astronomical Union defined reference spheroid with spacecraft position reconstructed from tracking and attitude information determined by the onboard attitude control and articulation subsystem. The images were projected to a scale of 1 m/pixel. To reduce the impact on image comparison of small, cyclic roll oscillations that differentially displace features observed in two line-scan images, we additionally registered the orthographic projections by warping the images to a set of tiepoints. Additional cosmetic processing was applied to enhance features.
10. This processing took advantage of the sharp demarcation of slopes in the low–Sun elevation images. Processing involved a combination of thresholding to increase the contrast of slopes to the surrounding horizontal surfaces, gradient amplification to isolate the slopes from the horizontal surfaces, and erosion to replace each slope with a single line. Histograms provided the integrated perimeter length and image area.
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