The Mars Global Surveyor Mars Orbiter Camera: Interplanetary Cruise through Primary Mission

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ABSTRACT

More than three years of high resolution (1.5 to 20 m/pixel) photographic observations of the surface of Mars have dramatically changed our view of that planet. Among the most important observations and interpretations derived therefrom are that much of Mars, at least to depths of several kilometers, is layered; that substantial portions of the planet have experienced burial and subsequent exhumation; that layered and massive units, many kilometers thick, appear to reflect an ancient period of large-scale erosion and deposition within what are now the ancient heavily cratered regions of Mars; and that processes previously unsuspected, including gully-forming fluid action and burial and exhumation of large tracts of land, have operated within near-contemporary times. These and many other attributes of the planet argue for a complex geology and complicated history.

INTRODUCTION

Successive improvements in image quality or resolution are often accompanied by new and important insights into planetary geology that would not otherwise be attained. From the variety of landforms and processes observed from previous missions to the planet Mars, it has long been anticipated that understanding of Mars would greatly benefit from increases in image spatial resolution.

The Mars Observer Camera (MOC) was initially selected for flight aboard the Mars Observer (MO) spacecraft [*Malin et al.,* 1991, 1992]. After that vehicle was lost just 3 days prior to arriving at Mars in August 1993, the instrument—renamed the Mars Orbiter Camera—successfully competed with other experiments for reflight aboard the Mars Global Surveyor (MGS). Launched on November 7, 1996, MGS was inserted into Mars orbit on September 12, 1997. MOC completed its Primary Mission on January 31, 2001, and subsequently entered an Extended Mission phase. This paper provides an overview of the conduct of MOC experiment and a “snapshot” of our perspective on its observations and primary results—particularly regarding narrow angle camera views of the martian surface—through January 2001. The results generally indicate a planet far more diverse than previously known (and in some cases than was previously thought), and in several cases substantially unlike the broad consensus views developed during the past 20 to 25 years of analyses of Mariner 9 (1971–1972) and Viking (1976–1980) orbiter data (e.g., as summarized in *Kieffer et al.* [1992]).

MOC EXPERIMENT AND CONDUCT

Mission Summary

The MGS mission, conceived in the months following the MO failure, was based on three premises. First, that the original MO payload represented the appropriate mix of instruments necessary to advance understanding of Mars and its global properties. Second, that aerobraking (the use of atmospheric drag to reduce the orbit altitude and eccentricity), rather than propulsive orbit corrections, would be used to attain the requisite circular polar orbit. And third, that MGS would be targeted to the original MO orbit parameters (e.g., 117 minute period, 378 km average or "index" orbit altitude, equator crossing at 2:00 PM local solar time, south polar “frozen” orbit geometry, etc.).

Shortly after launch on November 7, 1996, MGS experienced a problem during deployment of one of its two solar panels (*Albee et. al,* [*2001*]). After orbit insertion on

September 12, 1997, and subsequent initiation of aerobraking, it was determined that substantial damage to the solar panel had occurred during the initial deployment. Concern that the damage could propagate and lead to structural failure of the panel forced revision of the plan to attain the circular orbit.

The revised MGS mission plan incorporated a four-phase approach to reaching the mapping orbit: (1) an initial phase of relatively gentle aerobraking, reducing the orbital period from about 44 hours to 11.6 hr, called Aerobraking Phase 1 (AB-1), followed by a small propulsive maneuver to raise the periapsis of the orbit out of the atmosphere, suspending aerobraking; (2) a 4 week period of science observations from the elliptical, 11.6 hr orbit called the first Science Phasing Orbit period (SPO-1), prior to a moratorium on spacecraft operations imposed by solar conjunction; (3) a second 10 week, period of science observations following solar conjunction, also in the 11.6 hr orbit (SPO-2), followed by a small propulsive maneuver to lower periapsis once again into the atmosphere; and (4) a second period of aerobraking (AB-2), lasting for almost 6 months (including final small adjustments to the orbit), leading to the mapping orbit. At the end of AB-2, MGS would be in the desired circular, polar, mapping orbit, albeit with a 2 AM instead of 2 PM equator crossing node—in other words, on the day side of Mars the spacecraft would be ascending (south to north) rather than following the originally-planned descending path (north to south).

AB-1 began in mid-September 1997 and continued until mid-February 1998. SPO-1 was conducted during April 1998. Solar conjunction occurred during May 1998. SPO-2 occurred between early June 1998 and mid-September 1998. Aerobraking was resumed in late-September 1998, and was completed in February 1999. After successfully attaining the desired low-altitude circular orbit, several activities were performed before mapping began. A “Gravity Calibration” period of about two weeks was devoted to “quiet spacecraft” observations of the radio signal, in order to develop a gravity model of Mars sufficient for orbit determination predictions for the rest of the mission. Instruments were turned on and their functions checked prior to the start of routine operations. A 9-day MOC calibration period permitted the focus and photometric properties of the camera to be established.

Following the instrument turn-on and calibration period, the spacecraft entered a hybrid operational mode for about three weeks. The “Fixed High-Gain Antenna” (FHGA) mode consisted of 7–8 orbits of nominal nadir observations followed by 4–5 orbits where the spacecraft was maneuvered to point the High Gain Antenna, held firmly in its pre-deployment position on the spacecraft’s X-axis, toward Earth. The reason for this period was concern about the deployment of the High Gain Antenna (HGA), which involved the same type of motion damper that had failed during the solar array deployment shortly after launch. The intent of the FHGA period was to acquire a set of “contingency science” observations as a backstop against failure during HGA deployment. Following three weeks of FHGA operations, the HGA was successfully deployed.

The Primary, or Mapping, mission of MGS was defined to last one Mars year (~687 days). Mapping operations began on April 3, 1999. Unfortunately, after about two weeks of operation the spacecraft experienced a major problem and entered a safe mode, suspending data acquisition. It was eventually determined that the HGA gimbal had encountered an obstruction, preventing it from moving in azimuth to values lower than about 40°. Fortunately, it was also recognized that beginning in early May the spacecraft would enter a period of 9 months when the gimbal could be operated normally. “Normal” operations resumed on May 6, 1999 and continued until February 7, 2000, when an alternative strategy, termed “Beta Supplement,” was used. This strategy used the flexibility in the two degree of freedom HGA gimbal to flip the antenna “upside down” and to reverse the movement in the azimuth direction. Normal operation of the HGA requires the motion to be reversed each orbit, nominally during Earth eclipse. Beta Supplement requires the motion to be reversed on the “day side” of the planet, reducing communications with Earth on each orbit by about 20 minutes. Table 1 outlines the chronology of the MOC Primary Mission operations. Additional information about the mission can be found in *Albee et al.* [1996, 1998, 2001].

Experiment Background

As described by *Malin et al.* [1991, 1992], MOC consists of three imaging systems in a common package. Two wide angle (WA) cameras with 140° fields-of-view can acquire horizon-to-horizon images of the planet at a best nadir scale of 230 m/picture element (pixel) and a limb scale of 1.5 km/pixel. One WA camera observes through a 575 to 625 nm color filter; the other, through a 400 to 450 nm filter. The primary purposes of the WA cameras are to acquire daily global images, reduced in resolution by on-board editing for meteorological and non-imaging science context observations, and full-resolution, nadir-oriented context frames into which the high resolution images may be placed.

The centerpiece of MOC is a 3.5 m focal length, f/10 telescope capable of achieving a 3.7 microradian instantaneous field-of-view over a 2048 pixel field. From an altitude of 400 km, this covers a region just over 3 km across at a scale of slightly better than 1.5 m/pixel. Printed on standard 9-inch aerial photographic paper, a full-resolution MOC image has a map scale of somewhat better than 1:15,000, and a spatial resolution that exceeds that of typical 1:48,000 aerial photographs.

Unlike aerial cameras, or previous planetary cameras, MOC acquires images one line at a time, much like a facsimile machine or computer flat-bed scanner. For MOC, spacecraft orbital motion “sweeps” the scene across the detector. The NA camera uses a 2048-element charge-coupled device (CCD); the WA cameras use 3456-element CCDs. Line-array imaging, sometimes called “pushbroom” imaging, was selected in order to accommodate the high data rates needed to acquire a line every 500 microsecond (i.e., 1.5 m ÷ 3000 m/sec, the orbital ground rate). Data are accumulated into a 12 MByte digital random access memory (DRAM) buffer. Line array cameras are extremely sensitive to platform motion, manifested in the form of image distortions. MOC sensitivity to this motion is mitigated in part by the extremely short image acquisition periods (typically a few seconds at most).

To achieve a 3.5 m focal length in a short 88 cm tall package, MOC’s folded optics include substantial magnification on the secondary mirror. Late in development of the Mars Observer instrument, it was determined that, despite its low coefficient of thermal expansion, the camera's graphite/epoxy structure and primary mirror changed shape with temperature, defocusing the telescope. Active focus control was added, using a novel approach without moving parts--differential thermal expansion controlled by heaters--to symmetrically distort the primary mirror. Owing to the sensitivity of the camera focus to temperature, and the large temperature variations seen in the elliptical orbits of AB-1 and SPO-1 and SPO-2, MOC images from these periods are out-of-focus. Thus, although the theoretical scale of MOC images ranges from 2 to 20 m/pixel, the actual resolution of images acquired during these periods is probably 2–3 times poorer. Once the spacecraft was in the final mapping orbit, the camera was focused. Periodic adjustments to focus were made, and the camera is considered to have generally attained its resolution objectives.

Data Acquisition and Downlink

The primary limitations on the number of MOC images acquired on any given orbit is the amount of DRAM available in MOC buffer, and the amount of time allocated to recording and later transmitting science data to Earth. The buffer is divided into 44 units—or *fragments*—of 240 KBytes each. Lossless data compression implemented in a custom integrated circuit increases the amount of data that can be put into the memory by about a factor of 1.7. The DRAM is used to buffer between the intrinsic rate of data acquisition—about 40 Mbits per second—and the substantially lower rates at which data are read out of the camera by the spacecraft data system. At its highest continuous rate to the solid state recorder, the spacecraft polls the camera for data at 9,120 bits per second. At this rate, it takes slightly under three hours to empty MOC buffer. At the lowest rate, the spacecraft polls the camera at 1105 bits per second, and it takes nearly 20 hours to empty MOC buffer.

MOC data may also be read by the spacecraft directly to the telecommunications subsystem. The "realtime" rates are substantially higher than the rates to the recorder, but are subject to potentially higher loss rates because the data are not available to be replayed if lost in transmission. However, there is little practical difference in the quality of data (see below), and “realtime” orbits provide many more imaging opportunities than do “record” orbits. The two realtime rates are 63,808 and 29,260 bits per second (depending on Earth-Mars distance). A set of 4–5 realtime orbits were nominally scheduled once every three days, but in practice realtime opportunities have occurred somewhat more often during the mapping mission.

Typical MOC sequences include 5–8 fragments allocated to low resolution red/blue wide angle images of the planet and its atmosphere, and a variable number of high resolution images. MOC is an extremely versatile camera. Images can range from 256 to 2048 elements across, in increments of 16 pixels, and downtrack lengths can be any integer value in units of 128 lines. There are 12 different image dimension combinations that could theoretically be acquired in a one-fragment image. There are 72 different image dimension combinations for images that are 16 fragments in size. Although there are many hundreds of different image sizes, in practice a much smaller number of images dimensions were commanded. Still, MOC pictures come in many sizes, chosen according to how best to address the science objectives. Versatility is also afforded by the fact that some images may be obtained in twilight, owing to atmospheric aerosol scattering of sunlight over the horizon—the very first narrow angle image, AB1-00305 was acquired in twilight, and many twilight images were obtained in 1999 and 2000, particularly of frost-covered surfaces near the terminator in late southern winter.

Data Quantity and Quality

Through January 31, 2001, approximately 83,000 image acquisitions had been commanded, and 116 Gbytes of image format data received. Figure 1 shows the number of images by image type (Wide Angle, Wide Angle Context for Narrow Angle, Narrow Angle, and Daily Global Wide Angle) and by mission phase and cycle. Figure 2 shows the data volume returned as a function of image type and mission phase/cycle. Data compression is used extensively by MOC; during realtime orbits NA images are losslessly compressed. WA images and context images are not usually compressed, but during record orbits, especially at low data rates, both NA and WA images are processed using lossy software discrete cosine transform compression. Over the course of the mission, approximately 70% more data have been returned using the compression than would have been possible without it.

The use of compression, and other attributes of MOC software design, make the imaging data particularly susceptible to data corruption. During the design and development of the Mars Observer Camera, considerable effort went into designing the custom MOC software system, in order to function properly as part of the MO data system. The MO was the first major JPL project to include packetized telemetry, wherein data are delivered to the spacecraft communications system in discrete chunks similar to modern computer network protocols. The spacecraft design included a Payload Data System that polled the instruments through a Project-provided Bus Interface Unit for data in these discrete formats. The spacecraft system then provided further “wrapping” of these data packets and sliced them into transfer frames during radio transmission to Earth. Reed-Solomon error correction coding was embedded within the downlink communications to insure a very low bit error rate. MOC software was designed to take advantage of these system attributes.

Unfortunately, the JPL ground data system as implemented failed to provide the data quality assumed during the MOC design. Packet loss rates of $1:10$ to $1:10^2$ were encountered despite bit error rates of $1:10^6$. The MO Project accepted a packet loss rate of $1:10^4$ as a goal, despite the objection that at that rate one out of every five MOC images would, in some way, be corrupted. The loss rate, which reflects data lost on the ground after they have been successfully acquired and transmitted by the spacecraft, has typically exceeded the goal.

Operationally, MOC experiences both data loss and data corruption. Data loss (commanded images that are never received) has averaged just under 7% through the Mapping Phase, and approximately 15% of all received images have been corrupted by packet loss. Figure 3 shows the history of lost and corrupted data. Only a slight trend with data volume is seen, reflecting the changing quality of the signal with distance from the Earth. The majority of the losses are not correlated with telecom performance but instead represent the stochastic nature of human error (data loss) and the statistical nature of data corruption within the ground system.

It should be noted that in many instances useful data can be distinguished in an image that has been corrupted. The number of images that are rendered completely uninterpretable by data corruption is quite small; however, the number of images that have some form of corruption is quite large (over 12,000. One way that could have been used to reduce the impact of the corruption would have been to return only uncompressed images. However, we decided that the increase in total data volume from compression (almost doubling the amount of data received) outweighed the 15-20% corruption experienced.

MOC Image Identification

During pre-mapping mission operations, MGS orbits were counted incrementally with each closest approach to the planet (periapsis), Mars Orbit Insertion being considered the first closest approach. MOC imaging began shortly after the third periapsis (p003). Initially, MGS orbits were very elliptical, and each orbit took almost two days to complete. Later, aerobraking reduced the size of the orbit and its period. Typically, only a few images were acquired each orbit. The numbering scheme was restarted once the mapping orbit was attained. Originally, the spacecraft and payload were to have operated in a consistent manner, establishing roughly month-long periods of time based on a repeated pattern of orbit groundtracks, called *mapping cycles*. However, owing to the number of non-standard operational activities experienced by the spacecraft, and based on knowledge gained during operations, the coordination of designated operational periods was generally abandoned. For MOC, the first six periods of operations were more-or-less arbitrary in length. However, beginning in September 1999, all MOC mapping cycles were defined to be one Earth month in length.

MOC images are identified by a three character prefix representing the mission phase/cycle and a five digit incremental counter for images acquired during that phase/cycle. For pre-mapping mission phases, the prefix is the mission subphase and the incremental counter is the pre-mapping orbit number and the number of the image within that orbit (e.g., AB1-00405 is the fifth image acquired on orbit 4 during AB-1). Prefixes AB1, SP1, and SP2, refer to the AB-1, SPO-1, and SPO-2 subphases, respectively. Data acquired from late February 1999 into early March 1999 for purposes of calibrating and focusing MOC are designated with the prefix, CAL. Data from the Fixed High Gain Antenna subphase in March 1999 are designated by FHA. Image identifications during the Mapping phase are indicated by the mapping cycle ("M*xx*" with "M" for mapping and "*xx*" indicating a numerical month) and the incremental number within that cycle (e.g., M07-02554 is the 2,554th image commanded during the 7th mapping cycle, in September 1999). By Project mandate, the first month of Mapping was M00, the second, M01. When the mapping cycles were redefined by MOC team to correspond to a given Earth month in September 1999, that month was designated to be M07. No Mapping cycles were designated as M05 or M06 (i.e., cycles skip from M04 in August 1999 to M07 in September 1999). The Mapping phase of the mission ended with M23 on January 31, 2001; the Extended Mission began February 1, 2001, and is expected to run to at least April 2002. Extended mission images are designated by the prefix, "E*xx*" in which *xx* is a number referring to the month since the start of the Extended mission phase.

MOC images archived with the NASA Planetary Data System (PDS) each have a comment, up to 80 characters in length, associated with the picture. For AB-1, SPO-1, and SPO-2 data, these comments indicate the main object of the acquired image. The comments for the pre-mapping images were generated by the authors upon careful inspection of each image after it was received. For CAL, FHGA, and Mapping images, these comments were written prior to acquisition of the data and indicate the intent of the image at the time it was commanded. Each Mapping phase comment was further reviewed and edited by the authors prior to data archiving. Owing to a variety of factors, including imprecise orbit prediction and attitude control excursions, and the effect of these factors on the placement of the narrow field of view (3 km) of the narrow angle camera, intended targets were often missed. Hence the comment may not reflect the nature of features contained within the acquired image. In the PDS archive, images with the comment, “sample,” are mainly those that were acquired semi-randomly without specific human selection of the target (i.e., downlink “fillers”); some of these include twilight images when extra realtime downlink was available on the night side of the planet.

Cruise Operations

Owing to the hygroscopic nature of the formulation of composite/epoxy available at the time MOC was designed, MOC focus changes substantially when exposed to normal, humid atmosphere. In order to insure that MOC met its “dry” focus performance after experiencing the “wet” environment in Florida before launch, a bakeout heater was wrapped around the camera, under its multi-layered insulation blankets. During the cruise to Mars, this heater was used to dry the composite structure. Drawing 50 W, the heater raised the camera to temperatures in excess of 50°C (the tube was raised close to 80°C); power constraints during cruise required that bakeout occur during a few-month period mid-way to Mars.

Several weeks after launch, an attempt was made to observe the Earth/Moon system as a means of determining the post-launch state of alignment of the wide angle and narrow angle cameras, and the alignment of the cameras relative to the other instruments and the spacecraft attitude control system. Although the appropriate region of the celestial sphere was scanned, a multiple-degree error between the attitude control system and camera alignments prevented the narrow angle camera from imaging the Earth. WA observations confirmed that those cameras had maintained their pre-launch relationships, and comparison to TES observations (*Christensen and Pearl* [1997]) confirmed that the overall MOC structure had maintained its pre-launch alignment.

During cruise, observations were taken of the Pleiades star cluster to determine both focus and spatial orientation of the NA detector. Such observations involved scanning or “slewing” the spacecraft such that the 0.44° field-of-view (FOV) of the NA camera moved across the star cluster. This was repeated several times to offset the FOV in order to accommodate the apparent large discrepancy between spacecraft pointing and the camera. Each set of multiple slews was repeated with the camera focus heaters set to different values. As with a telescope or microscope, the intent was to move the focus from one side of best focus to the other, and then to return to the best focus position (Figure 4). These measurements indicated that, despite exposure to air of normal humidity prior to launch, the camera was relatively dry; a short bakeout was conducted in early 1997 during the C4 period of cruise.

Two sets of observations were made of Mars during cruise. The first, in early July 1997, was designed to provide support for the landing of the Mars Pathfinder spacecraft. Observations by Hubble Space Telescope (HST) in May 1997 had found a large dust storm moving through the Valles Marineris, and there were concerns that this storm might spread northward into the Pathfinder landing area. The MOC image, acquired on 2 July, although not as high resolution as that acquired by HST (MGS was, at the time 17 x10^6 km from Mars), clearly showed that the dust storm had remained within the confines of the Valles Marineris. Pathfinder successfully landed two days later.

A second set of observations of Mars were made in late August 1997, when MGS was approximately 5.5 million km from Mars and 24 days from Mars Orbit Insertion (MOI). Over the course of two days, eight views of Mars, taken on approximately 45° centers, were acquired. These views represented “contingency” science—insurance against catastrophic loss of the spacecraft during MOI. Although of relatively low spatial resolution (~20 km/pixel at nadir), these data provided an initial comparison of Mars with the nearly two-decades-old Viking observations, showing evidence of regional changes in albedo (Figure 5).

Pre-Mapping Operations

MOC, fixed rigidly to the body of MGSthe MGS spacecraft, can only look where the spacecraft points the side to which it is affixed. For the nominal mapping orbit, the camera views directly down toward the planet (nadir). During the pre-mapping period (i.e., the first year of operations), both nadir and non-nadir observations were acquired. When aerobraking, the spacecraft was maneuvered to protect the science payload from direct exposure to associated aerodynamic heating and forces. For most of each orbit, the spacecraft was oriented with its high-gain antenna pointed toward Earth, the solar panels pointed towards the sun, and the spacecraft spinning around the high-gain antenna's axis. This rotation was parallel to the orientation of the CCD line array. Since the camera can only image when motion is perpendicular to the array, images could not be acquired during most of each aerobraking orbit. However, after each periapsis pass the spacecraft transitioned from the aerobraking attitude to the Earth-oriented spinning attitude, and by careful spacecraft team planning this transition was accomplished by a rotation perpendicular to the detector. "Rollout" maneuvers were used to acquire images during AB-1, SPO-1, and SPO-2 (no images were obtained during AB-2). During SPO-1, additional observations were made with specially "targeted rollouts" that were designed at the request of NASA Headquarters and the Mars Surveyor Project to obtain narrow angle images of the Viking 1, Viking 2, Mars Pathfinder landing sites and selected massifs in the Cydonia region. Observations of the martian satellite, Phobos, were obtained during 4 passes in SPO-2 [*Thomas et al.,* 2000a]. Nadir-oriented observations were acquired during a brief two-week hiatus early in AB-1, during non-targeted orbits in SPO-1, and throughout SPO-2.

Ground tracks for all AB-1, SPO-1, and SPO-2 orbits upon which MOC images could be acquired were carefully inspected by the authors (and occasionally visiting MOC science team members). Red/blue wide angle images, nominally taken during each "rollout" (AB-1) or nadir-viewing (SPO-1, SPO-2) period, were commanded to be acquired over as much of the observable portion of Mars as possible. Other wide angle images and all narrow angle images acquired on these orbits were selected by careful review of each predicted orbital ground track, usually within a day or two of acquisition to ensure that the best possible predicted orbit was used. During the pre-mapping phase, emphasis in selecting MOC image targets was placed upon obtaining “contingency” observations in the event that the spacecraft or instrument did not survive the aerobraking events of either AB-1 or AB-2. Narrow angle images were chosen with the intent that they cover a range of geologic and geomorphic features and could be used to address the specific research topics and questions raised in the original MOC proposal of 1985 and described by *Malin et al.* [1992].

After Mars Orbit Insertion, periapsis of MGS orbit was initially at mid-northern latitudes, on the afternoon side of the planet, with the spacecraft moving from north to south. It was summer in the southern hemisphere at the time. These factors, combined with the restriction that imaging occurred after periapsis, focused MOC observations in the equatorial and mid-southerly latitudes during AB-1. A specially-delayed series of rollouts in December 1997 and January 1998 permitted observations in the south polar region—at reduced resolution—to support Mars Polar Lander landing site studies. During the course of the first year, periapsis migrated under the influence of the martian gravity field northward over the pole and continued southward toward the equator. At the same time, the local solar time of the orbit evolved westward (toward earlier times of day) as Mars (and MGSthe MGS spacecraft) revolved around the sun, and the season progressed from northern winter to spring. These effects combined to move the region visible to the camera northward and into the morning hemisphere. By the end of SPO-2 (September 23, 1998), the orbit was essentially parallel to the terminator, and observations were again possible in the late afternoon.

The evolution of illumination conditions had a substantial impact on the nature of the pre-mapping imaging data. Observations made during early AB-1 and mid-to-late SPO-2 were acquired at low sun elevation angles—ideal for morphological studies because of the highlighting and shadowing. Observations in late AB-1, SPO-1, and early-to-mid-SPO-2 were acquired at relatively high sun elevations; these observations mostly show albedo variations, and some morphology from photometric variations resulting from slope effects. A special set of AB-1 observations were collected in February 1998 to examine photometric effects at zero phase; the MGS spacecraft was directly between the sun and the martian surface during WA and NA observations collected on AB-1 orbits p130 through p137 (the camera had previously been turned off after p120 and been turned back on for these special observations).

Diurnal and seasonal meteorological effects also impact the quality of imaging. On Mars, fog, low-lying clouds, and thin hazes are common in the morning; afternoons are generally clear in the equatorial region except in areas around the large volcanoes in Tharsis and Elysium, and within the large canyons of the Valles Marineris. However, during some seasons afternoon cloudiness occurs throughout the equatorial region. AB-1 observations were mostly under afternoon conditions, SPO-1 in the late morning, and early- and mid- SPO-2 under mid- and early-morning conditions; as noted above, towards the end of SPO-2, observations were again possible in the late afternoon. Winter and early Spring in both hemispheres are typically cloudy (although the southern hemisphere is less so thanthe northern), with multiple layers of optically thick hazes—the polar “hood”—obscuring the surface from the poles to latitudes of 40°. Mid- to late-Spring is marked by the dissipation of the polar hood and the development of dust-storms along the margin of the retreating seasonal frost cap. The most intense dust storms develop during southern summer. A regional dust storm during AB-1 (southern summer) obscured portions of the planet for over a month, and the north polar hood (northern early to mid Spring) obscured much of the northern hemisphere during early SPO-2. The polar hoods and dust storm seasons in both hemispheres have subsequently been observed during the Mapping mission.

Mapping Operations

The Mapping orbit was achieved in February 1999, although the official Mapping phase of the mission began after the High Gain Antenna deployment in April 1999. Though nominally “circular,” the mapping orbit is slightly elliptical. The eccentricity was selected to provide a gravitational “lever arm” to limit variation in the orbit’s argument of periapsis. The mapping orbit's periapsis is "frozen" over the south polar region. Orbit altitudes periodically vary from about 350 km to as much as 420 km; the spacecraft moves south to north on the day-lit side, and crosses the equator around 2 o'clock in the local afternoon. With equatorial and tropical incidence angles around 30°, the final mapping orbit is less-than-ideal for high resolution imaging.

Four basic types of MOC images may be acquired on any given Mapping orbit: (A) daily global maps, which are typically 7.5 km/pixel-resolution swaths using both red and blue wide angle cameras to provide global weather and variable feature monitoring; (B) narrow angle images, typically 1.5 to 12 m/pixel, for geology, geomorphology, and variable feature monitoring; (C) context frames, typically 240 m/pixel red (and/or occasionally blue) wide angle frames which were acquired simultaneously with more than 50% of the narrow angle images to locate the high resolution view; and (D) selected red and/or blue wide angle images of resolution ranging from 240 to 960 m/pixel for regional monitoring of variable and seasonal features. As one of the primary objectives for the Mapping mission is to obtain daily global coverage (for atmospheric and seasonal surface monitoring) over an entire martian year, with few exceptions daily global maps are attempted on every orbit.

Other than the daily global images, each MOC picture requires individual planning. Using spacecraft and planet ephemerides (orbit prediction files) provided by MGS Project Navigation team and a model of the instrument pointing and spacecraft attitude (either nadir-oriented or the rollout pointing geometry and rate), custom software is used to predict the visible field-of-view and to project this prediction onto maps and images of Mars derived from Viking, Mariner 9, and previously-acquired MOC data. Through January 2001 and except during MOC calibration period in early March 1999, the Geodesy Campaign in May 1999, and the Science Campaign F in December 2000, every predicted MGS orbit was examined for imaging opportunities presented by the unique circumstances (ground track location, solar incidence angle, downlink periods and rates, and martian season) of each specific orbit. Many of the narrow angle and selected red/blue wide angle images represented "targets of opportunity" planned within

1–4 days of data acquisition. Other images were planned in advance of when they would be acquired—opportunities for these time-independent observations are identified by checking predicted MGS ground tracks against a database of desired images that were entered as far back as 1992. New time-independent imaging plans were created and added to the database throughout MGS mission, typically as new potential targets were identified in the on-going data analysis effort. Whenever possible, narrow angle images obtained during the Mapping phase of width < 2048 pixels were biased toward the higher-numbered pixels on the line array (i.e., a 1024-pixel-wide image would go from pixel 1024 to 2048 instead of 512 to 1536 or 0 to 1024) so that pixels on the array included the location of the MOLA ground track (i.e., sample 1560 ±50). Thus, the majority of MOC NA images are "MOLA compliant," allowing correlation of the two sets of data.

During the Calibration subphase in early March 1999, images used to adjust the NA camera focus were obtained by imaging stars (particularly, Beta 1, Omega 1 and Omega 2 Scorpius) and surface features at relatively high solar incidence angles (i.e., in this case, over the martian north polar region). Calibration subphase images also included wide angle and narrow angle stray light tests and flat-field observations acquired by rotating the spacecraft so that the motion was parallel to rather than perpendicular to the detector. Additionally, coverage of the sub-earth point on each orbit (near 15.6°N) and simultaneous Hubble Space Telescope Wide-Field Planetary Camera (WFPC) images were obtained to allow cross-calibration. The Fixed High Gain Antenna observing period began March 9, 1999, and ran through March 27, 1999. This period provided contingency observations against possible failure of the high gain antenna during deployment in early April 1999. Recognizing that MOC was, for the first time, focused and able to photograph Mars from nominal mapping orbit altitudes, we decided that the FHGA period would emphasize acquisition of full-resolution (1.5 m/pixel) narrow angle images that might be used to address the range of specific geologic and geomorphic questions for which the camera was designed (see objectives described in *Malin et al.* [1992]). The FHGA period also included acquisition of daily global maps at nearly twice the spatial resolution planned for nominal Mapping—i.e., 3.5 km/pixel instead of 7.5 km/pixel.

Mapping began after deployment of the High Gain Antenna in early April 1999. A problem developed with a gimbal on the High Gain Antenna in that same month, resulting in a ~12-day hiatus in operations, followed by a week of operations similar to those of the FHGA mode. The second month of the Mapping phase, M01, began with a return to nominal Mapping operations on May 6, 1999. During this month, the first MOC Science Campaign(Science Campaign A, was also known as the Geodesy Campaign) was conducted (*Caplinger and Malin* [2001])., There were five basic objectives during this period: (1) obtain full-resolution (240 m/pixel) red wide angle coverage of the entire illuminated hemisphere of Mars (70°S to 90°N), (2) obtain the same at an off-nadir angle to allow stereophotogrammetry of the planet (as a complement to the MGS Mars Orbiter Laser Altimeter data set), (3) obtain medium-resolution (~480 m/pixel) blue wide angle coverage to allow color mapping when used in conjunction with the red wide angle images, (4) continue acquisition of daily global coverage using at least the blue camera, and (5) acquire 3 km x 3 km, 12 m/pixel narrow angle samples of the planet's surface in an equal-area distributed pattern relative to latitude and longitude on the illuminated hemisphere of the planet.

Regular MOC operations resumed in early June 1999 after the Geodesy Campaign. In June 1999 a major effort began to provide narrow angle images within a latitude/longitude zone (72°–78°S and 170°–230°W) identified by the Mars Polar Lander team as their desired landing site. At first, these images were obtained in late winter twilight (prior to sunrise). In August 1999, the final and a back-up landing ellipse were selected by the Mars Polar Lander (MPL) project, and narrow angle imaging of these specific areas began in earnest. Meanwhile, potential equatorial landing sites for the Mars Surveyor 2001 lander (subsequently cancelled after the loss of MPL) were identified and photographed by MOC. Operations through 1999 emphasized observation of seasonal change (e.g., south polar frost retreat seen in wide angle and narrow angle images), continued acquisition of images to satisfy the original 1985 MOC science objectives, and imaging guided by the observations and on-going analysis of data by MOC team. One series of observations of seasonal polar frost retreat focused on acquisition of 12 m/pixel images forming a ring around the south pole at 87°S, the minimum latitude accessible to MOC on nominal nadir-pointed orbits. These “south polar ring” observations were repeated periodically through southern spring and summer in 1999 and early 2000. Occasional opportunities to acquire off-nadir images of terrain poleward of 87° were provided in 1999 and 2000 by MGS spacecraft slews designed for MOLA coverage at these latitudes. In August 1999, Science Campaign B obtained complete global color imaging (red/blue wide angle) from pole-to-pole at the time of the southern spring equinox. Science Campaign C was conducted in December 1999, at the time of southern summer solstice, with the main objective for MOC of completing Geodesy Campaign coverage for the high south polar latitudes—regions hidden in winter darkness during Science Campaign A.

Operations in September to early December 1999 also focused on support for MPL, including continued narrow angle imaging of the primary and back-up landing ellipses at increasing spatial resolutions (as the subsolar latitude moved further south during this period and illumination conditions permitted better signal-to-noise ratios). Wide angle imaging of the landing site was also obtained to monitor local weather (dust storms) and frost retreat.

Following the loss of Mars Polar Lander and the Deep Space 2 microprobes on December 3, 1999, MOC operations included two efforts to recover and/or find the lost landers. The first began immediately: using the combined capabilities of the Mars Relay radio receiver and the MOC buffer memory to listen for the DS-2 radio signals at specific times when MGS flew over the landing location, and commanding and listening for signals from MPL itself. The second support effort came in the form of off-nadir targeted narrow angle camera observations of the final landing ellipses computed by the navigation teams for MPL, in an effort to find evidence of the spacecraft’s fate. Both of these activities were conducted in December 1999 through February 2000. No convincing evidence for the lander or its parachute was found. The search for MPL also allowed several attempts to test the procedure via off-nadir imaging of the Mars Pathfinder and Viking 1 lander sites, and these areas were successfully photographed although the landers were too small to be distinguished in the 1.5 m/pixel images under northern winter 2 PM illumination and atmospheric conditions.

Operations beginning in February 2000 were at a much reduced data rate during the “Beta Supplement” phase designed to work-around the gimbal obstruction problem suffered by the High Gain Antenna. Approximately 70% fewer images were commanded and obtained in the February through January 2001 than during a similar-duration period at higher data rate. Imaging during this period concentrated on continued monitoring of south polar cap retreat, examination and mapping of the spatial extent of newly-discovered landforms (e.g., gullies attributed by *Malin and Edgett* [2000a] to recent water seepage), and the usual array of science objectives as described in the original 1985 proposal. The objectives of Science Campaign D (May 2000) were cloud-free, full-resolution wide angle coverage of the Hellas Basin, and filling in gaps in global stereoscopic coverage acquired during Campaign A. On June 21, 2000, MOC was turned off for a period of Solar Conjunction, in which Mars was behind the Sun relative to Earth. MOC operations resumed July 13, 2000. Campaign E occurred in September 2000 and was used to compile 500 m/pixel red wide angle and 1000 m/pixel blue wide angle coverage of the entire region poleward of 60° N. MOC NA focus was adjusted monthly based on the computed focus/temperature curve; it was checked against observations of the Pleiades star cluster in April and September 2000. A final science campaign, F, was conducted at northern summer solstice in December 2000; during this time a global color (red, blue WA) map (90°N to 56°S) was acquired at ~1.5 km/pixel scale, and a series of evenly-spaced NA samples (~5 m/pixel) were obtained.

SCIENCE OVERVIEW

Every Picture Tells a Story

We found very early in MGS mission that nearly every single MOC NA image can, in and of itself, tell a story about the nature of martian geomorphic and geologic history. To illustrate, we begin with image AB1-00406, one of the very first MOC pictures (Figure 6), obtained just a few days after MGS's successful orbit insertion. Image AB1-00406 covers a cratered, mare-ridged plain in Terra Sirenum near 30.8°S, 172.8°W. What is most striking is the appearance of the impact craters—some of them cast long, late-afternoon shadows across their floors, but others do not. Which craters cast big shadows and which do not appears to be uncorrelated with size: craters of all sizes fall into both categories. In the size range illustrated here (the largest crater has a diameter of about 3.2 km), craters without shadows are shallower than those with big shadows. The largest of the shallow craters exhibit small bedforms on their floors (*e.g.,* Figure 6d). The fact that some of the craters are deeper and do not have such bedforms (*e.g.,* Figure 6c) must indicate that the process by which certain craters became shallow (a) predates the formation of the deeper craters, and (b) involved a material that can create bedforms. It is a reasonable supposition, based upon the scale and relationships of these forms, that these materials were wind-transported. Eolian bedforms result from subaerial transport of granular material via saltation and traction, which on Mars (as on Earth) typically requires sand-sized grains [*Iversen and White*, 1982; *Edgett and Christensen*, 1994]. The interpretations that emerge from the geomorphic relationships seen in Figure 6 are as follows: (1) Some impact craters of diameters up to and including the largest in image AB1-00406 formed on a pre-existing ridged plains surface. (2) The formation of the initial crater population was accompanied or followed by a period in which sand-sized sediment was introduced to the area, presumably by wind. (3) As windblown sand passed across the ridged plains surface, some of this material became trapped within the craters, making these craters shallow. (4) Sand that was not trapped within craters eventually passed through (and left) the area shown in image AB1-00406. (5) Meteorite impacts that post-date the passage of the windblown sand formed craters that have remained deep (*i.e.,* those with long shadows). The sand transport period occurred roughly half-way back in this area's cratering history—about as many craters are deep as are shallow. The most interesting aspect of this story is the evidence for change: first permitting sand to enter and move through the area and later reflected in the end of the period in which sand was available. Modulation of a source of sediment is one of the hallmarks of environmental change.

Purpose and Goals

Mars has been known since Mariner 9 to be a world of diverse geologic features and landforms. The high resolution views provided by the MOC NA camera reveal a surface—and clues regarding the upper 1–10 km of the subsurface—that is more complex than previously known. Many surface patterns and textures seen at the scale of MOC NA images are common only to specific locations, regions, or latitudes. Indeed, we find that—owing to the unique textures, patterns, tones, and geomorphic expressions in each region—an experienced observer can often correctly estimate the geographic location (*e.g.*, Isidis Planitia, Pavonis Mons west flank, Cydonia Mensae, Hellas Planitia) of a MOC NA image without prior knowledge of the targeting of that image. Many of the observations answer old questions raised by Mariner 9 and Viking orbiter data analyses, while many other pictures raise new questions.

In this section, we provide a brief summary of selected observations that we have made through the end of the Mapping phase of the MGS mission. The purpose is to provide a “snapshot” that captures our thoughts at this mission milestone via overview of the observations we have found to be important because they answer pre-MGS questions, test pre-MGS hypotheses, and/or have emerged as a result of the MOC investigation as being interesting or potentially useful in further understanding the planet’s geologic history. The amount of text devoted to each topic generally reflects the amount of time we have spent in the past 3–4 years addressing these subjects; in some cases the text is brief, instead referring to more detailed work by the authors or other MOC investigators. The observations we present are a key to understanding how the MOC NA data were collected, because, in many hundreds of cases (e.g., discovery of gully landforms described by *Malin and Edgett* [2000a]), new observations had direct impact on the targeting of new pictures. To keep the paper brief relative to the volume of information MOC NA images have presented to us, we offer observations and hypotheses with little specific supporting detail, following the precedent of *Masursky*

[1973] in his overview of Mariner 9 results. While the ideas presented here certainly capture some of the range and depth of topics addressed by MOC and discussed by the authors during the Primary mission, it is likely that some of the hypotheses presented and conclusions drawn will not be borne out by subsequent, more detailed study. Readers interested in wide angle camera results should see papers regarding polar caps, dust storms, and the MOC Geodesy Campaign by *James et al.* [2000, 2001], *James and Cantor* [2001a, b], *Cantor* [2000], *Cantor et al.* [2001] and *Caplinger and Malin* [2001]. Initial results and observations from the SPO-2 Phobos imaging campaigns were described by *Thomas et al.* [2000a]. It is our hope that the observations presented here will stimulate and suggest a variety of new directions for further research.

Perspective and Procedure

Our perspective on MOC imaging results is based on experience that has come from working with MOC on a daily basis, as well as a pre-MGS perspective gained from the humbling process of working with terrestrial aerial photographs of scales comparable to those of MOC NA images. A common experience for geologists is to prepare for field work by examining aerial photographs of a site. One typically makes a sketch map that highlights geologic units and structures, and this preparation is used to efficiently guide the field work. However, geologists often find, upon entering the field, that some interpretations made using aerial photos (and other remote sensing data, where available) are basically wrong. Aerial photographs and other remote sensing observations are just the beginning of a geologic investigation; in the absence of field work—as is the case of MOC investigations of Mars—great care and humility must be exercised when interpreting the landforms evident in these pictures.

Our sense of being humbled by what is visible in MOC NA images also comes from having seen, very early in the mission during the AB-1, SPO-1 and SPO-2, that many of our Viking and Mariner 9-based preconceptions of Mars were simply wrong or lacked important detail. Our perspective on MOC images also comes from having examined nearly all of the >80,000images thus far acquired, and from careful inspection of each ground track relative to the U.S. Geological Survey's Mars Digital Image Mosaics (MDIMs) as part of target selection. It also comes from a continuous daily effort to examine each image received and relate that image to the intent of its target and its geomorphic and geologic setting, as well as almost-daily discussions between the authors as to what we are finding and learning as the mission unfolds. These discussions and examinations feed back into the targeting effort. Many of the issues we have seen emerge from the MOC investigation arise not only from the new MOC data, but also from the frequent inspection of the planet at lower resolution in previous Viking and Mariner 9 images. The opportunity to spend nearly every day for more than 3 years pouring over pre-MGS maps and data, as well as MGS observations, have contributed much to our understanding of the questions addressed and new questions raised by MOC.

Conventions

Tone and Albedo.

Throughout the discussions that follow, we use the terms "dark-toned" and "light-toned" to refer to the relative albedo of features seen in MOC NA images. MOC NA data are not sufficiently well-calibrated to provide a quantitative measure of albedo, and all of the grayscale images presented here have been contrast-enhanced to emphasize geologic and geomorphic detail. The term "albedo" is used in a similar relative sense, unless otherwise noted to have a quantity. For simplicity, all albedo quantities noted here come from published 2° x 2° near-global maps derived from Viking Infrared Thermal Mapper (IRTM) observations by *Pleskot and Miner* [1981] and *Christensen* [1988].

Particle Sizes.

Unless otherwise noted, particle sizes are described in terms of the standard *Wentworth* [1922] sedimentology scale. The exception to use of the Wentworth scale comes in the term, "dust," which in Mars scientific literature commonly refers to the very fine-grained materials capable of long-term transport via suspension in the modern martian atmosphere. Previous research has shown that martian dust particle sizes are < 10 µm and in most cases < 2 µm in size [*Pollack et al.,* 1995; *Tomasko et al.,* 1999].

Image Identification.

Unless otherwise noted, all MOC pictures shown in the figures should be understood to be sub-frames of the full image identified in the figure caption. MOC NA images are typically (though not always) too large and display too diverse of an array of features for the entire image to be shown in a printed publication. Some pictures are identified in the text by a number but are not shown in a figure, to save space. The reader should refer to MOC data archived within the Planetary Data System to see these images.

Surface Patterns and Properties

We begin with the general nature of the surface of Mars as it appears in images with scales between 1.5 and 12 m/pixel, with particular emphasis on its nature at the highest resolution of the majority of MOC NA pictures (1.5–6.0 m/pixel). MOC was designed to bridge the gap between what can be seen from a lander and what can be seen in pictures from previous orbiters and flyby spacecraft. A MOC NA image of the Mars Pathfinder landing site (Figure 7) shows that MOC has sufficient resolution to identify, from orbit, some of the larger rocks and features seen from a lander, but has insufficient resolution to see objects the size of the lander or smaller. The terrain surrounding the Mars Pathfinder landing site has a rippled texture that, as it is seen elsewhere in association with Ares and Tiu Valles (Figure 8), we attribute to deposition via the floods interpreted to have passed through the region [e.g., *Smith et al.,* 1997, *Ward et al.* 1999]. The Mars Pathfinder site provides one example of a martian surface texture; indeed, the planet exhibits thousands of variants on surface texture and pattern, too many to present in this paper. Instead, we discuss basic trends and observations, such as the nearly ubiquitous occurrence of mantling units and the latitude-dependent occurrences of rough-surfaced mantles. The observations are presented in the context of mantles, albedo patterns, and surface texture as defined at the hectometer and decameter scale. Patterns and textures common to polar latitudes—such as polygons—are discussed in a later section regarding polar regions.

Mantles and Latitude Relations.

As on Earth, much of the martian surface is covered by mantles. On Earth, such mantles typically consist of soil and Pleistocene glacial debris that lie atop much more ancient bedrock; on Mars, most of the surfaces are covered by a mantle that drapes all but the steepest topographic features. The martian materials are thought to have been emplaced by settling after transport via suspension in the atmosphere [e.g., *Christensen,* 1986; *Zimbelman and Greeley,* 1982; *Schaber,* 1982]—as occurs in the cases of airfall tephra and eolian loess on Earth. Mantling units are in many locations thick enough to have their own geomorphic expression: in equatorial regions their surfaces are smooth at the scale of MOC NA images, while at middle and higher latitudes they are often rugged and display a pit-and-knob appearance which we often term *scabby* (Figure 9). Middle and high latitude mantles, with their rugged, roughened appearance, often correlate with regions described by *Squyres and Carr* [1986] and *Squyres* [1989, pp. 256-269] from lower-resolution Viking orbiter images to be “softened terrain.” In many cases, the roughened surfaces in the southern and northern hemisphere are nearly identical in appearance (Figure 10). On poleward slopes at middle latitudes, it is common to find mantles that are pitted (Figure 11A), and/or extra-thick accumulations of material (Figures 11B, C). In Arabia Terra, both the smooth-surfaced and rough-surfaced mantles (Figure 9) correspond to areas of low thermal inertias derived from Viking Infrared Thermal Mapper (IRTM) data and interpreted by *Zimbelman and Kieffer* [1979] and *Christensen* [1986] to be regions covered by dust mantles at least ~2 cm thick. The two textures cannot be distinguished within the thermal observations, suggesting that both the smooth-surfaced and rough-surfaced mantles in Arabia Terra have a thin mantle of dust on them that obscures any thermal signature of the underlying materials. It is possible, if not likely, that the materials are essentially the same, and that the difference in surface expression reflects an additional process that has “roughened” the surface. The nature of this process is unknown but the development of pits (which suggests a volume change or differential removal of material), the preference for certain morphologies to occur on slopes with specific solar insulation relationships, and the correlation with middle latitudes, leads to speculation that volatiles were emplaced with the mantling dust and that devolatilization created the observed textures and patterns.

Mantles and Other Relations.

Mantled surfaces display a variety of albedos and colors; indeed the “bright red” surfaces of central Arabia Terra, the “dark red” surfaces of western Arabia Terra, and the “dark gray” surfaces of Terra Meridiani [see *Presley and Arvidson*, 1988; *Arvidson et al.*, 1989] are all found at the tops of thick (10s to 100s of meters), smooth-surfaced mantle units. Figure 12 shows examples of high and low albedo mantle surfaces in Arabia Terra and Sinus Sabaeus. As discussed by *Edgett and Malin* [2000a], dark mantle units were unanticipated by Viking and Mariner observations and may indicate the existance of fine-grained material that is dark-hued material and can be transported via eolian suspension (in addition to the typical light-hued “dust” considered by most investigators to be transported in modern dust storms). As predicted largely from low predawn temperatures observed by the Viking IRTMs [*Zimbelman and Kieffer,* 1979; *Zimbelman,* 1984; *Christensen,* 1986], the surfaces of the great Tharsis and Elysium volcanoes are also mantled, in some places to a thickness in excess of several meters. However, mantle thickness on the Tharsis volcanoes varies from place to place—for example the upper flanks of Ascraeus Mons are less-thickly covered than the lower flanks (e.g., MOC image M09-02155). Mantles in some places in Tharsis are so thick that they obscure all evidence of underlying lava flows, while in other places underlying flow morphology is visible and the mantles are grooved and scoured by wind, as shown by comparing the Mars “radar stealth” terrain west of Arsia Mons [*Muhleman et al.,* 1991, 1995; *Butler,* 1994; *Edgett et al.,* 1997, *Ivanov et al.,* 1998] with the smooth-surfaced, thick mantles at the lower northern flank of Pavonis Mons (Figure 13). Mantles in much of Tharsis exhibit grooves or other modifications. Images of the surfaces of mantles off the north flank of Ascraeus Mons appear “fuzzy” or “out-of-focus,” but in reality this is an optical illusion created by highly modified surface features (Figure 14).

Hectometer- and Decameter-scale Textures.

As part of a process to characterize terrains as a tool to be applied to selection of landings sites for the now-cancelled 2001 Mars Surveyor lander, we spent several months in 1999 acquiring data at or near full MOC NA resolution in a wide variety of terrains throughout the martian equatorial latitudes. One result of this effort was the observation that in more than ~70% cases in which a surface appeared to be a smooth plain at the hectometer-scale of a Viking or Mariner 9 orbiter image, that surface appeared to be quite rugged at the meter- and decameter-scale visible in MOC NA pictures (Figure 15A, B). This observation contrasts with the Moon, where mare-ridged plains surfaces appear relatively smooth at both hectometer and decameter scales. An opposite relationship was found to be true, as well—martian surfaces that are rugged at the hectometer scale tend, while retaining their rugged pattern at this scale, to be rather smooth at the meter and decameter scale (Figure 15C, D). Figure 16 shows a selected range of surfaces, from a very smooth, flat, mantled surface in east Terra Meridiani (which is an exception to the rule—it is smooth at hectometer as well as decameter scales) to very rugged, ridged surfaces composed of wind-eroded yardangs on plains and slopes adjacent to the Medusae Fossae Formation units of southern Amazonis and southeastern Elysium Planitia. Surfaces in the vicinity of the MPL landing site in the south polar layered terrains showed the same relationship—surfaces that appear to be relatively smooth at the hectometer scale are frequently found to be quite rugged at the decameter scale (Figure 17).

Albedo Patterns and Relations.

Time-variable albedo patterns on Mars have been attributed for centuries to everything from vegetation to windblown dust. As a result of Mariner 9 and Viking monochromatic and multi-color images and infrared observations, the most widely-held interpretation generally (though not exclusively) centered on the view that martian albedo patterns are controlled by the distribution of windblown dust and sand, and that darker surfaces would consist of darker sediments, regoliths, and rock exposures [e.g., *Sagan et al.,* 1973a; *Christensen,* 1988; *Arvidson et al.,* 1989]. Contributing to these views were observations that large eolian dune fields observed prior to MGS have some of the lowest albedos on the planet [e.g., *Thomas and Weitz,* 1989; *Edgett and Christensen*, 1994], while coatings of dust deposited on rocks during the Viking lander missions had higher albedo [*Guinness et al.,* 1982], consistent with those of the Arabia, Tharsis/Amazonis, and Elysium regions interpreted by IRTM investigators to be mantled by dust [*Christensen,* 1986]. MOC NA images show, as noted above, that some low albedo regions—particularly in Terra Meridiani and Sinus Sabaeus—are covered by mantles of material probably deposited from suspension and do not exhibit much evidence of windblown sand [*Edgett and Malin,* 2000a]. Other areas, such as the Memnonia/Mangala Valles region (Figure 18) and dark features in Arcadia Planitia have albedos governed by texture rather than by windblown surface materials (dunes, mantles). Still othe examples show that some albedo patterns, at least at local scales, are governed by underlying geologic units. This is true in places where surface materials have been stripped away and/or are derived directly from underlying “bedrock,” as seen, for example, with the interior layered units of the Valles Marineris chasms and intracrater units such as the “White Rock” feature in Pollack Crater (Figure 19).

Ridged Units.

One of the more puzzling aspects of the martian surface to emerge from the MOC investigation has been the plethora of surfaces with ridges or grooves that are too small to have been observed in previous spacecraft images. In particular we refer to a suite of such features that are contained within specific layers exposed at the martian surface that do not exhibit the typical “inverted boat hull” morphology of wind-sculpted yardangs and, at first glance, seem to resemble dunes or ripples, but in detail cannot be modern dunes. Figure 20 shows a collection of examples; these are found largely at equatorial latitudes but one (that may not be the same type of unit) is found in a portion of the south polar residual cap (Figure 20H). Most occurrences of the types of ridged units shown in Figure 20 are confined to specific geologic units with sharp boundaries that, in many cases, are steep cliffs a few to tens of meters high. They are nearly always exposed by erosion—usually draped unconformably upon underlying materials—in a sequence of two or more layered units. Many examples have lower albedos than surrounding terrain, but this is not always the case. Ridges are nearly always closely-spaced (a few 10s of meters) and apparent ridge heights and groove depths (which cannot be measured directly , are not seen in laser altimeter data, and thus can only be crudely estimated to be of the order of a few meters) are generally equal from one to the next. In some cases the continuous ridge-forms degenerate to smaller, aligned knobs along the unit margins. In many observed cases, the ridges and grooves appear to reflect local slopes (*e.g.,* buttes, buried craters). In some cases—especially in the Terra Meridiani hematite areas and on the floors of the Valles Marineris—there are superposed smooth layers and/or superadjacent mesas and buttes, indicating that in these locations the ridged units were formerly buried. The ridged units generally appear to be indurated and some retain impact craters (Figures 20D, E).

The relative importance of these ridged units is underscored by the fact that some of these materials correspond with the hematite-rich surfaces (Figure 20A) identified by the MGS Thermal Emission Spectrometer (TES) team in Terra Meridiani [*Christensen et al.,* 2000].

The origin of the ridged units is unknown; *Malin and Edgett* [2000b] grouped these among a class of possible sedimentary materials they termed “thin mesa-forming units”. It is possible, and maybe likely, that in Figure 20 we have lumped together features that share similar morphologic expression but have diverse origins; it is also possible that they involve materials of either similar or differing physical properties. Erosion and weathering along joints in the ridge-forming layer is one possible explanation; alternatively, the ridged units are paleobedforms originally formed by eolian saltation/traction and subsequently buried, indurated, and now in a state of being exposed to the surface again. Their exposure may result from eolian deflation or, if the south polar example is providing an important key, by sublimation of a volatile. Because most examples occur at equatorial latitudes, we tend to favor exposure via deflation, despite the fact that we see few near-by examples of the products of deflation.

Subsurface Patterns and Properties

MOC NA images offer considerable insight into the nature of the upper few kilometers of the martian crust. Nearly everywhere that the subsurface is exposed—in chasm walls, crater walls, mesas, buttes, and valleys—the upper crust is seen in MOC NA images to be layered. Layers, wherever they occur in the martian crust, mean that there is preserved a geologic record of changes that occurred on the planet at some time in the past. On Earth the observation of layers would not be a surprise, but the prevailing consensus (as described in models pertaining to the nature of the crust in papers such as *Carr* [1979, pp. 3000-3001], *Tanaka and Golombek* [1989, p. 386], *Davis and Golombek* [1990, pp. 14244-14245], and *Clifford* [1993, p. 10975]) prior to the MGS mission held that much of the martian crust, particularly in the ancient, heavily-cratered highlands, should be something like that of the lunar highlands—an upper kilometer or two of interbedded crater ejecta, lava flows, and perhaps sediments and soils, underlain by tens of kilometers of megabrecciated primordial crust, perhaps consisting of a uniform “basement” lithology as in the case of the lunar anorthosites. Layered materials were certainly known before MGS; indeed the larger light-toned mesas and mounds within the Valles Marineris chasms were recognized very early in Mariner 9 and Viking orbiter images as exhibiting evidence of layering [*Sharp,* 1973a; *McCauley,* 1978; *Blasius et al.,* 1977]. Other layers and layered materials were seen in the Medusae Fossae Formation units of west Tharsis and south Amazonis [*Scott and Tanaka*, 1982], in exposures seen in Kasei Valles [*Tanaka and Chapman*, 1992] and northern Terra Meridiani [*Schultz and Lutz*, 1988; *Edgett and Parker*, 1997]. Hints of bands or layers were also seen in the upper walls of the Valles Marineris chasms [*Sharp*, 1973a, Fig. 4b; *Malin*, 1976, Fig. 13; *Blasius et al*., 1977, p. 4079; *Lucchitta*, 1979, Fig. 2a], though at least one investigator advocated that these might be hardpan deposits (invoking a megaregolith model for the upper martian crust) rather than true rock layers [*Treiman et al*., 1995].

Valles Marineris Walls.

Early AB-1 images of the walls of the Valles Marineris chasms provided the initial MOC observations of layering (Figure 21), including realization that some layered units extend to depths as much as 10 km below the martian surface [*Malin et al*., 1998]. While the lead author has been an advocate for nearly a quarter century for a layered upper martian crust [*Malin*, 1976], both authors were surprised by the depth to which the layered crust was seen to extend; it certainly is layered to a substantially greater depth than prevailing models had portrayed [e.g., *Davis and Golombek*, 1990, Fig. 10]. Because the layered walls of the Valles Marineris chasms underlie extensive plains of "Hesperian" age [*Tanaka*, 1986], these materials were interpreted to be very ancient—early Hesperian and Noachian in age (i.e., dating to the earliest billion years of the planet's history) [*McEwen et al*., 1999]. The origin of the layered wall materials is not known. Several excellent examples of light-toned "lenses" of layered outcrops exposed in the Valles Marineris walls that are identical to those found in mounds and mesas in the chasm interiors have been identified [*Malin and Edgett*, 2000b]; Figures 22–24 show some of these examples, others, particularly in western Candor Chasma, were noted by *Malin and Edgett* [2000b] and/or occur in the walls and ridges of Coprates Chasma (e.g., Figure 24 and AB1-06306, M21-00693, M21-01589, M23-00469; M23-01361), Ius Chasma (e.g., M08-07173) and Ganges Chasma (Figure 22 and M23-00552). The outcrops in Figures 22–24 suggest that a complex and heterogeneous stratigraphy of interbedded impact craters, sediments, and lavas is preserved in the Valles Marineris walls. Early work with AB-1 images suggested to *McEwen et al*. [1999] that all of the wall rock could be the result of basaltic flood volcanism. We note, however, that there are few boulders at the base of Valles Marineris walls. This observation suggests that the boulders derived from layered materials do not have sufficient strength to survive descent down the colluvial aprons and scree slopes beneath the walls. *Malin and Edgett* [2000b] noted that where troughs or steep scarps (e.g., caldera walls) occur in volcanic terrain, there are usually boulders at the base of these slopes (e.g., Figure 25).In the rare cases where boulders are seen in the Valles Marineris, their emplacement appears to have been eased by rafting within or support by the head units or main bodies of extremely large landslides (e.g., in Ganges and Ius chasms) or, in the case of slopes at the southwest and west end of Ius Chasma and Noctis Labyrinthus, they appear from Viking photographs to be derived from clearly volcanic materials. The absence of boulders in the Valles Marineris troughs suggests that in general the wall materials are composed of fine-grained sedimentary rock or of extremely weathered and crumbly volcanic flows that break up into small clasts upon transport down the chasm wall slopes. It must be noted, however, that boulders may actually be present in greater numbers than seen if they are covered by the dark-toned mantles that are common on talus slopes and the floors of many of the chasms in this region [*Malin and Edgett*, 2000b].

Sedimentary Rock Units.

Light-toned mounds and mesas in the Valles Marineris chasms were recognized as layered from Mariner 9 images [*Sharp*, 1973a; *Malin*, 1976; *McCauley*, 1978]. However, some of the banding that was attributed to layering, such as the pattern of dark bands seen in the large mound in Ganges Chasma in Mariner 9 B-frame views (Figure 26A), is illusory. Figure 26 shows that the Ganges mound is indeed layered, but at a scale too fine to be observed in the Mariner 9 image. The dark bands are surficial accumulations of eroded, dark mantling material whose occurrence is guided by topographic variations in the underlying layered material (themselves likely to be controlled by variations in the layered rock). Other mounds and mesas similar to those found in the Valles Marineris were seen in Viking and some Mariner 9 images to occur in impact craters, particularly those of western Arabia Terra and a few isolated examples like Pollack Crater in Terra Sabaea and Gale Crater in Aeolis. Some features on the Gale Crater mound were interpreted as possible evidence of layering [*Cabrol et al.,* 1999], but those features do not correlate with the actual layers observed in MOC NA images [*Edgett and Malin*, 2001]. *Malin and Edgett* [2000b] presented a detailed treatment of light-toned layered and massive outcrops found in a variety of equatorial settings, including the chasms of the Valles Marineris, the chaotic terrain east of the Valles Marineris, the impact craters and intercrater terrain of northern Terra Meridiani and western Arabia Terra, northern

Hellas, and other examples found in craters around the planet. Figures 27 and 28 show examples of the types of layered and massive outcrops presented by *Malin and Edgett* [2000b], for which they described properties consistent with an origin via sedimentation (air fall or subaqueous deposition). A group of intercrater layers of this type are preserved beneath a large "pedestal" crater (craters whose ejecta appears raised above the surrounding terrain by eolian deflation of that terrain, where crater ejecta has served as an armor to protect underlying material from erosion [*McCauley*, 1973], *Barlow et al.* 2000) in Arabia Terra (Figure 29). This observation suggests that this portion of the martian highland intercrater plains also include these materials. The regularly repeated pattern of some of the layering implies episodic change, the cliff-forming nature of the materials implies they are indurated, and the presence of erosional unconformities between some layered units and the vertical change from one type of layering to another imply significant passage of time (presently not quantifiable) [*Malin and Edgett*, 2000b]. Outcrops in the Valles Marineris and chaotic terrains were interpreted to indicate the presence of formerly-buried impact craters that had been filled with layered materials, just as had the craters of western Arabia Terra and northern Terra Meridiani. Given their stratigraphic placement within the walls of the Valles Marineris, *Malin and Edgett* [2000b] inferred that all of these layered units must be extremely old, perhaps dating back to the “Noachian Period,” more than 3.5 billion years ago. *Malin and Edgett* [2000b] also noted that in some cases, such as in western Candor Chasma, northern Terra Meridiani, and Gale Crater, it is possible to identify in MOC images specific, true lithostratigraphic formations and begin to decipher their implied geologic history.

Cratered Highlands Crust.

Layered materials are not limited to the Valles Marineris and certain craters and plains discussed by *McEwen et al.* [1999] and *Malin and Edgett* [2000b]. Layers are ubiquitous on Mars, and we have seen with MOC that nearly everywhere that the subsurface of the martian cratered highlands are exposed, the upper crust is layered. Some of the early examples of martian cratered highland layer exposures from the AB-1 and SPO mission subphases are shown in Figure 30. Eroded and exposed martian cratered highlands materials were described on the basis of Viking images of northeastern Arabia Terra by *Moore* [1990], although at the time it appears that *Moore* [1990] did not recognize that the layers are a manifestation of the highland crust rather than an eroded mantle superposed on the highlands. Similarly, *Edgett and Parker* [1997] and *Christensen et al*. [2000] failed to make this distinction in the layered exposures of central and northern Terra Meridiani—again, we have seen in our analysis that these, too, are an integral part of the cratered highlands of Mars, not a material superposed on a pre-existing, lunar-like cratered terrain. *Malin* [1976] presented several examples—on the basis of Mariner 9 images—of craters that appeared to be partly exhumed from beneath scarps in several locations where the martian cratered highlands had been cut by faulting, mass wasting, and/or outflow channel formation. He used these observations to infer that the upper martian crust is best described not as a heavily-cratered surface, but as a heavily-cratered volume (shown in two dimensions in cartoon form in Figure 31). In this model, cratering and deposition of layered materials occurred on early Mars at the same time. In such locations, large crater rims might stick up through many layers of subsequently-deposited material, while younger craters of comparable age would be buried, others might be exhumed, and still others might be eroded away. Erosion, deposition, and cratering on early Mars would have all been happening at the same time, resulting in a complex interbedding of craters and previously-exposed surfaces. This model contrasted sharply with the prevailing view, which held that the martian cratered highlands were essentially like that of the Moon, and the surface we see today is the result of the imposition of erosion and deposition upon that cratered surface. For example, works such as *Craddock and Maxwell* [1990, 1993] and *Grant and Schultz* [1993] assume that the martian surface begins initially cratered and lunar-highlands-like, and is then eroded to its present configuration. This view neglects the possibility that the surface presently seen was itself once buried and later exhumed, or that much of the material deposited in large impact craters does not result from erosion of the neighboring terrain but from distant terrain now vanished, as is known to occur on Earth.

Burial and Exhumation.

The most striking characteristic of Mars that we have seen has been the evidence for substantial amounts of burial and subsequent exhumation of ancient surfaces, including large and small impact craters. As noted previously, some evidence for exhumation was described on the basis of Mariner 9 observations by *Malin* [1976], but this topic was not further explored following acquisition of Viking orbiter images. Our impression of vast amounts of exhumation come not only from MOC images, however, but also from daily examination of the Viking Orbiter image-based MDIMs. It is very difficult, for example, to imagine how Reull Vallis—seen in a Viking Orbiter view in Figure 32—cut through crater rims and massifs unless the valley, like the Susquehanna River cutting through the Appalachian Mountains of Pennsylvania, initially began cutting down through a material that once covered and buried these craters and massifs, but has subsequently been eroded away. It is likewise difficult to understand the complex relations between craters and mesas seen in Viking orbiter views of Noachis Terra (Figure 33) without supposing that large amounts of material have been removed to expose previously-buried landforms. Smaller, more localized examples of exhumation are common in MOC NA images. For example, it appears to us that many of the ridges and mounds with shallow summit depressions common across Isidis Planitia may be manifestations of exhumation in which the depressions on mounds and ridges represent the floors of former impact craters and pit chains that have become elevated as surrounding material was removed (presumably via eolian deflation). Figure 34 notes several examples of craters in states of exhumation from beneath mounds and mesas on Isidis Planitia.

Exhumation in martian cratered terrain on a grand scale is common in northeastern Arabia Terra, as noted by *Moore* [1990]; it is also prevalent in western Arabia Terra/northern Terra Meridiani as hinted by *Presley* [1986], *Schultz and Lutz* [1988], and *Edgett and Parker* [1997]. Additonal examples of features interpreted to imply exhumation are abundant on the martian surface. *Malin and Edgett* [2000b; Fig. 11] advocate that entire 100–200 km-diameter impact basins such as Trouvelot, Gale, and

Henry may have once been completely buried and have subsequently undergone extensive exhumation. Here we present two small, simple cases to illustrate the point that burial and exhumation attests to a complex geologic history for Mars. The abundance of buried and exhumed surfaces complicates issues in establishing relative and absolute age for surfaces on Mars using impact crater counts; this topic is addressed in a later section.

Figure 35A provides context for the first example; it shows the location of a MOC NA view of the floor and wall of a trough that trends east-southeast down the eastern slope of the Elysium rise. This trough is one of several "volcano-tectonic depressions" that surround the Elysium rise. Although the western troughs are often considered to have been the source of, and partly shaped by, some an erosive fluid (alternatively lahars or fluvial outflows [*Mouginis-Mark*, 1985; *Christiansen*, 1989; *De Hon*, 1992]), those to the east do not display similar erosional landforms and instead taper downslope to a thin fracture or graben. Figure 35B shows an example of the wall and floor of this valley. Note that the wall exhibits many layers expressed as rocky ledges, as well as smooth-surfaced mantles. The floor exhibits many crater-forms, including two relatively-large, degraded, raised-rim craters that are only partly-exposed from beneath the wall. The larger one is nearly 1 km in diameter, the smaller is closer to 500 m in diameter (Figure 35B, E). Also of interest are the many smaller craters (Figure 35D) found on the valley floor. Similarly-sized craters on the plains surrounding the valley are less abundant and heavily mantled (Figure 35C). Clearly, it is difficult to establish that a crater is exhumed. A crater immediately subjacent to a cliff but uncovered could have formed after the wall. A young crater whose rim is partly buried could have formed close enough to the superjacent cliff to permit talus to cover a portion of the crater. And debris from a superjacent cliff will more than likely completely hide a crater if the cliff transects the crater. Despite the low probability of finding craters being exhumed from beneath cliffs, several dozen candidates, including the two identified here (Figure 35), have been seen in MOC images.

The second example comes from the floor of Trouvelot Crater. Figure 36 includes a mosaic of three MOC NA images that traverse across a light-toned wind-eroded mound in south-central Trouvelot. The light-toned material appears to be a remnant of a formerly more-extensive unit that once covered a cratered surface that today includes several “pedestal” craters. Small outliers of light-toned material occur up to ~10 km from the main mass of light material (Figure 36C), and similar light-toned outcrops occur on the lower southern crater wall (Figure 36E). The presence of outliers and outcrops on the crater wall indicate that the light-toned unit was once more extensive. Figure 36D shows a pedestal crater emergent from beneath the light-toned material. The scarp bounding the crater’s pedestal appears to be sharp and distinct as it emerges from beneath the light-toned unit, suggesting that the deflation that created the pedestal occurred before the light-toned material was emplaced. In other words, there was once a cratered surface on the floor of Trouvelot. Wind eroded the upper few meters of this surface, leaving behind the pedestal craters seen in MOC images. Then, these pedestal craters and all of the adjacent cratered and pitted surface was covered by the light-toned material. Later still, the light-toned material was eroded away, leaving only the remnants we see today. Given these observations, it should be apparent that, because the cratered surface beneath the mound spent some time buried, crater counting would not provide a reliable estimate of the surface’s age.

Eolian Processes and Landforms

Eolian processes affect much of the uppermost surface of Mars. Thus, any area seen by the MOC NA has the potential to have been influenced by eolian erosion (deposition and/or removal). In this section, we briefly review some of the observations made with MOC images regarding eolian processes and landforms. Papers by *Malin et al*. [1998], *Thomas et al*. [1999], and *Edgett and Malin* [2000a] also discussed eolian features observed by MOC. Eolian bedforms result from subaerial transport of granular material via saltation and traction, which on Mars (as on Earth) typically requires sand-sized grains [*Iversen and White*, 1982; *Edgett and Christensen*, 1994]. For purposes of discussion, we divide eolian bedforms into two basic categories: dunes, which in MOC images (as in Viking and Mariner 9 images) are always dark-toned; and ripples or ripple-like bedforms, which are abundant and in some cases may be similar to the “granule ripples” of *Sharp* [1963] and “megaripples” of *Greeley and Iversen* [1985, p. 154]. Terrestrial eolian granule and megaripples are typically composed of granules and sometimes very fine to fine pebbles.

Bedform Relative Albedo.

Nearly all eolian bedforms known prior to MGS were low albedo (< 0.15) dunes [*Cutts and Smith*, 1973; *Thomas and Weitz*, 1989]. A few examples of ripple-like bedforms found in troughs, depressions, and on some plains were known from the highest resolution Viking orbiter images [*Peterfreund*, 1985; *Zimbelman*, 1987; *Edgett*, 1997]. These forms typically had albedos indistinguishable from the surrounding terrain. *Edgett and Parker* [1998] characterized bedforms on the basis of their brightness relative to adjacent terrain such that a bedform or field of dunes is either darker than, brighter than, or has the same relative albedo as its surroundings. From the very first orbits of the Aerobrake-1 subphase (Figure 6), MOC NA images revealed nearly ubiquitous occurrences of ripple-like bedforms (Figure 37). Although there are some exceptions (Figure 37C), these bedforms are almost always lighter than or have the same albedo as the surrounding terrain, whereas larger dunes—in most cases closely resembling typical sand dunes found on Earth—are almost always darker than the surrounding terrain unless covered by seasonal frost. No examples of bright, or light-toned, large eolian dunes have been found after three years in orbit. In many locations where small, light-toned bedforms and large, dark-toned dunes occur together, the dark dunes superpose the smaller, brighter features (Figure 38). This superposition relationship indicates that, at least in these specific cases, the dark dune material is more mobile than the material in the lighter-toned bedforms, perhaps because the latter material is indurated or coarser-grained. The distinguishing characteristics of bright and dark bedforms, both in terms of albedo and morphology, probably indicates that there is something fundamentally different about the composition, sorting, and particle sizes of materials that comprise the two.

Dune Morphology and Activity.

Deposits of low-albedo sand come in a range of sizes and shapes from broad, flat sand sheets [*Breed et al.*, 1987]to complex dunes in topographically-confined spaces such as impact crater floors (Figure 39). Most dunes reflect a dominant unidirectional wind. In such cases, following the definitions of *McKee* [1979], the dunes exhibit barchan or similar transverse morphologies, although in many cases the slip faces are low and occasionally narrow, the stoss broad, and distance between horns is large relative to terrestrial counterparts (possibly a reflection of differing saltation path length in lower gravity and thinner atmosphere). In other cases, barchan horns are seen in a state of extension, becoming linear, or seif, dunes downwind (Figure 39E). Extension of barchan horns to create linear "seif" dunes was an idea proposed by *Bagnold* [1941] that seems to be borne out on Mars. MOC NA images show that dune morphologies indicative of multi-directional wind regimes, such as seif dunes and more complex, star-like forms, are most common in topographically-confined areas, as noted previously on the basis of sparse Viking observations by *Edgett and Blumberg* [1994] and *Lee and Thomas* [1995].

Comparisons of dune fields observed by MOC with those observed by the Viking and Mariner 9 orbiters as much as 10–14 martian years earlier show no evidence of dune migration during this period. Of course, this observation is limited by the resolution of the earlier Viking and Mariner images, and typically means that a given dune cannot have moved more than 1 pixel—usually 40–100 m—during that time. Figure 40 illustrates an example from western Arabia Terra; *Edgett and Malin* [2000a] and *Zimbelman* [2000] described additional examples. Further, no large scale motion of, for example, dune crests or outline perimeter, has been evident in the few locales which MOC has been able to re-image after as much as three-quarters of a martian year. MOC pictures, however, do provide abundant evidence that material is moving on the dunes in the modern environment: some dunes have sharp brinks at the top of their slip faces, and exhibit streaks that run downslope, indicating recent avalanching (Figure 41). Still other dunes, especially those within southern hemisphere high latitude impact craters, have rounded brinks and rounded or smoothed surfaces suggestive of erosion or mass loss followed by relative inactivity (Figure 39B). Still others, such as those in Herschel Basin (Figure 42), exhibit grooved surfaces which suggest that the sand is moderately indurated, and subject to erosion by grain release and eolian scour.

Ripple-like Bedforms.

The lighter-toned bedforms on Mars are smaller than the dark dunes and dune fields. They are very common, and are most often found in depressions (e.g., troughs, shallow pits and craters). Not all such ripple-like bedforms are light-toned—some have the same albedo as surrounding terrain (usually indicating that they are mantled by the same material covering the surroundings), and some are dark-toned (Figure 37C). Ripple-like bedforms are found on the flanks (and in some cases the calderae) of the Tharsis volcanoes (Figure 43), indicating that eolian processes have occurred at high elevations and presumably lower than average atmospheric pressures. Several different ripple-like forms can be distinguished on Mars, some of which are undoubtedly eolian ripples because they resemble terrestrial granule ripples and occur on larger eolian dunes (Figure 44). Figure 45 shows other examples of ripples and ripple-like bedforms as seen on the floor of Auqakuh Vallis and amid mounds on Isidis Planitia. The features in Figure 45 are typically very narrow in their transverse dimension (the assumed direction of motion), with essentially symmetric lee- and stoss- slopes. Where they occur in troughs, they are perpendicular to the trough trend. Where they encounter obstacles, their pattern appears to refract around or between the obstacles. Smaller bedforms exhibit smaller wavelengths, larger bedforms exhibit larger wavelengths. Unfortunately, it is not possible to uniquely attribute all light-toned ripple-like forms to eolian processes, as there are other ridge patterns on Mars (as described in the preceding section about surface properties) that resemble ripple-like bedforms but are instead likely the expression of an erosional property of the material (Figure 20).

Paleo-bedforms.

One of the original objectives of MOC when it was proposed in 1985 was to determine whether there are paleo-bedforms on Mars which, like cross-bedded sandstones on Earth, might provide insight into past environments. While some dunes, as in Figure 42, appear to be moderately indurated and subject to eolian erosion, others appear to be cratered and much more strongly indurated. Figure 46 shows an example of a large field of crescentic dunes that is heavily cratered and may be emerging from beneath the yardang-forming material to the immediate north. Other examples of paleo-bedforms center on smaller, ripple-like features such as those seen in Figure 47. In these examples, some of the bedforms are superposed by impact craters, and some are only partly exhumed from beneath a mantle that formed after the bedforms were in place.

Wind Streaks.

Wind streaks are typically linear albedo features that extend and taper downwind from a relatively compact topographic obstacle such as a hill or impact crater [e.g., *Greeley et al.,* 1974a,b, *Thomas et al.,* 1981]. As with Viking and Mariner 9 observations, MOC images exhibit a wide variety of wind streak patterns, morphologies, and configurations, including streaks formed by deflation of intracrater or intratrough material and in the lee of obstacles [*Edgett and Malin*, 2000a, c]. As known from Mariner 9 and Viking, some wind streaks are ephemeral features, while others are persistent, at least over decades. Figure 48 shows an example of ephemeral wind streaks that formed sometime between July, 1998 and August 2000; Figure 49 shows a wind streak associated with an impact crater in Daedalia Planum that is essentially a long-term feature, with differences in geomorphology exhibited on the surrounding plains (ridged-and-grooved surfaces) relative to the streak interior (smoother surface distinguished by the absence of the ridged-and-grooved material). Wind streaks have been used for three decades to infer atmospheric circulation at the martian surface/atmosphere interface, which has then been compared with the results of general circulation models [*Sagan et al.,* 1973a; *Thomas,* 1982, *Greeley et al.,* 1993]. *Thomas et al*. [1979] identified streaks comprised of seasonal frost associated with atmospheric circulation during spring retreat of the south polar cap; similar streaks have been seen in MOC wide angle images in the north polar region (Figure 50). In addition, we have seen streaks form on frost surfaces; Figure 51 shows an example observed at a high southern latitude during the spring retreat of the seasonal frost cap in late 1999. Many similar streaks were observed. It is unclear whether the streaks in Figure 51 represent a material superposed upon the brighter frost, or if they are caused by erosion down into the frost cover. In either case, the streaks provide excellent indicators of local, topographically-influenced wind patterns. When areas in which such streaks are completely defrosted, the streaks are no longer apparent (Figure 52), suggesting they are the result of processes directly linked to the distribution/redistribution of seasonal frost or the underlying surface.

Dust Devils and Streaks.

Thousands of MOC NA images show numerous dark, thin (a few meters to several tens of meters wide) streaks that usually—though not always—exhibit no preferred orientation and typically are found crossing each other and over a range of terrain and surfaces. Such streaks are found nearly everywhere from the summit caldera of Olympus Mons (e.g., M12-01922) to the floor of Hellas Basin (e.g., M11-02348) to high polar latitudes including the site selected for the 1999 Mars Polar Lander (M12-00223). Figures 53A and 53B show typical examples of mid-latitude low albedo plains in both the northern and southern hemispheres. These plains appear to owe their low albedo to the presence of abundant, crisscrossing dark streaks. Figure 53C shows streaks in Syria Planum that are lighter than their surrounding terrain; light streaks are not as common as dark ones. Streaks are not confined to a specific type of surface or landform, although many occur on dunes or other small ripple-like bedforms (e.g., Figures 53D, E). Some streaks cross contacts between very different material units, as in Figure 53F where dark streaks cross the boundary between a dark dune (right) and brighter plain (left). Some of the streaks form curly loops (Figure 53G). When we first began to see these streaks (e.g., Arabia Terra image SP1-26403), we suspected that they reflected surface disruption and disturbance caused by the passage of wind vortices (the visible apparitions of which are dust devils). Dust devils had been observed in Viking orbiter images [*Thomas and Gierasch*, 1985] and interpreted to have been observed at the Viking and Mars Pathfinder landing sites [*Ryan and Lucich*, 1983; *Schofield et al*., 1997*; Metzger et al*., 1999]. Late in 1999, a few MOC NA images revealed examples in which dust devils were actually found at one end of several dark streaks (Figures 53H, I). Dozens of additional examples were seen at middle south latitudes during early southern summer in January–March 2000. However, not all dust devils observed by the MOC NA or WA cameras were seen to be creating streaks (Figure 54). Multiple observations of the same locations on Mars have shown that streak patterns change considerably over short time intervals; for example Figure 55 shows a completely different pattern at the same location in less than 1 martian year, and Figure 56 shows a case where dark filamentary streaks completely disappeared after a 0.18 Mars-year interval. The ephemeral nature of the filamentary streaks suggests that they involve a very thin veneer of dust at the upper surface—perhaps a veneer only a few microns thick. Dark filamentary streaks were recognized in Mariner 9 images [*Veverka*, 1976], although some of them, such as those south of the Proctor Crater dune field described by *Grant and Schultz* [1987], turn out to be relatively permanent features denoting a boundary between surfaces of differing texture and landform distribution rather than ephemeral streaks formed by wind vortices (Figure 57).

Wind Erosion.

Erosion via removal of material by wind has probably played a major role in shaping the martian landscape, including the exhumation of previously buried surfaces. For example, early in the Mariner 9 data analysis phase it was recognized that some impact craters seemed to have ejecta deposits that are raised relative to the surrounding terrain [*McCauley*, 1973; *Arvidson et al.,* 1976]. Many of these pedestal craters are found on the northern plains, but in MOC images these turn out to be so heavily mantled such that the actual relationship to the pre-mantled plains is not seen. However, many other examples of pedestal craters are found in terrain where deflation has occurred; Figures 36 and 58 show several examples. To form a pedestal crater, it was proposed that the boulders and cobbles of a crater’s ejecta formed an armor that protected the material beneath the ejecta from deflation; one example in which a crater's ejecta consists of boulders large enough to be seen by MOC has been found (Figure 58B).

Yardangs are a commonly-recognized positive relief feature created by wind erosion in arid regions on Earth as well as on Mars [*McCauley et al*., 1977; *Ward*, 1979]. MOC NA images reveal many yardang ridges, usually in places that they were already known from Viking and Mariner 9 orbiter images (e.g., the southern Amazonis Medusae Fossae Formation units of *Scott and Tanaka* [1982, 1986]). Because they form largely by grain-release and subsequent entrainment at the surface-atmosphere interface, their presence is an excellent indicator of the physical properties of the eroded material—they usually consist of weakly-indurated (at least at the surface) particulate materials dominated by sand-sized grains (62.5–2000 µm). Early MOC observations of yardangs in the Medusae Fossae region were described by *Malin et al*. [1998]. In the case of the Medusae Fossae Formation units, the most surprising result is the abundance of small yardangs superposed on cratered uplands and outflow channel valleys of the Mangala Valles/Memnonia region (Figure 59), indicating the former extent of the Medusae Fossae units. However, still more surprising is the suite of meter- to decameter-scale features formed in the thick mantles covering much of the Tharsis region. Figure 60 shows some examples of the variety of wind-erosion features in Tharsis, including grooved mantles (or mantled grooves) over lava flows in western Daedalia Planum (Figure 60A), pits developed around boulders in Mangala Valles (Figure 60B), and triangular accumulations or remnants of eroded material on the lee sides of obstacles on the slopes of Olympus Mons (Figure 60C) and Ceraunius Tholus (Figure 60D).

Polar Processes and Landforms

The regions beneath the martian north and south polar caps were known from Mariner 9 and Viking orbiter images to exhibit layering. Layers had been exposed on scarps and in trough walls, and it was argued shortly after the Mariner 9 mission that these layers must represent episodic or cyclic variations in martian climate over time, as reflected in layer thickness and sedimentary properties [*Murray et al*., 1972; *Soderblom et al*., 1973a; *Cutts*, 1973]. Attempts were made to correlate layers with variations in insolation resulting from changes in Mars' orbital relationships [*Blasius et al*., 1982; *Cutts and Lewis*, 1982]. Supporting evidence came from the limited available observations of layer thickness—for example, assuming that a martian global dust storm contributes a 100 µm-thick layer of dust to the polar cap each year, a layer about 10 m thick would develop in the approximately 100,000 years of each martian obliquity and eccentricity cycle. Direct measurement of layer thickness was not possible with Viking or Mariner 9 images, but the cumulative thickness of several tens of layers approaches 1 km, with the average thickness thus computed to be about 10 to 30 m. The general "order of magnitude" similarity between the global dust storm estimates and computed thickness for each layer was generally taken as evidence favoring dust storm modulation by astronomical variations as the principal mechanism for layer formation. An important test of these ideas was described in the 1985 MOC proposal—determine whether there are more and smaller layers in the polar cap terrain. If such layers exist, then they would require significant revision of the then-present models for polar cap layer formation and implications for past martian climate. One of the earliest MOC narrow angle camera results for the polar caps was, indeed, the identification of many more and smaller layers than could be inferred from Mariner 9 and Viking images (e.g., Figure 61). This particular observation implies climate-induced control over erosion and deposition patterns on time scales much less than the 10^5 and 10^6 year-periods attributed to martian obliquity variations.

North vs. South Residual Caps.

MOC images generally show that the north and south polar caps and associated terrain are quite different from each other at the meter to decameter scale. These differences are likely, though not certain, to indicate differences in depositional, erosional, and climate history between the two poles over long periods of time (perhaps millions of years). *Thomas et al.* [2000b] described initial observations of differences between the north and south residual caps at MOC NA scales. The two residual polar caps differ greatly from each other and from the rest of the martian surface as seen at MOC scale. The most striking texture is the “slices of swiss cheese”-like pattern exhibited on a large portion of the south polar residual cap (Figure 62A). No surfaces elsewhere on Mars have this pattern of circular depressions and sags among arcuate-scarped mesas. The north residual cap, by contrast, is largely flat at the hectometer scale and exhibits abundant decameter-scale pits (Figure 62B) or rugged buttes (e.g., M00-02476). The south polar cap surfaces do not have the pits or buttes seen in the north, nor does the north polar cap have any of the “swiss cheese” features seen in the south. In both cases, shadow-length measurements indicate that the pits, mesas, and buttes have only of a few meters relief relative to their surroundings. The “swiss cheese” layers of the south polar cap are long-term features, not ephemeral or seasonal landforms—in summer, this terrain was observed in a state of defrosting such that the arcuate scarps, some of them exhibiting layers within them (Figure 63) were darkened relative to their wintertime appearances (Figure 64). Thickness of seasonal frost that was deposited on the “swiss cheese” terrain can only have been in the range of a few meters or less, because the relief on the arcuate scarps that bound the mesas and “swiss cheese holes” appeared to be qualitatively constant (to within the limits of MOC spatial resolution) between winter and summer. MOC NA observations of the north polar residual cap received early in the second summer at the end of the Primary Mission likewise indicated that the residual cap frost cover is relatively thin and the pitted morphology of the cap is expressed in a darker, more permanent substrate (e.g., images M22-02253, M23-01651). The origin of the different forms of pitting is not known. The north polar morphology resembles pits seen in more temperate latitudes, and it is tempting to invoke differential devolatilization of subliming ices as the primary mode of origin. The "swiss cheese" terrain of the south polar region is harder to explain. One intriguing idea arises from noting the generally circularly-symmetric planimetric form of the pits, the abundance of disturbed regions at the center of each pit, and the concentric ridges within the depressions: these are attributes that are reminiscent of diapirism. A speculative possibility is that lower density, buried water ice is rising diapirically through carbon dioxide ice or mixtures of such ice and dust.

North vs. South Dark Lanes and Layers.

The layered units that surround and occur within and beneath each polar cap (and which are more extensive in the southern hemisphere) also exhibit differing expressions between north and south. In the north, equatorward slopes exhibit banding and ridge-and-trough morphology indicating layers of material of differing thickness, albedo, and resistance to erosion. Poleward slopes are generally mantled and featureless, showing no obvious layering or banding (Figure 65A). Many dark lanes in the south, which are equatorward scarps, are stair-stepped features within which relatively thin layers in upper and lower units bound a layer that erodes to form rugged, thick, ledges approximately half-way up the scarp (Figures 65B, 66). Layered outcrops in both hemispheres exhibit considerable evidence of diverse physical properties. For example, layers that are expressed as ridges must consist of material that is more resistant to erosion than the material in the troughs between the ridges. There is no clear reason why there is an apparent hemispheric difference in layered outcrop expression. Several alternatives can be posited: (1) the composition of the layers may be different between the two poles, (2) the mechanism by which the layers form may be different, (3) the mechanism by which the layers are exposed may be different, or (4) the environments under which the layers form or are exposed may be different. A similar list of alternatives applies to differences between the expression of the “dark lanes” and of the residual cap surfaces as well.

South Polar Layered Terrain.

As has been recognized since the time of Mariner 9, the south polar layered terrain extends far beyond the boundaries of the residual cap. *Murray et al.* [1972] divided south polar layered terrain into two types: pitted plains and laminated terrain; today the terrain is usually referred to as “polar layered deposits”. The layers expressed in these terrains are not fresh outcrops. In all cases (hundreds of images), the outcrops appear to have been covered by materials of thicknesses in the range of one to ten meters.

These mantles are often cracked or gullied, with some cracks displaying a radiating, “spidery” pattern (Figure 67A). Other south polar layer surfaces (usually mantled) have a relatively smooth texture at decameter scales (Figure 67B), while most have rough and rugged surface (Figure 67C). Low albedo dunes are superposed on layered terrain surfaces in many locations (e.g., Figure 67D); their presence indicates that—despite the region’s low thermal inertia which implies a mantle of unconsolidated dust [*Paige and Keegan*, 1994]—the layers and/or the mantles that cover them form a hard substrate across which sand can saltate.

Polar Layer Bedding Properties.

The polar layered materials exhibit many of the bedding characteristics of terrestrial sedimentary rock, including lateral continuity over hundreds of kilometers, vertical stratigraphic sequences with clearly-defined “formations” and marker beds, erosional unconformities, and beds exhibiting different degrees of resistance to erosion. Figure 61, in addition to exhibiting many and smaller layers that detected by Viking and Mariner 9, also shows layers of differing slope expression—some layers form ledges, while others are recessed back into the outcrop. These observations indicate differences in layer properties as expressed in erosional style. Although these variations may reflect composition, it is unknown whether these expressions indicate variations in the ratio of silicate to ice in each layer (it is not clear that the layers even contain ice or silicates). Figure 68 shows three MOC NA images spread out over ~100 km distance in single north polar trough—each exhibits a similar stratigraphy as indicated by a very noticeable, ledge-forming bed and repeated groupings of layers above and below that bed. This "marker bed" is also found in other troughs and outcrops and will perhaps be useful in north polar layered terrain regional stratigraphic correlation. The two images in Figure 69, located on relatively steep escarpments more than 280 km apart, display similar stratigraphic sequences including a jumbled, platy-looking lower unit overlain by a lighter-toned thick, flat-lying, evenly-bedded unit. Possible deformed beds and erosional unconformities are also seen in the polar layer outcrops; examples are shown in Figures 70 and 71. Despite evidence for deformation of polar layers, we have seen no surficial evidence for flow (glacial or otherwise) of polar materials.

Seasonal Frost on Polar Dunes.

James et al. [2000, 2001] and *James and Cantor* [2001] detail observations of martian polar cap seasonal retreat as observed by the MOC wide angle cameras. Hundreds of narrow angle images were also acquired with the intent to provide observations on the patterns of seasonal frost formation and retreat. It appears that, in general, sand (certainly as expressed in dunes, and potentially in sheets or intermixed with other particle sizes) controls both the initial location of frost formation during autumn and winter, and defrosting during the spring. Dunes are the first surfaces to frost in autumn and the first to show evidence of defrosting during the late-winter/early-spring. Despite starting to defrost early, frost may persist on dunes long after surrounding terrains have defrosted in late spring and early summer. Indeed, it has been known since Viking that some south polar dunes retain frost well into summer. Figure 72 shows representative examples of autumn frost formation (left) and late winter defrosting (middle/right). The process of frost formation has not been captured in MOC images—repeat coverage is very sparse and frost may simply appear one day relative to the previous. Defrosting, however, follows a pattern that may persist throughout spring and into summer. Defrosting proceeds from the initiation of small, dark spots typically located at the margins of the dunes or dune field (Figure 72B, C); these spots gradually enlarge, others are generated, and eventually all coalesce (Figure 73). The pattern the enlargement follows is distinct and characteristic: a dark nuclear spot enlarges slowly, often with a bright outer zone or “halo”. Initially, the areal enlargement of the dark spot and the areal enlargement of the bright halo appear linked, suggesting that the bright material is frost created as newly-released vapor moves outward from the warmer dark interior and freezes as it contacts the colder air and ground surrounding the dark spot. After some point in time, the spot develops two distinct zones—a darker interior and an intermediate (“gray”) exterior—while the brighter outer zone narrows until it is no longer present. These are progressive, centripetal phenomena: each location of the light zone is overtaken by the expanding dark zone. Although initially developed along the dune margins, spot formation quickly spreads onto and between dunes. As spring progresses, fan-shaped tails develop from the central spot. These tails initially demonstrate strong directional elements, wherein many spots display one or more streaks of identical orientation and relative length. An example of frosted dunes with such streaks and spots is shown in Figure 74; these streaks are attributed to wind re-distribution of dark material, although whether this dark material is dune sand or a manifestation of coarsened seasonal frost is unknown. It is not clear what attributes of martian dunes are contributing to the observed patterns of frosting and defrosting. It is possible that the thermophysical properties of the sand are contributors, it is possible that the dunes “breathe” water vapor that contributes to frost formation, and is also possible that the microstructure of dune surfaces (rough at 100 µm scales) contributes to formation and persistence of frost. Preliminary examination of TES temperature observations for the dunes in Richardson Crater (Figure 73) between June 1999 (L_s 150°) and August 2000 (L_s 36°) shows that the dune field was at frozen CO_2 temperatures (148 K) in late winter, rose through spring to reach frozen H_2O temperatures (273 K) in early summer, and fell again to frozen CO_2 temperatures in early autumn. The period of spot formation and coalescence corresponded to the period when temperatures were rising between 148 K and 273 K [*Supulver et al.*, 2001].

Interannual Variability of Frost Patterns—South Polar Cap

Other, non-dune surfaces also exhibit a pattern of spot formation and coalescence that leads to eventual defrosting of each seasonal polar cap. The first three years in Mars orbit offered our first opportunity to observe interannual variations in defrosting patterns on south polar surfaces. During AB-1 several opportunities arose in December 1997 and January 1998 to conduct high south latitude imaging. One feature photographed during this time was a rectilinear ridged landform known from Mariner 9 images by the informal name, “Inca City,” located at 81.5°S, 64.7°W. The initial MOC image of these features, AB1-07908, was acquired in late Spring at L_s 247°. Opportunities to photograph the Inca City ridges did not occur again until the landforms were illuminated in late winter in July 1999. Figure 75 compares several views of Inca

City as seen in the December 1997 AB-1 image and later Mapping images from July and August 1999. As only a small fraction of the area imaged during AB-1 could be re-imaged at the higher resolution of the Mapping mission, overlapping coverage is limited to small areas. Comparison of these areas shows that the pattern of defrosting (i.e., the dark spots) is reproduced from year to year. However, it is also clear from these examples that the defrosting began to occur a full 70° of L_s earlier in 1999 than in 1997, equivalent to 5 months. Several other areas deep within the seasonal south polar frost cap in 1999 showed similar early defrosting patterns relative to the limited coverage of AB-1. In contrast to these views of the interior of the seasonal frost cap, inspection of the margin of polar frost in wide angle images showed that retreat of the cap edge was essentially the same in 1997 and 1999 [*James et al.*, 2001]. The fact that local areas within the frost cap showed large differences from year to year, but the polar cap margin did not, suggests that local dynamic processes (e.g., local meteorology such as variations in wind speed and direction) may have contributed substantially to heat transport over and within the cap. Essentially, something either imparted the equivalent of 70° of L_s -worth of insolation (if the defrosting is controlled by spring processes) or engendered a deficit of frost deposited in the preceding winter. The Inca City landforms were imaged repeatedly throughout the remaining spring and summer in 1999 and 2000. These latter images will be compared with the subsequent corresponding seasons in 2001 and 2002 if images are obtained during these periods.

Interannual Variability of Frost Patterns—North Polar Cap

Although the retreat of the extended seasonal frost caps in both hemispheres has in general followed closely the recession rate and geometry seen from Earth and from previous Mars-orbiting spacecraft, some variations in that retreat are indeed seen both in detail and especially during the late stages of the retreat. As MGS began its second Mars years of coverage from the mapping orbit, these variations have become increasingly obvious. For example, Figure 76 shows evidence of changes in the configuration of the residual north polar cap as seen exactly 1 Mars year apart at L_s=103.5°. Indeed, some of these changes were detected more than 20° of L_s earlier than shown in this comparison. Some of the locations where changes occurred (in one case, frost was more extensive than it was a Mars year earlier; in three other places, the frost was less extensive) appeared to be correlated with color changes associated with dust storms [*James and Cantor*, 2001b]; in other areas, this correlation is not as clear. What is surprising about both the interior and marginal interannual variations in frost cover is the magnitude of the differences in L_s between comparable configurations. The 70° of L_s difference in frost relationships seen in the "Inca City" example, and the nearly 90° of L_s seen in the north polar cap example, represent substantial amounts of latent heat. Where this heat is going, where it is coming from, how it is transported, and why it manifests itself in the manner observed, remain unanswered questions.

Volcanic Landforms

Volcanism has played an important role in the evolution of the martian surface. Indeed some MOC science team members recently discussed whether volcanism has played a larger role, and in some cases a more recent role, than previously considered [*McEwen et al*., 1999; *Hartmann et al*., 1999; *Hartmann and Berman*, 2000], and interpretation of Thermal Emission Spectrometer has led the TES team to conclude that, with minor but important exceptions, essentially all of Mars has volcanic rock mineralogical composition [*Bandfield et al*., 2000; *Christensen et al*., 2001]. Volcanism that formed constructs around central vents and plains from fissures can be readily discriminated in Mariner 9 and Viking images [e.g., *Carr*, 1973; *Greeley*, 1973; *Carr et al*., 1977a; *Greeley and Spudis*, 1981], and numerous detailed studies of these landforms have been conducted [e.g., *Malin*, 1977; *Mouginis-Mark*, 1981; *Schaber*, 1982; *Zimbelman*, 1984; *Crown and Greeley*, 1993, *Plescia*, 1994, *Wilson and Head*, 1994; *Crumpler et al.,* 1996]. Discussion of martian volcanism in the years since Mariner 9 has focused on five basic themes: (1) large and small central edifices and associated flows, tectonics, and other landforms; (2) ridged plains, such as Lunae Planum and Hesperia Planum, denoting the "Hesperian Period" of martian history; (3) other, younger plains including Cerberus/Elysium, Amazonis, and the northern plains; (4) putative small volcanoes and cones in the cratered highlands west/southwest of Tharsis, along graben northeast of Tharsis, and along the north-south dichotomy boundary (among other places); and (5) evidence for and against voluminous tephra deposits, including the Medusae Fossae Formation, the surfaces of Hecates Tholus and Alba Patera, and elsewhere. Discussions have ranged from the nature, evolution, and loci of volcanism over time, to the specific emplacement mechanisms, rheology, and compositions of specific flows in Tharsis and Elysium [e.g., *Greeley and Spudis*, 1981; *Zimbelman*, 1984; *Greeley and Crown*, 1990; *Mouginis-Mark and Yoshioka*, 1998; *Peitersen and Crown*, 1999].

Hundreds of MOC NA images have been acquired to address questions of martian volcanism. Of paramount interest when MOC was first proposed was the utility of MOC images for morphometric measurements of flow surfaces (e.g., pressure ridge spacing, levee width, etc.) to estimate physical properties such as rheology during emplacement [e.g., *Zimbelman*, 1985]. While images have been obtained to address questions of flow morphology and eruptive properties, the authors have not studied this topic in any detail during the past three years, in part because so much of the volcanics are covered by mantles. Also of interest when MOC was proposed was the question of volcano age and timing of the most recent volcanism. This topic has received considerable attention using MOC images by *Hartmann et al*. [1999] and *Hartmann and Berman* [2000]. For the authors, five areas of observations have dominated our perspectives regarding MOC NA images of volcanic terrain: (1) the search for distinct lava flows on unmantled portions of many of the martian volcanic edifices, (2) observations of large platy and ridged plains-forming flows, (3) observations of channels clearly related to the Tharsis volcanics but of uncertain (volcanic vs. fluvial) origins, (4) burial and exhumation of most volcanic surfaces, and (5) questions centered on the topic of recent volcanism. The first three themes emphasize the fluid nature of flows during emplacement on the martian surface, the latter two emphasize the difficulty in using MOC images to decipher martian volcanic history. MOC has also acquired images of many small features interpreted to be volcanic edifices on the basis of earlier Viking and Mariner 9 images; some examples of these are presented here as well.

Flows on Large Volcanoes.

The upper and middle flanks of some of the larger volcanoes, particularly Olympus Mons, Elysium Mons, Arsia Mons, and Pavonis Mons, exhibit few discreet lava flows relative to their great surface areas. Smaller Tharsis volcanoes like Biblis Patera and Ceraunius Tholus also lack distinct flows. On Olympus Mons, most of the upper and middle flanks are dominated by leveed channels and ridged/troughed textures reminiscent of leveed channels but which cannot be traced far enough to attribute to specific flows (Figure 77). Lower volcano flanks, on Olympus Mons and elsewhere, do however exhibit some flow morphologies and, at least locally, leveed channels are common (Figure 78). A few flows are seen on the uppermost west flank of Olympus Mons (Figure 79) and the upper flanks of Ascraeus Mons (Figure 80). Caldera floors are typically cratered and lack flows. The caldera floor of Ceraunius Tholus has abundant rimless pits suggestive of collapse rather than impact cratering (Figure 81) but these features are rare among the martian volcanoes. The general relations observed on the large Tharsis shields suggest that typical lavas were erupted in a state too fluid to form distinct flow margins and terminal lobes until they cooled as they reached the lower shield flanks.

Platy Plains Lavas.

As suggested by *Plescia* [1990] on the basis of Viking orbiter images, the plains of southeastern Elysium Planitia, south Cerberus, and parts of adjacent Marte Valles appear to have been covered by plains-forming lava (Figure 82). The surfaces of these plains include multiple-kilometer-sized, occasionally-rotated plates separated by sinuous ridges; platy flow surfaces are found in parts of northern and eastern Tharsis (e.g., M08-00917, M13-00826, M13-01307), northeast of Lycus Sulci (the Olympus Mons aureole; e.g., M13-01796, M16-01117, M17-00275), in Amazonis Planitia (Figure 83); and on the floors of the deepest channels in Kasei Valles (Figure 84), although ascribing the Kasei Valles surfaces to be volcanic flows is less certain. Flows in Cerberus/Elysium and Marte Valles correspond to surfaces of high radar reflection identified by *Harmon et al*. [1992]. *Keszthelyi et al*. [2000] provided an initial analysis of the platy-ridged flow surfaces in the Cerberus/Marte Valles region; they concluded that these are mafic flood lavas formed at relatively high eruption rates and emplaced in two modes--by insulated sheet flow and by sudden, flood-like breakouts.

Channels and Valleys in Tharsis.

Mouginis-Mark [1990] identified groups of shallow outflow channel-like valley systems in Tharsis, including a one located immediately southeast of Olympus Mons and a second group associated with the Olympica Fossae south of Alba Patera (Figure 85). MOC NA images of these valley systems show a range of complex geomorphic relations, including valleys that appear—as *Mouginis-Mark* [1990] suggested—to have been conduits for flow of a low-viscosity fluid. The images southeast of Olympus Mons (e.g. Figure 85A) show flows emanating from these channels; further study will be needed to determine whether these flows consist of mud or lava. The images of the Olympica Fossae suggest the largest, deepest valley system to be largely formed by collapse. What fluids played a role in these valleys, and whether lavas were sufficiently fluid to have been involved in their creation (as with valley/channel systems on Venus [e.g., *Baker et al*., 1992]) is unknown.

Burial and Exhumation.

As noted in a previous section on mantling (Figures 13, 14), most large volcanic edifices and much of the volcanic terrain of Tharsis and Elysium, are thickly mantled. In some places, these mantles have been eroded into grooves and wind tails (Figures 13, 60). The mantles are thicker in some locations than in others. Mantling of volcanic surfaces has also obscured the primary morphology of flows and valley networks on the flanks of Alba Patera (Figure 86); the presence of these mantles make it nearly impossible to address the genesis of the small valleys on the volcano flanks. There are also volcanic surfaces that appear to have been exhumed. This is particularly true of Apollinaris Patera, upon which small pedestal craters and yardangs composed of the previous volcano-covering material are found (Figure 87) and of the platy flow surfaces of southeastern Elysium Planitia (Figure 88A). Similar platy-flow surfaces appear to be in a state of exhumation all along the margins of the Medusae Fossae Formation terrain of southern Amazonis (Figure 88B).

Recent Volcanism.

One question that has persisted since the first volcanic landforms were identified in Mariner 9 images has been that of the age of the most recent volcanism on the planet. Crater counts indicated that the large Tharsis shields were among the youngest volcanic landforms, with the last central vent activity perhaps occurring at Olympus Mons or Ascraeus Mons [e.g., *Blasius*, 1976; *Crumpler and Aubele*, 1978; *Plescia and Saunders*, 1979]. The presumed-volcanic plains of Amazonis [*Scott and Tanaka*, 1986] and interpreted volcanic plains south of Cerberus [*Plescia*, 1990] were considered to be as young or younger than the most recent volcanic landforms in Tharsis. Finally, dark patches in the Valles Marineris troughs were interpreted by *Lucchitta* [1987a] as possible evidence for recent martian volcanism in the form of pyroclastic eruptions. *Hartmann et al.* [1999]; *Hartmann* [1999], and *Hartmann and Berman* [2000] have investigated crater count-derived ages for volcanic surfaces that were considered to be relatively young, and concluded that the floor of the Arsia Mons caldera is no older than 40–130 Ma; they arrive at ages in the 10–100 Ma range for the platy plains south of Cerberus. Volcanism as recent at 10 Ma implies that the planet may remain capable of volcanic activity today. However, we strongly caution that Figure 88 and other MOC images (e.g., M07-05459, M08-02320, M19-00718) along the contact between the platy lava plains south of Cerberus and the ridged/grooved yardang surfaces immediately south of these plains indicates that the platy plains—interpreted to be young by *Hartmann and Bermann* [2000]—are exhumed surfaces and thus may be considerably older than these authors have proposed. With regard to possible recent mafic volcanism in the Valles Marineris—proposed by *Lucchitta* [1987a]—we have found no clear evidence of any form of volcanism that may have occurred in the Valles Marineris at any time since the chasms opened [*Malin and Edgett,* 2000b]. Figure 89 shows an example used to test that hypothesis. In most cases, the dark spots identified by *Lucchitta* [1987a] are either low-albedo, thin mesas or mantles (discussed in an earlier section) that are seen to cover many surfaces in the Valles Marineris [*Malin and Edgett,* 2000b, Figs. 5, 12], or patches of dark windblown sand.

Small Volcanoes.

A variety of small (~a few to a few tens of kilometers) rises with summit depressions were identified in Viking orbiter images as possible small volcanoes [e.g., *Scott*, 1982; *Hodges and Moore*, 1994]. MOC NA images of some of these features have been acquired. Examples include a small volcano in Tempe Terra (Figure 90A) described by *Hodges and Moore* [1994, p. 63], a mound near the summit of Pavonis Mons proposed by *Wood* [1979, p. 2827] as a possible cinder cone (Figure 90B), and a landform in Terra Cimmeria proposed by *Greeley and Spudis* [1978, Fig. 3) as a possible “Noachian volcano” (Figure 90C). In all three of these examples, the surfaces are mantled; the origin of the mound on Pavonis Mons (Figure 90B) and the rise in Terra Cimmeria (Figure 90C) cannot be uniquely determined. Images of many other small features proposed as possible volcanoes have been acquired, for example the pitted-summit mounds in Isidis Planitia have been proposed by some as possible volcanoes [*Frey and Jarosewich,* 1982] but we have found no evidence for volcanism in Isidis (for example see Figure 34). Other proposed volcanoes, such as the cones identified by *Lucchitta* [1990, Fig. 6c] in the Valles Marineris, have not been over-flown by MOC during the first 3 years of operations. Finally, it has long been supposed that a chain of small shield volcanoes might cross the floor of the Arsia Mons caldera [e.g., *Carr et al*., 1977a; *Zimbelman and Edgett*, 1992]—Figure 91 shows an example confirmed by MOC.

Valleys

Outflow channels and valley networks are often-cited as key evidence that past martian environments were considerably different from those of the present. Since their initial discovery in Mariner 9 images, these two suites of landforms have been largely, though not exclusively, attributed to formation by fluvial processes [e.g., *Milton*, 1973; *Baker*, 1982; *Sharp and Malin*, 1975; *Mars Channel Working Group*, 1983, *Carr*, 1996]. Thousands of MOC NA images have been devoted to documenting the nature of valley networks and outflow channel surfaces at high spatial resolution. In addition, MOC NA imaging has resulted in the discovery of a new class of gullies seen typically on poleward slopes at mid-latitudes [*Malin and Edgett*, 2000a].

Outflow Channels.

The large martian outflow channels, particularly the circum-Chryse valleys, received considerable attention and discussion in the years immediately following their discovery in Mariner 9 images [*Milton*, 1973; *Baker and Milton*, 1974; *Sharp and Malin*, 1975], continued to be of high interest through analyses of Viking orbiter images [e.g., *Carr*, 1979; *Baker and Kochel*, 1979; *Baker*, 1979, 1982; *Lucchitta*, 1982; *Robinson and Tanaka*, 1990; *Tanaka and Chapman*, 1992; *Rotto and Tanaka*, 1995; *Moore et al.*, 1995], and again in the years leading up to and including the Mars Pathfinder landing in the Ares/Tiu Vallis region [e.g., *Golombek et al.*, 1997; *Komatsu and Baker*, 1997; *Tanaka*, 1997, 1999; *Parker and Rice*, 1997; *Chapman and Kargel*, 1999]. A goal of MOC when it was proposed was to image boulders in the outflow channels, to allow quantitative evaluation of fluvial models for their formation and discharge (e.g., as was done with boulders observed at the Mars Pathfinder site [*Smith et al.*, 1997]). Examination of the size and spatial distributions of debris (in the form of large boulders) in outflow channel floors, banks, and deposits was expected to help distinguish between models for outflow channel formation by catastrophic flood, debris flow, ice, etc. [*Malin et al.*, 1992, pp. 7701-7702]. However, as noted in Figure 7, very few boulders relative to the number of clasts seen from the perspective of a lander can actually be identified in MOC NA images. Figure 92 shows another example from a “bar” in Ares Vallis—this is a surface that should have abundant boulders, but only a few are visible in a full-resolution MOC image. This pattern holds throughout the circum-Chryse region; the Mars Pathfinder image (Figure 7) provides a primary clue—the clasts (which we know are present at the Mars Pathfinder site in lander images), if present at all, are too small to be seen at the highest MOC resolution (~1.5 m/pixel) under the mid-afternoon near-equatorial illumination (and seasonal cloud) conditions of the region. Other outflow channels present additional problems. For example, the primary valley floors of most of the Mangala Valles system are covered with a later material that has been subsequently eroded by wind to create sharp ridge-and-grooved yardang patterns (Figure 59).

MOC NA images do, however, reveal new information about outflow channels. First, the Chryse and southern Acidalia plains north of the “mouths” of Tiu, Simud, and Ares Valles have a rippled texture (Figures 8A, 93). This pattern is present at the Mars Pathfinder landing site (Figure 7) and was attributed by *Greeley et al*. [1999, 2000] to eolian processes. However, the ripples in the MOC image of the Mars Pathfinder site correlate with the undulatory pattern visible from the lander [e.g., *Smith et al.*, 1997] and is a pattern confined to specific topographic channels (Figure 8). This ripple pattern is not, however, seen in the main channels where they cut through the Xanthe and Lunae Planum highlands—Figure 93B shows an example of the floor of Ares Valles south of the Chryse plain. Indeed, this surface exhibits no obvious fluvial patterns at all. It is not clear what these two disparate observations mean: perhaps these valley surfaces were once subjected to outflow channel-forming erosion but the evidence has subsequently been removed by other processes (e.g., eolian deflation). Alternatively, the valleys we see headward of the contact between the Chryse basin and the Xanthe uplands may not have formed purely by outflow processes. Finally, the Kasei Valles exhibit landforms that suggest later activity in at least this one outflow valley system. Found between the ridges of a “longitudinal groove” set near 15°–19°N, 76°–78°W, are lobate flows with knobby or bouldery surfaces (Figure 94); in the case shown in Figure 94C, the margins of the flows also appear to have retreated from their greatest extension. These features are interpreted to be mudflows rather than lava flows, with the backward retreat of the flow margin attributed to the removal of fines (and/or volatiles) from the flow matrix. These flows in Kasei Valles are not found in the other outflow channels (although some features in Marte Valles—e.g., M00-02492—might be mudflows rather than lava flows) and appear to be of limited areal and longitudinal extent.

Valley Networks.

Since their discovery in Mariner 9 images [*McCauley et al*., 1972; *Milton*, 1973], “runoff channels” [*Sharp and Malin*, 1975], or, more properly, “martian valley networks”

[*Pieri*, 1976, 1980; *Mars Channel Working Group*, 1983] have been almost universally cited as the best evidence that the martian environment was once capable of supporting the flow of liquid water across its surface. Unlike the outflow channels, which appear to result from relatively brief, catastrophic releases of fluid from localized sources, valley networks often display arborescent patterns, sinuosity and occasional meanders that imply processes of overland flow, drainage basin development and sustained surficial transport of fluid. The origins of these valleys have remained controversial: surface runoff and incision or entrenchment, and groundwater processes (sapping), are the two leading models. Advocates of the former view point to ramified network patterns, relief-controlled head locations, and circum-basin arrangements (centripetal drainage patterns) [*Masursky*, 1973; *Milton*, 1973; *Sagan et al.*, 1973b; *Craddock and Maxwell*, 1990; *Gulick and Baker*, 1990]; proponents of the latter interpretation note the strong structural control, occasional absence of true integration, box-heads, and the absence at Mariner 9 and Viking orbiter image resolution of dissection of the surrounding upland surface [*Sharp and Malin*, 1975; *Pieri*, 1976, 1980; *Laity and Malin*, 1985; *Kochel and Piper*, 1986; *Grant*, 2000]. In MOC NA images, valley networks generally appear to have been subject to considerable modification since they formed—their floors are often obscured by ripple-like bedforms and mantles, and their walls have retreated as a result of mass wasting [*Malin et al.*, 1998]. Initial MOC NA results on valley networks were summarized by *Malin and Carr* [1999] and *Carr and Malin* [2000], including observation of structural control for some valleys; here we present a few additional observations on the topic.

AB-1 MOC NA observations of martian valley networks, and indeed of all martian surfaces, led to the early recognition of the absence of smaller valleys contributory to the larger valley networks [*Malin et al.*, 1998; *Malin and Carr*, 1999]. This simple observation, long anticipated for MOC [*Malin et al.*, 1992, p. 7702], seems to favor the groundwater/sapping model for valley network formation over a surface runoff model. It was argued that precipitation would have led to runoff in small valleys that merge to larger and larger valleys. *Malin and Carr* [1999] presented evidence in the form of an inner channel that argued that there may have been sustained fluid flow in Nanedi Valles, as seen in Figure 95. *Carr and Malin* [2000] further explored the implication of the possible sustained flow in Nanedi Valles and indeed used the term “river” to describe what the valley may once have been like. However we here advocate extreme caution regarding the interpretation of the channel in Nanedi Valles. Within the AB-1 image shown in Figure 95 is, perhaps, the best evidence found of sustained fluid flow on Mars—the small, inner channel seen at the north (top) end of the image. However, little additional evidence has been found of this inner channel in the many branches of the Nanedi system. Although the canyon floor is covered by wind-blown sediment, this material is not sufficiently thick to completely bury all but the single exposure of the inner channel. The absence of attendant features (such as inner benches or terraces) in any of the other reaches of Nanedi imaged in the past three years further differentiates this reach from the rest of the system.

Inner channels within other valley networks are extremely rare. In several thousand images of valley networks, only two other examples have been clearly identified. The first occurs in the valley that most visually resembles Nanedi (displaying, for example, a pattern reminiscent of large-scale meanders): Nirgal Vallis. Two features are seen interior to the walls of Nirgal in a few limited locations (Figure 96): paired, broad terraces extending from the walls toward the center of the valley and defining a flat-floored channel between them, and a smaller, sharply-defined interior channel with what appear to be raised, leveed banks. The inner channel of Nanedi Valles (Figure 95) also seems to exhibit levees. The second example is seen in a nameless valley near 35.9°S, 155.3°W that exhibits an intra-valley channel system including streamlined forms (Figure 97). This example may be the best evidence to date for sustained flow in a system that is more typical of martian valley networks than are the Nanedi and Nirgal valleys. The evidence for sustained flow in Nirgal, Nanedi, and the valley in Figure 97, and its virtual absence nearly everywhere else, suggests that sustained flow was extremely rare on Mars during the time represented by the present surface expressions of valley networks.

Arguably the best or at least most-often cited example of an arborescent, “Earth-like” valley network on Mars is the Warrego Valles system (Figure 98A) [e.g., *Masursky et al*., 1977, Fig. 9c; *Clifford et al*., 1988, Fig. 1]. Earlier Viking images and now MGS MOC views (e.g., Figure 98B) raise serious questions concerning the interpretation of these valleys as a result of surficial drainage. First, these valleys are not through-going, but rather consist of transected, elongate, occasionally isolated depressions (tributary valleys are usually not physically connected to main trunk valleys). Second, mass movements appear to have played a role in both extending and widening the valleys. Third, the valley walls are extremely subdued, reflecting either mantling or collapse. Taken together, the attributes of the Warrego Valles suggest that collapse may have played a dominant role in their formation. Alternatively, the valleys were once buried and now are partly exhumed, giving the impression of discontinuity and collapse.

Groundwater follows topographic gradients nearly as effectively as surface water. The principal issue is whether the apparent contributory pattern of surficial water can be produced solely by groundwater, or if groundwater processes mimic pre-existing tributary patterns. If the former is possible, then martian valley networks may require little or no surficial flow. Even if it is not, the relationships seen in MOC images suggest that few, if any, surfaces preserve the evidence of surficial fluid flow—these features may have been removed or buried. The intriguing possibility remains that most valley networks we see at the surface of Mars today are exhumed or partly-exhumed. This latter conclusion would be consistent, for example, with the fact that the Nanedi Valles seem to appear, full-born, at their southern ends, then terminate abruptly at close to their maximum width and depth, at their northern ends, with no evidence of depositional features and no geomorphic expression farther down-gradient.

Gullies.

MOC NA images have revealed a third class of landforms that appear to result from fluid flow on martian slopes. As initially reported by *Malin and Edgett* [2000a], these gullies seem to have formed via release of a fluid at the intersection between a layered bedrock outcrop and a steep crater or valley wall located at middle and high martian latitudes. Figure 99 shows a typical example with its main geomorphic attributes labeled: the head alcove appears to form by mass-wasting of material from above the location where a fluid has seeped or otherwise been liberated from within a slope; a channel, in some cases with meanders, banks, inner channels, and levees, runs down the slope from the apex of the alcove (point from which fluid has seeped); and an apron of debris transported down the slope via processes of both mass-wasting and fluid transport, found at the base of each slope. *Malin and Edgett* [2000a] noted there is a range of configurations for alcoves, channels, and aprons, but all share some common features—they are found over twice as often on pole-facing slopes (those slopes that currently spend most of the martian year in shadow) than on equator-facing slopes, they are found in both martian hemispheres between latitudes 30° and 70° (they are more common in the southern hemisphere, possibly because there are more craters and troughs at these latitudes than in the north), and they are usually found in regional clusters (Figure 100).

The gullies and associated landforms appear to be the youngest geomorphic features in most places where they occur—aprons are superposed on surrounding terrain, including eolian dunes (Figure 101), channels cut surrounding terrain, and of several hundred examples found, extremely few (<1%) examples of superposed impact craters have been found (e.g., cratered aprons in image M23-00984 is the leading exception). Figures 102–104 display additional examples of these geologically-young martian landforms. *Malin and Edgett* [2000a] proposed that the gullies represent sites of geologically-recent seepage and surface runoff of liquid water, primarily because water is the most geochemically and cosmochemically likely substance. We considered a wide range of variations on the water theme—e.g., brines, clathrates, all predominantly composed of water— as well as other, less conventional materials (liquid CO_2, liquid hydrocarbons, etc). Despite suggestions that have been made by colleagues since June 2000, water, whether or not it contains salts or other freezing-point depressants, remains the most likely fluid. The observation that the occurrence of gullies appears to show a relationship to solar insolation—i.e., they are mostly found on slopes opposite of those illuminated during the present obliquity cycle—is strongly suggestive of the involvement of a volatile that responds in some way to insolation. The further observation that gullies are typically found in regional clusters, and those within a given location such as Gorgonum Chaos always emerge from beneath the same geologic layer (Figure 104), strongly suggests that the fluid involved in gully formation percolates through the ground while confined to distinct layers of specific fluid-transmissive properties. In other words, the regional clustering indicates the presence of aquifers. The gullies appear in nearly all cases to be associated with release of fluid from a layer that is within 500 m of the local surface outside the crater or trough in which the feature occurs—this implies that the fluid involved in gully formation is in the shallow sub-surface, an observation that seems to defy many of the models for martian groundwater and ground ice formulated prior to the MGS mission.

Fretted Terrain

The ensemble of martian fretted terrains, taken together, constitute one of several erosional landscapes initially recognized in Mariner 9 images [*Sharp*, 1973b]. For the purpose of discussion, we focus on the original fretted terrains of *Sharp* [1973b], located in the transition zone between Arabia Terra and the northern lowland plains (30°–50°N and 315°–360°W), although we acknowledge that similar landforms occur in part of the transition zone between Tempe Terra and the northern plains, and in the southern hemisphere in Promethei Terra [e.g., *Crown et al.*, 1992; *Carr*, 1996, Fig. 5-7]. Believed to date from a time associated with the formation of the planetary topographic and physiographic north-south dichotomy, fretted terrains are characterized by landforms that transition from narrow rectilinear valleys on the upland side of the dichotomy boundary to isolated mesas on the lowland side of the boundary. Two geomorphic attributes of fretted terrain are especially notable in distinguishing them from other martian landforms: the occurrence of lineated valley floors (longitudinal striations down the medial axes of the rectilinear valleys) and circum-mesa or fretted terrain aprons (areas immediately subjacent to fretted terrain escarpments with relatively smooth surfaces, crudely convex proximal to distal slopes perpendicular to the escarpment, and sharp contacts with underlying plains); craters containing concentric ridge/trough patterns similar to lineated valley floor material were also identified [e.g., *Squyres*, 1978, 1979, 1989]. From MOC NA images, the story of these landforms appears to be complicated and the landforms polygenetic. Widening of valleys, disintegration of mesas and buttes by scarp retreat, and pitting of mantles that are meters to tens of meters thick appear to be contributing factors in the fretted terrains. The lack of small impact craters on fretted terrain surfaces may indicate that the processes involved include some that are contemporary. *Carr* [2001] has recently summarized an initial MOC NA investigation of fretted terrain; here we present a few additional observations that we have made.

Lineated Valley and Concentric Crater Floor Material.

Many of the valleys in north Arabia Terra have longitudinally-lineated (ridged and grooved) materials on their floors. These are usually called “lineated valley fill” [*Squyres*, 1978, 1979, 1989], however the subject landforms do not "fill" the valleys (though they may cover their floors). We prefer the term “lineated valley floor material.” A typical MOC NA example of lineated valley floor material is shown in Figure 105. Floor materials typically resolve into a pitted texture (the texture resembles in some places the surface of a brain or certain forms of tropical coral). Similar materials and textures are also seen in mid-latitude valleys in the southern hemisphere (Figure 106). The relation between pitting and latitude leads to the obvious speculation that removal of a volatile (e.g., ice) is a contributing factor in creating the pits and rugged meter-scale textures.

Investigators that have examined these lineated landforms in Viking images most often attribute them to creep or flow of ice-rich debris (first from valley walls, then down the valleys) [e.g., *Carr and Schaber*, 1977; *Squyres*, 1978; *Lucchitta*, 1984]. However, we have found no clear evidence in MOC NA images for such down-valley flow. The principal feature we have used to seek evidence for flow are circular forms interpreted to have once been impact craters (Figure 107). Though highly degraded from what we assume was initially a typical impact crater form, the circularity of features superposed upon or conformal with valley floor lineations have not been deformed or distorted by the process that created the lineations; this observation indicates that, while the craters have had sufficient time to become severely degraded, the materials in which they formed have not moved, flowed, or in some other way experienced deformation since the craters were emplaced. Closed fretted terrain valleys with lineated floor materials support the contention that the materials need not have flowed to create the lineations, because they are not open at either end (hence, have no place to “flow”) and yet exhibit the same characteristic patterns seen in open valleys (Figure 108). The walls of fretted terrain valleys are typically smooth but differ on poleward and equatorward slopes, with the equatorward slope usually appearing exceptionally smooth and possibly mantled while the poleward slope is commonly more rugged and often displays manifestations of subsurface layering within the material in which the valley has formed (Figure 109). Valley floor lineations (grooves, ridges) often mimic the planimetric pattern of the valley walls and rims, even where there is an impact crater at the brink of the wall/upland contact (Figure 110)—such observations suggest that the ridges reflect the former locations of valley walls that have been widened largely by scarp retreat.

At least four processes appear to have contributed significantly to the present morphology of lineated valley floor material (these factors appear to be extensible to concentric crater floor materials, as well): pitting, mantling (and removal of mantles), mass movement, and layering. Perhaps the most obvious implication of the morphology of fretted terrain valley floor material is that certain layers and/or mantles of materials have properties that have caused them to become pitted and to appear rugged at the meter scale. Pitting has given the valley floor materials their “brain”-like textures and the overall rough appearance of the terrain (Figures 105–107). As with the upland surfaces of northern Arabia (Figures 9, 10), valley floors and walls have to some extent been mantled; these mantles in some places (except equatorward slopes; Figure 108) have also become pitted and rugged. The third factor, mass movement, has resulted in regressive scarp retreat, particularly on poleward valley walls (Figures 110, 111). Results of these mass movements often include aligned ridges and/or accumulations of blocks at the terminus of the deposit; each successive mass movement event may create a successive ridge or alignment of blocks—this process contributes to some but not all of the linear pattern seen on fretted terrain valley floors (Figure 111). Finally, with MOC NA images we have also come to realize that subsurface layering may also have played a role in creating the apparent linear features in fretted terrain valleys and concentric patterns in craters of the same region. The ridged and troughed nature of lineated and concentric floor materials may be, in part, the result of erosional outcrop expression of subsurface layers exposed in the lower valley slopes and floor (Figure 112). Observations suggesting this relationship come from comparing fretted terrain examples (Figure 112B) with outcrops of layers at equatorial latitudes—which are nicely stair-stepped and usually not thickly-mantled (Figure 112A)—and with layers of similar slope expression in the polar regions (Figures 112C). Some of these factors may work together; others may be mutually exclusive. At present we cannot form a coherent view of lineated valley material formation or emplacement; rather, specific sites appear to have had one or more of these processes at work.

Fretted terrain materials similar to those in valleys are found in craters of the same region. *Squyres* [1989] attributed these to flow of ice and “softening” of the crater terrain; *Zimbelman et al.* [1989] suggested they result from eolian erosion of layered materials. Figure 113A shows a lobate form within a crater in northern Arabia observed during SPO-1; its lobate morphology lends itself to speculation that some form of flow or creep of ice-rich material contributed to its formation (i.e., as proposed for concentric crater floor materials by *Squyres* [1979, 1989]. This view, however, is not consistent with the observation that the crater wall adjacent to the lobe does not appear to have contributed material to the lobe. Figures 113B and C show remnants of layered material trapped on the floors of craters at similar latitude in northwestern Elysium Planitia—when crater interiors are compared between Figures 113A–C, it seems most plausible that the features seen in the first picture are mantled and modified/pitted versions of the layered materials such as those seen in the latter two pictures. Figure 114 compares a more typical concentric crater floor material with layers in the north polar residual cap; in both cases, layers are expressed as ridges and troughs (layers more resistant to erosion form ridges), and the surfaces are rugged.

Aprons.

Aprons are common at the base of escarpments and surrounding massifs and mesas in fretted terrain regions. As with lineated valley floor material, these were attributed by some [e.g., *Squyres*, 1979] to flow or creep of debris away from the scarps and massif slopes around which they occur. Indeed, they are commonly called "debris aprons" despite the lack of evidence that they consist of debris—for this reason, we prefer to simply call them by the non-genetic terms "aprons" or "fretted terrain aprons." In Viking images, these aprons appear to have relatively smooth surfaces (occasionally displaying lineations that seem radial relative to the central mesa or massif) and apparently convex topographic profiles [e.g., *Eppler and Malin*, 1981; *Malin and Eppler*, 1983]. Hundreds of MOC NA images of fretted terrain aprons in northern Arabia and their counterparts in Promethei Terra, southern Argyre, and north Tempe Terra have been acquired. In Figure 115 we present a particularly instructive example obtained early in SPO-1 in the Deuteronilus Mensae region near 40.2°N, 337°W. The 2.05 m/pixel image, SP1-20504, covers an area approximately 1.5 km wide by 45 km long across a fretted terrain apron. A MOLA elevation profile was acquired at the same time and runs down the extreme eastern edge of MOC image. Figure 115C shows MOC and MOLA data at the same spatial scale, with the MOLA data vertically exaggerated by 4x. Although the MOLA data do not resolve many of the small scale features seen in MOC data, they show four attributes of interest: (1) the steep slope near the top of the mesa, which averages about 15° but may be as steep as 30° at it steepest; (2) a relatively horizontal section of the apron (extending 11 km at an average slope of substantially less than 1°); (3) a distinct break in slope wherein the slope increases for about 3 km by almost an order of magnitude, after which the apron continues to descend at a low slope (~1°); and (4) a terminal toe at the base of the apron. Total relief down the apron is about 600 m over about 30 km.

Figures 115D–L show representative samples along the length of SP1-20504. Each image is 1.5 km square. The upland surface (D) displays the roughened texture typical of martian mid-latitudes (e.g., Figure 10). This morphology is characterized by closely-spaced knobs replacing the upland surface, and crater ejecta and rims are almost non-existent. The headslope from the upland to the apron (E) shows azimuthal variations, with ridge/groove forms suggesting down-dip material transport or shear. Small ridges parallel to the base of the cliff suggest material has been shed; a difference in albedo and texture along the lower 10% of the cliff may indicate an area of recent slope movement or rejuvenation. The upper slope of the apron (F, G) is characterized by closely-spaced, non-aligned pits/troughs and knobs/ridges separated by zones of smooth (not pitted) surface whose margins are defined by lineaments, and occasional low amplitude, long-wavelength ridges transverse to the lineaments and zones. At only one location do these ridges suggest diversion of material around an obstacle (H). No distinctive morphology characterizes the break in topographic slope, but the morphology below the break is different from that above. Below the break, the pits/troughs are aligned downslope, and the surface transitions gradually from consisting almost entirely of equidimensional pits/troughs and knobs/ridges to one with a smooth, occasionally pitted surface (I, J). The toe of the apron has small ridges conforming to the perimeter of the apron (K), and a steep slope meeting the basal plains. These plains are somewhat topographically rough and large boulders appear to be liberally scattered across the surface (L).

From Figure 115 and other NA images of these landforms (e.g., Figure 116), we find that there is, at best, only minor evidence that the material has flowed from the head to the toe of the aprons. There is no evidence at all of surficial transport as might be expected for materials emplaced by debris flow, and there are no landforms that would indicate or function as conduits for flow as is, for example, the case on terrestrial alluvial fans (i.e., there are no leveed channels, gullies, etc.). Creep of ice-rich material in the form of a rock glacier may be consistent with some of the features seen (for example, the steeper toe), but the gradient and potential energy/lithostatic pressure available are extremely low, and there is little evidence of material being shed into the apron by any head-supply mechanism. As with other aspects of fretted terrain, the latitudinal and solar azimuth relationships suggest that devolatilization has played a role in pit formation. In the case of aprons, however, the pervasive pitting, its spatially-distinct relations (high on the apron is more pitted than lower), and the terminal ridges suggest further that either the upper slopes are in extension and the lower slopes compression, or that the upper slopes are experiencing greater erosion or devolatilization than the lower slopes. The topographic and morphologic relations resemble terrestrial pediments—that is, tsubstrate layers whose slopes and erosional forms reflect the composition and physical properties of material. In our view, fretted terrain apronsmay not result from flow or creep of debris and/or ice, but may instead be the erosional expression of a layered substrate that underlie the material comprising the mesas and massifs around which they occur.

Northern Plains

Although most of the martian northern lowland plains are named the “Vastitas Borealis,” they should perhaps instead have been called “Terra Incognita.” Most Mariner 9 and Viking orbiter attempts to image this region were obscured by haze, clouds, or complicated by seasonal frosts. After these missions, *Scott and Underwood* [1991] still found it appropriate to describe the northern plains as “the most ambiguous materials on [sic] all martian images.” Most geologic or geomorphic contacts between northern plains surfaces are dashed in the regional map by *Tanaka and Scott* [1987], which also reflects the lack of useful information about these plains. Mariner 9 views showed bright-and-dark-mottled surfaces in which bright features tended to be craters [*Soderblom et al.*, 1973b]. Many of the craters seemed to stand above the surrounding terrain, earning them the name “pedestal crater.”. Despite the occurrence of some impact craters, the northern plains were seen as lightly cratered and thus considerably younger than the martian southern cratered highlands. More recently, Viking images were used by some to propose that the northern plains had once been the site of oceans, seas, and/or glaciers [e.g., *Parker et al.*, 1989, 1993; *Kargel et al.*, 1995; *Scott et al.*, 1995]. Recent MOLA data indicate that the northern plains are relatively flat at kilometer scales [*Aharonson et al.*, 1998] and some researchers suggest there is topographic evidence supporting the contention that the region was once the site of an ocean [*Head et al.*, 1998, 1999].

General Aspects.

Hundreds of MOC NA images of the northern plains typically 3 km wide by 18 km long have been acquired; many are hazy or somewhat obscured by clouds, but those taken during L_s 100°–160° (March–June 1999), L_s 240°–270° (November–December 1999), and L_s 25°–110° (August 2000–January 2001) are generally cloud-free and show surface morphology well. No distinct volcanic landforms (e.g., flows, edifices) have been seen. The most striking aspect of the northern plains as viewed in MOC images is the impression that there is a surface very similar to that of the southern cratered highlands located “just beneath” the plains surface. In some locations, especially around 48°N, 230°W, in Utopia, there are so many craters evident beneath the thin plains covering that the surface resembles (or is more cratered than) many southern highland surfaces at the same scale (Figure 117). The plains surface material is often so thin that boulders on buried crater rims and ejecta deposits are exposed at the surface (Figures 118, 119), and sometimes the full crater ejecta morphology can be easily distinguished through this material (Figure 120). While the northern plains appear to have little relief variation at the hectometer to kilometer scales accessible to MOLA [*e.g., Aharonson et al.*, 1998], at the meter to decameter scales visible to MOC the plains are anything but smooth. Buried topography associated with impact craters and boulder-covered knobs (Figure 121) dominate the region; in some places the thin plains-covering material has been mostly or partly removed to leave behind stacks of remnant layers on exhumed crater floors (Figure 122). Periglacial processes appear to have modified the upper plains surfaces in many regions, creating small polygons observed in the vicinity of the Viking 2 lander site (Figure 123A) that are at about the same scale as those observed in the lander panoramas [e.g., *Mutch et al.*, 1977, *Sharp and Malin,* 1984], extremely large polygons on the floors of some craters (Figure 123B), boulder-bounded polygons near Lyot Crater (Figure 123C), and bumpy and ridged textures that resemble the surfaces of basketballs (Figure 123D) and corduroy fabric (Figure 123E).

Ocean Hypothesis.

MOC NA images have provided an opportunity to test the hypothesis that the northern plains were once the site of a series of large seas [*Scott et al*., 1992, 1995] or an ocean [*Parker et al*., 1989, 1993, *Edgett and Parker*, 1997]. In particular, the cited investigations presented interpretations of features seen in Viking orbiter images that they proposed to be coastal landforms; *Pieri* [1999] did the same using MOC images acquired during SPO-1. Other advocates of a northern plains ocean, *Baker et al.* [1991] and *Head et al.* [1998, 1999], did not cite specific locations, landforms, or features, as might be seen in an image, for example, that could be identified and photographed by MOC. *Parker et al.* [1989, 1993], described features seen along the margins of the northern plains, particularly in Deuteronilus Mensae and Cydonia, that they compared directly with coastal landforms found around the margins of Pleistocene lake sites in the Great Basin of North America (particularly, Lake Bonneville and Lake Lahontan). Coastal landforms may be erosional or depositional, and often both are found in close proximity—these include beach ridges, spits, bars, barriers, tombolos, wave-cut terraces and platforms, and fluvial deltas (e.g., in Great Basin Pleistocene Fort Rock Lake as described by *Forbes* [1973] and Lake Bonneville as described by *Gilbert* [1890]). *Parker et al.* [1989, 1993], *Scott et al*. [1992, 1995], and *Edgett and Parker* [1997] presented Viking orbiter photographs of specific landforms that they interpreted as being formed by the erosional and depositional processes that occur along coastlines. Dozens of MOC NA images were targeted to test the specific cases presented in the figures published by these authors; additional hundreds of images can also be used to test the hypotheses, although not at locations specified by the original authors. Figures 124 and 125 present two examples of these tests; additional tests were published by *Malin and Edgett* [1999].

Figure 124A shows a Viking orbiter image described by *Parker et al.* [1993, Fig. 2a] as showing banding along the plains/upland contact that they interpreted as coastal landforms. Figure 124B shows a sub-frame of MOC image M11-02987, that reveals that the banding observed in the Viking image is indeed present, but that it is caused by exposure of multiple layers that dip gently toward the northwest and are each bounded by a southeast-facing scarp. In other words, the boundaries between bands seen in Figure 124A to parallel the plains/upland contact are seen in Figure 124B to be escarpments that face the upland. If the bands had resulted from coastal erosion, the scarps would be expected to face in the opposite direction. The presence of exposed layering along the plains/upland contac, while interesting, offers no substantiation for a coastal geomorphic interpretation. The second example, Figure 125, shows a group of knobs on the northern plains near 45°N, 186°W, that was shown in *Parker et al.* [1993, Fig. 2b]. Each knob in the Viking image appears to have a series of concentric terraces around its base. The MOC NA image in Figure 125B shows that the concentric pattern is very subtle at the decameter scale—the features are only non-concentric, discontinuous, and appear only as slight undulations in a relatively featureless mantle that covers the slopes of an otherwise boulder-covered knob. Although their origin cannot be determined specifically, the features seen in Figure 125B do not resemble the wave-cut terraces/scarps that were suspected by *Parker et al.* [1993] on the basis of the Viking orbiter image of the same landforms.

The difference between unverifiable speculation and testable hypothesis is often very small, and generally rests on the availability of unequivocal factual evidence: if one can dispute the observations, then the interpretations are automatically suspect. In the Viking Orbiter image-based studies that led to the ocean hypothesis, such unequivocal evidence is generally absent. Our effort to re-image the locations cited in the literature failed to reveal the landforms inferred by previous investigators to exist. What remained were still-unexplained topographic relationships. In our view, the absence of coastal landforms falsifies the interpretation based on their presumed occurrence—that is, there is no evidence supporting the hypothesis that there was an northern ocean. Unfortunately, ideas that become popular are substantially more difficult to falsify than ideas that are unpopular; the result is that the burden of proof shifts from those proposing a hypothesis to those attempting to test it.

The more recent hypothesis that an ocean explains the topographic relationships of the northern hemisphere plains (e.g., *Head et al.* [1998, 1999]) is more difficult to test. The offerers of that hypothesis have not provided sufficient specificity in either predictions of landforms or in the nature of processes they would attribute to their ocean to permit us to focus the camera on specific locations or landforms. We are thus reduced to less satisfying efforts to surmise what such an ocean might be like in order to test the hypothesis. We think that the observations presented in Figures 117–120 regarding the presence of a relatively thin material covering much of the northern plains do not support the ocean hypothesis. In our view, the northern plains-covering material cannot be explained as “ocean sediments” because, as shown in Figures 126 and 127, similar surfaces (thinly-buried impact craters and rings of boulders indicating the location of buried craters) are also common at comparable middle and high latitudes in the martian southern hemisphere at elevations 3–5 km above the planet’s datum. We don’t know the origin of the relatively thin, plains-covering materials observed on the northern plains (and southern highlands at comparable latitudes), but suspect that they are the result of latitude-dependent processes, perhaps some combination of mantling by dust (as described by *Soderblom et al.* [1973b]) and periglacial modification of these surfaces.

Mass Movement

Mass movements on planets are usually less well-studied because they do not often capture the imagination of scientists mostly interested in the “Big Picture.” This is unfortunate, since mass movements tell so much about materials and processes. Still, we admit to succumbing to “Big Picture-itis" and have thus narrowly focussed our interests in mass movements. Features investigated via MOC NA images include: 1) deposits of large (> 2 m) boulders at the base of steep slopes, 2) the surface characteristics of the large landslides in the Valles Marineris, and 3) light-and dark-toned streaks occurring on slopes in dust-mantled regions.

Boulders.

As MOC was designed to see boulders and use them as tools for deciphering martian surface geologic flow properties, it was greatly satisfying when one of the earliest pictures from MOC, AB1-02003 (Figure 128), showed a hundreds of house-sized boulders at the base of steep layered slopes in troughs off the west side of the Elysium rise. Boulders at the base of steep slopes are most commonly found in volcanic regions, particularly Tharsis and Elysium. Their presence implies that there are materials exposed in the slope that are strong or coherent enough to create boulders large enough to be seen by MOC after surviving down-slope transport. That most boulders occur in volcanic regions implies that they are a product of the mechanical weathering of local volcanic rock (e.g., lava flows). In the volcanic areas, there is little evidence of the paths of the boulders down the accumulated colluvium; this suggests that the slope debris is also relatively coarse. The few examples in which boulders that have rolled down a slope and created a trail behind them are found in areas that from other evidence appear to be heavily mantled (Figure 129 and MOC image M23-00980); in these areas the nature of the indentations provides excellent information from which lunar experience shows that one can derive the physical properties of the mantling material [e.g., *Mitchell et al.,* 1973]. Boulders are also found at the surfaces of the large landslide deposits in the Valles Marineris (Figure 130). Their presence on the landslide masses but not in general on talus slopes was discussed in our earlier section on the walls of the Valles Marineris.

Large Landslide Deposits.

On the basis of Viking orbiter observations, there have been suggestions that the large landslides in the Valles Marineris may have involved transport of water or ice, perhaps with these agents acting to “lubricate” the material during emplacement [e.g., *Lucchitta*, 1978, 1979, 1987b]; other work suggests that transport can occur in dry materials [*McEwen,* 1989]. We have not seen evidence in MOC NA images for any liquids that might have percolated up out of the landslide bodies and ponded or flowed onto or across their surfaces, nor have we seen any evidence of fluid flow out of their lateral margins or distal toes (e.g., Figure 131). The lack of “dewatering” features may imply that very little water or other liquid was involved in the emplacement of these deposits.

Slope Streaks.

Despite their relatively small size, perhaps the most dramatic mass movement features observed by MOC are dark slope streaks and their light-toned counterparts (Figure 132). Slope streaks are long, typically narrow, occasionally tapered and sometimes digitate features common to and oriented generally down slopes in the higher-albedo, thickly-mantled equatorial latitudes of Mars—particularly Tharsis, Arabia, and the southern Amazonis/Medusae Fossae regions. Slope streak occurrence, general attributes, and possible origins were recently discussed by *Sullivan et al.* [2001]. Slope streaks were first observed in some of the highest-resolution Viking orbiter images [*Morris*, 1982; *Ferguson and Lucchitta*, 1984; *Williams*, 1991] and thousands of new examples have been found among the MOC data. They appear typically to result from mass movement, but details regarding the particle sizes, nature of their flow, and initiation mechanisms are the subject of continuing uncertainty. The particle sizes involved are believed to be very small—sand, silt, and clay-sized particles—because they occur mainly in dust mantled regions and show no evidence of clasts large enough to be imaged by MOC (i.e., no boulders). *Sullivan et al*. [2001] presented the case that the streaks may be very thin scars or disruption surfaces resulting from avalanching of dust. In this model, only a thin veneer at the surface of a mantled slope is affected; the underlying bedrock slope is never exposed (i.e., dust is avalanching on a surface of dust). The darkest slope streaks are only about 10% darker than their surroundings. The streaks often appear to have flowed in a fluid manner, and in some places have over-ridden topography at the base of the slope on which they occur [*Sullivan et al*., 2001]. A few opportunities to obtain repeated coverage of surfaces with slope streaks have revealed a some cases in which new streaks have formed in less than 1 martian year [*Edgett et al*., 2000]; Figure 133 shows an example. In places where new slope streaks have formed between two MOC or a Viking and MOC image (e.g., Viking image

748A12 and MOC image M04-01105; see *Edgett et al.* [2000]), we find that their rate of formation is of the order of one streak per linear kilometer of slope per Mars year. The initiation of slope streaks is a mystery. They usually begin at a point high on a mantled slope [*Sullivan et al.*, 2001]. We suspect that wind gusts and the occasional passage of a wind vortex (e.g., dust devil) may contribute to the initiation of slope streaks; Figure 134 shows one of very few examples in which a long, thin, filamentary streak attributed to passage of a dust devil intersects a dark slope streak (it should be remembered, too, that not all dust devils create dark streaks, as in Figure 54).

Impact Craters

In planetary science, impact craters are "tools of the trade." By comparing craters among planets and with model and experimental results, they provide information about crustal properties, surface erosion processes, and various degrees of the timing of events that have shaped a surface. In the martian context, the size and abundance of craters is strongly dependent on factors directly related to the martian environment—small crater populations, for example, must reflect the complex interaction between primary influx, atmospheric filtering of incoming bodies, and surface processes modulated by climate. The smaller the crater, the shorter the timescale over which these interactions occur. As noted by *Hartmann* [1999], the smaller craters provide information about the most recent martian geologic evolution. For larger martian craters, material properties may have played important roles in determining the configuration of ejecta and crater morphology—for example, "flow-ejecta" or "rampart" craters are believed by many to reflect the influence of volatiles on ejecta distribution [e.g., *Carr et al.*, 1977b, *Mouginis-Mark*, 1979]. The size, number, and sorting of debris associated with both impact cratering and with debris flows is very characteristic of the emplacement mechanism, so it was hoped that MOC NA images would provide evidence on whether or not volatiles (i.e., water in debris flow) were involved in emplacement of flow ejecta [*Malin et al.*, 1992, p. 7703].

More than 95% of all MOC NA images contain impact craters (most polar residual cap surfaces do not, although we have found a few on the north polar residual cap—e.g., M19-01628, M22-00889), and many hundreds of pictures were specifically targeted to examine impact crater and/or crater ejecta morphology. Long traverses across impact craters and basins of tens to hundreds of kilometers diameter were obtained with simultaneous MOLA elevation profiles so that the two might be compared—it is interesting to note that it was among these "targeted" images that *Malin and Edgett* [2000a] first began to notice gullies on pole-facing slopes of middle- and high-latitude craters. With regard to "flow ejecta" craters, and as with large landslides, MOC NA images (e.g., Figures 135, 136) show no evidence of surficial ponding within or fluid flow beyond the distal margins of the ejecta deposits. Terrestrial mudflows exhibit small channels extending beyond the flow terminus that result from "dewatering" of the flow after movement of the debris-laden material has stopped. We have not seen any features of this type at the margins of any flow ejecta deposit. Unfortunately, MOC NA images usually do not show boulders on flow ejecta deposits, either. The latter observation implies that models for mud and debris flow on Earth may not be extended to the martian craters unless higher-spatial resolution images (showing boulders and cobbles) are obtained. Regarding small impact craters, MOC NA images have generally shown a lack of obvious ejecta deposits around most impact craters of kilometer and subkilometer sizes. The absence of ejecta in some cases—particularly on the extremely pitted floors of some of the outflow channels (e.g., Ares Vallis at the Mars Pathfinder site as seen in SP1-25603 and Ma'adim Vallis as seen in M08-03445) and volcanic surfaces (e.g., Arsia Mons caldera floor in AB1-03308)—makes it difficult to distinguish craters formed by impact from those formed by endogenic processes. The lack of ejecta implies that processes have acted on relatively rapid geologic timescales to remove or bury these materials. We note, however that there are some excellent examples of small impact craters exhibiting the many of the classic attributes of ballistic impact ejecta and ray emplacement processes. Figure 137A shows an example from the summit of Ulysses Patera, other examples are illustrated in Figures 137B and 137C. Some of the best examples, like in Figure 137A, are found among the multiple-meters-thick mantles covering much of the Tharsis region. Figure 137D shows the largest such example, although the crater cavity has not yet been overflown by MGS and imaged by MOC. Craters exhibiting these rayed patterns are likely to be geologically very young.

CONCLUDING REMARKS

What does all of this mean? In what context do these disparate observations and conclusions make sense? We provide here a highly speculative view of Mars, developed over the past three years of detailed examination of the planet's surface at meter to decameter scale, and offered with acknowledgment that it is probably wrong.

The Mars revealed by MOC is very different from the planet we anticipated finding, and that most of the scientific literature describes. The geology and geologic history of that other planet were well delineated: a lunar-like crust beneath a near-Earth-like atmosphere evolved into the present static, composite state. The timescale of the change and evidence for it were intertwined in the fluvial history displayed in valley networks and outflow channels responsible for relatively minor redistribution of highland materials and the final vestiges of the planet's former thick, water-rich atmosphere. Three geologic periods were defined based on this change and whether a given place or landform was thought to predate, post-date, or occur during the change. Lakes were speculatively thought to have developed late in the process, so that their handiwork was still visible on the surface, and arguments were raised in favor of an ocean covering much of the lower northern plains, possibly episodically, until relatively late in martian history. In this view of Mars, the volcanoes of Tharsis were young, and the ocean potentially even younger.

This is not the planet we think we see. The pervasive layering of the crust, to depths of ten kilometers or more, attests to a place that is most definitely not the Moon with an atmosphere. Deposits, some of which rise to elevations higher than the rims of the craters in which they are found, point to massive amounts of material being weathered, transported, and deposited during a period when changes in environmental conditions produced sequences of hundreds of nearly identical layers. The heavily cratered terrains seen on Mars today are a patchwork of surfaces of different ages, most dating back to the first billion years of Mars' history. Relationships previously difficult or impossible to reasonably explain—for example, how valley networks could dissect crater walls and appear to breach craters from both the upslope and downslope directions—can now be understood in simpler terms (in this example, the valleys are superimposed drainages). Such relationships are circumstantial evidence for overland flow processes—the primary evidence is buried beneath mantles or has been subsequently eroded by other processes.

The planetary dichotomy is primarily and fundamentally a geophysical feature: the surface topography gives us little insight other than to hold with enormous respect the ability of global-scale gravitational forces to shape a planet. The likely scenario is that core and mantle processes thinned the lithosphere and may have resurfaced the northern hemisphere with volcanic rock, but that this occurred relatively early in the middle history of Mars. Evidence of substantial numbers of thinly buried craters a few hundred to a few thousand meters across show that, at that size range, the northern hemisphere is no less cratered than the southern hemisphere.

Not every process operated early in Martian history and then subsequently with less or no vigor. Measurably large areas on Mars are devoid of impact craters to the limit of MOC images to resolve. The “bedrock” as exposed in some of these areas cannot have been formed recently, so they have been buried for most of martian history and only recently exhumed. What process exhumed them, and when, is not clear. Many other landforms and relationships (for example, the light-toned ripple-like bedforms, indurated dune fields, dark mesa-forming units, and seepage gullies) seem at odds with both the present environment, and our presumptions about how the environment behaves over hundreds of thousands to tens of millions of years. These attributes strongly suggest that Mars as we see it today is not what it has been like over much of its history. Just as deposits and landforms in Europe and North America strained interpretations in the Nineteenth Century before the realization that ice ages had occurred, so too is it likely that many martian landforms are relicts from environments other than those found on Mars today.

If there is one idea to take from this report, it is that Mars is substantially more complicated, and its geology more complex, than anyone had previously thought. Because of this, simplistic interpretations and models must be given extra scrutiny. Look carefully at the data to see if you agree with what are claimed to be observations, question the interpretations, and consider speculations with healthy skepticism. Exercise this approach with MOC data, with the views we have expressed herein, and with data and views of every other investigator in the field. Nothing can be taken for granted when considering the “new Mars.”

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FIGURE CAPTIONS

1. Total number of MOC images commanded as a function of mission subphase from Mars Orbit insertion on September 12, 1997, (the start of AB1) through the end of the Primary Mission on January 31, 2001 (the end of M23). The total number of images commanded through the end of the Primary Mission is 83,591. WAs = regional red and blue wide angle images, NAs = narrow angle images, Ctx = wide angle context pictures for narrow angle images, Globals = daily global red and blue images.

2. Total data volume received from the MOC cameras as a function of mission subphase from the start of the MOC calibration subphase (CAL) on February 28, 1999, through the end of the Primary Mission with subphase M23. Data volume is a direct function of data playback rates and downlink availability, with more data available during the opposition year of 1999 (CAL–M10) than in the conjunction year of 2000 (M11–M22). The total volume of MOC data received through the end of the Primary Mission is 116.7 Gbytes decompressed (66.2 Gbytes compressed). WAs = regional red and blue wide angle images, NAs = narrow angle images, Ctx = wide angle context pictures for narrow angle images, Globals= daily global red and blue images.

3. History of lost and corrupted MOC data from the start of AB1 through the end of the Primary Mission, as percentage of images. Data are considered "lost" if a command to the instrument is created and submitted for transmission to the spacecraft but no image is ever returned. Images lost owing to flight hardware or software problems or MOC operations errors are tracked separately and constitute a very small fraction of the data. The largest sources of lost data are DSN outages and failures of the Project Ground Data System to properly handle MOC commands. Data that are actually received may be corrupted by packet loss, which occur as a result of spacecraft commanding during data transmission or from numerous, singleton packet losses within the Project Ground Data System. These

are, for the most part, irrecoverable errors introduced on the ground. Cumulatively over the mission, 6.6% of all commanded images were never received; 16.2% of received images been corrupted.

4. Focus range of MOC Narrow Angle Camera as seen in images of stars within the Pleiades star cluster during cruise to Mars in late 1997 and early 1998. The MOC uses heaters to distort the primary mirror to change focus. This control is needed to account for the natural change in focus as a function of overall instrument temperature and for possible moisture in the graphite/epoxy structure. The slant of the out-of-focus star images is the result of astigmatism in the optical design; when in focus, the astigmatism is minimal and the star image symmetric. This is a composite of images taken during several different cruise sequences (C3 through C5).

5. Comparison of albedo features observed by (A) Viking Orbiter with the albedo patterns seen during (B) Mars Global Surveyor's approach in August 1997 (L_s 167°) for a portion of Mars between 75°N and 35°S, 290°W and 310°W (north is up). Features labeled 1–4 exhibit the most obvious changes. Feature 1 is Cerberus, it had been noticed to have brightened by the mid-1990's in Hubble Space Telescope images [*James et al*., 1996]. (A) Mosaic of Viking compiled by A. McEwen (personnel communication, 1993) (B) Mosaic of MOC Cruise Phase images acquired on 19 and 20 August 1997. MOC Cruise Phase images 556480166.21, 556557746.51, 556579886.61; archived in NASA's Planetary Photojournal by catalog numbers PIA00930, PIA00933, PIA00934.

6. MOC image AB1-00406, one of the first NA pictures acquired from orbit, shows eolian bedforms and impact craters on a ridged plain in Terra Sirenum near 30.8°S, 172.8°W, on September 17, 1997. Some craters are shallow and contain bedforms, other craters are much deeper and have no bedforms. A period in which windblown sand was transported through the region before the population of deep

craters formed is inferred. (A) Original image with no map projection. (B) Map-projected image with scale and direction toward north indicated. (C) Example of deep crater without bedforms, to compare with (D), example of similar-sized crater that is nearly filled and contains bedforms. Illumination is from the left.

7. Mars Pathfinder landing site near 19.3°N, 33.3°W. (A) Map-projected composite of M11-02414 and SP1-25603 with local landmarks identified by the informal names used by the Mars Pathfinder team. (B) Expanded view of a portion of M11-02414 showing the location of the Mars Pathfinder lander. The hardware is not visible in this 1.5 m/pixel image, and only one large boulder, “Couch,” can be tentatively identified. The plethora of smaller boulders and cobbles known from the lander’s images cannot be seen in the highest resolution of MOC NA images under typical illumination and atmospheric conditions for the Chryse/Acidalia plains. Image M11-02414 is illuminated from the lower left, SP1-25603, which forms part of the right side of A, is illuminated from the lower right.

8. The ripple texture in the lower two-thirds of this image—with strikes oriented diagonal from upper left toward lower right—indicates the floor of a shallow channel that is part of the distal Tiu Valles system on southern Acidalia Planitia. The contact between the darker, ripple-textured surface and the lighter-toned surface in the upper third of the picture is the channel’s margin. This ripple pattern is common in Chryse and southern Acidalia Planitia in areas affected by the Ares and Tiu Valles floods; this pattern is observed at the Mars Pathfinder site in Figure 7. This is a portion of SP2-53005, near 25.3°N, 34.9°W, illuminated from the lower left.

9. Comparison of (A) smooth-mantled and (B) rough-mantled surfaces in central Arabia Terra. The context of both images is shown at the top center; the images were taken on the same orbit within 2 minutes of each other and are thus subject to similar illumination conditions with sunlight from the left. (A) SP2-51905 near 25.2°N, 232.5°W; (B) SP2-51906 near 30.0°N, 323.5°W.

10. Comparison of roughened mid-latitude mantled surfaces in (A) the northern

hemisphere and (B) the southern hemisphere. (A) SP2-51906 near 30.0°N, 323.5°W; (B) M00-03091 near 41.0°S, 171.6°W; both images are illuminated from the left.

11. Mid-latitude landforms exhibiting relations to poleward and equatorward slopes. (A) Pitted poleward slopes on crater rim near 32.8°S, 227.7°W, in M07-05957, illuminated from the upper left. (B) Smooth material on poleward slope of mesa in Cydonia near 40.8°N, 9.8°W, in M03-04566, illuminated from the lower left. (C) Rough material in pits and craters on poleward slopes in Acheron Catena terrain near 36.6°N, 101.6°W, in M02-01153, illuminated from the lower left.

12. (A) Light- and (B) dark-toned mantled surfaces observed under similar illumination conditions on the same orbit ~5 minutes apart. The relative albedo difference between the two surfaces is preserved in the figure, both are illuminated from the right/lower right. (A) SP2-41004 in central Arabia Terra near 5.3°N, 326.5°W; (B) SP2-41005 in eastern Sinus Sabaeus near 8.4°S, 328.4°W.

13. Comparison of thick, smooth-mantled surface (that has a "typical" Earth-based radar signature) on the lower north flank of Pavonis Mons with a thinner, grooved-mantled surface on lava flows west of Arsia Mons (located within the “radar Stealth” terrain first identified by *Muhleman et al.* [1991]). (A) Context for MOC NA view of lava flow surface within the Stealth region west of Arsia Mons; illuminated from the left, this is a portion of a mosaic of Viking orbiter images 731A39 and 731A41 near 2.7°S, 138.4°W, location of figures F and G are indicated. (B) Context for MOC NA view of mantle on troughs north of Pavonis Mons; illuminated from the upper right, this is a portion of a mosaic of Viking orbiter images 090A33–36 with the location of figures D and E indicated. (C) Regional context showing locations of figures A and B; dark outlines from *Edgett et al.* [1997] indicate the radar Stealth location. (D) MOC NA view of thickly-mantled lava flow surface and troughs north of Pavonis Mons in SP2-37703, illuminated from the lower right. (E) Mantle exposed on upper trough wall in SP2-37703, illuminated from the lower right. (F) Grooved mantled surface within the radar Stealth region

atop larger pressure ridges of lava flow surface in AB1-02406, illuminated from the left. (G) Expanded view of grooved-mantle surface from E (see A for context).

14. Thick mantles on some lava flow surfaces in Tharsis, particularly north of Ascraeus Mons, have a “blurry” or “out-of-focus” appearance. Despite appearances, the cluster of small, sharp craters in the upper right corner of this view indicate that the MOC NA camera was in focus when the picture was acquired. Located near 16.6°N, 99.9°W, M02-04870, illumination from the left/lower left.

15. “Rough is smooth and smooth is rough.” Surfaces that appear relatively smooth at typical Viking orbiter image hectometer scales (A) typically appear rugged at the meter and decameter scales of MOC NA images (B). In contrast, surfaces that appear rugged at Viking orbiter hectometer scales (C) are typically smooth at meter and decameter scales in MOC NA images (D). Pictures (A) and (B) are in the Amenthes region near 1.1°S, 252.3°W; (A) is a portion of Viking orbiter image 379S44 and is illuminated from the right; (B) is from M00-01619, illuminated from the upper left. Pictures (C) and (D) are in the Nepenthes region near 5.3°N, 241.0°W; (C) is a cropped mosaic of Viking orbiter images 381S31–46 and is illuminated from the upper right; (D) is from M00-01454, illuminated from the upper left.

16. An array of typical meter- and decameter-scale surface textures and patterns at equatorial latitudes on Mars, ranging from very smooth (A) to very rugged (I–L). Each picture covers an area 1.5 km by 2.2 km; each is illuminated from the left, and north is toward the upper right. (A) Smooth light- and dark-toned mantled surfaces in contact in eastern Terra Meridiani bright/dark albedo boundary near 4.9°S, 341.4°W, M02-01085. (B) West-central Terra Meridiani on surface with interpreted hematite spectral features in MGS TES data [*Christensen et al.,* 2000], near 2.0°S, 6.7°W, M00-01660. (C) Cratered highland surface in Nepenthes Mensae region near 5.2°N, 241.0°W, M00-01454. (D) Dark mantled surface in south Terra Meridiani near 5.7°S, 1.9°W, M02-00444. (E) Cratered highland surface in the Aeolis/Nepenthes region near 0.3°N, 236.0°W, M00-01788. (F)

Southern Elysium Planitia/Cerberus platy flow surface near 3.3°S, 195.9°W, FHA-01649. (G) Pitted surface in eastern Terra Meridiani near 5.8°S, 349.8°W, M00-01820. (H) Floor of Escalante Crater near 2.9°S, 244.1°W, M00-01056. (I) Southern Amenthes region near 1.1°S, 252.4°W, M00-01619. (J) Northwestern Melas Chasma floor near 10.0°S, 71.4°W, M00-00970. (K) Central Terra Meridiani ridged surface with TES hematite signature, near 2.1°S, 2.4°W, M00-02022. (L) Grooved/yardang surface in Mangala Valles/Memnonia highlands near 11.8°S, 157.1°W, M00-01030.

17. Surface patterns and textures in vicinity of the December 3, 1999, Mars Polar Lander site near 76.3°S, 195.0°W. Image on the left is composed of Viking orbiter images with white boxes representing the mosaic of MOC NA images acquired December 1999 through February 2000 in an effort to locate the missing lander. Pictures on the right are full-resolution (1.5 m/pixel) views extracted from the lander search mosaic, each shows that the polar terrain is much more rugged than implied by the lower-resolution Viking images; each is illuminated from the upper left.

18. While some brightness patterns and variations on the martian surface may be attributable to differences in particle size and/or composition, this is an example in which the brightness patterns seen at Viking orbiter scale are caused by decameter-scale relief. Picture (A) shows Burton Crater at 13.5°S, 156.3°W, in Viking image 637A77. Picture (B) shows MOC image M00-02351, pictures (C) and (D) show sub-frames of M00-02351 at the two albedo boundaries crossed by the image. In both (C) and (D), the darker-toned albedo feature in the Viking context image is seen to be a surface covered by closely-spaced (at meter-scale) ridges and grooves. The ridges are yardangs that result from wind erosion. The Viking image is illuminated from the upper right, the MOC image from the upper left.

19. Although many albedo patterns and features on Mars have long been attributed to distribution of dust and sand, some landforms exhibit relatively dust- and sand-free surfaces in which the albedo is a attribute

of the underlying bedrock material. In this view of the “White Rock” feature in Pollack Crater, a dust-free, light-toned surface across which dark eolian ripples have formed is shown. The image is M19-00309, located near 7.9°S, 334.7°W, and is illuminated from the upper left. Arrows indicate rim of a crater that is covered with dark sand and underlies a remnant of the eroded light-toned, cliff-forming material. This crater indicates the presence of a gap in the geologic record between the time when the light-toned material was deposited and the underlying substrate was in place.

20. Examples, characteristics, and configurations of “ridged units”. Pictures are subframes of the MOC images indicated, north is toward the upper right and illumination from the left except where noted. (A) Ridged upper layers corresponding to TES hematite unit, M04-03468, 3.6°S, 2.7°W. (B) Ridged unit (top) in Ius Chasma, M02-01296, 8.0°S, 78.9°W. (C) Ridges in relation to partly-exhumed crater in Schiaparelli Basin, M02-03362, 2.4°S, 344.0°W. (D, E) Ridges in relation to superposed craters, Candor Mensa, M02-02913, 6.1°S, 23.8°W. (F) Dark, ridged remnants on bright substrate southwest of Nirgal Vallis, M10-00406, 28.4°S, 47.9°W. (G) Ridge texture possibly imposed by subjacent unit, Schiaparelli Basin, M00-02181, 1.1°S, 346.1°W. (H) Possible analog on south polar residual cap, illumination from lower right and north toward bottom, M08-01792, 86.3°S, 57.5°W. (I) Expanded view of grooves developed in mesa shown in (J), which is grooved/pitted mesa surrounded by ridges in Melas Chasma, FHA-01277, 8.8°S, 76.9°W, box shows location of picture in (I).

21. Early MOC NA view of layers (e.g., arrows) exposed on the steepest surfaces of the lower north wall of western Candor Chasma, AB1-08403, 5.1°S, 75.0°W; illumination is from the left.

22. Lenses of light-toned, massive (i.e., not obviously layered) bedrock (arrows) outcropping on southwestern wall of Ganges Chasma, M04-01352, 8.8°S, 52.4°W. Illumination is from the left.

23. Stair-stepped layered outcrops similar to those of Valles Marineris interior layered units exposed in Valles Marineris chasm walls. (A) Ius Chasma north wall example, showing a portion of Viking orbiter image 065A15 near 7.1°S, 81.5°W, with the location of MOC NA image M23-00556 indicated as a dark-toned strip at the lower right. (B) Portion of the M23-00556 (as indicated by white box in A) in which a stair-stepped layered outcrop is exposed in a spur about half-way up the chasm wall. The Viking image in (A) is illuminated from the upper right, the MOC image in (B) is illuminated from the left. (C) Southwestern Candor Chasma in Viking image 919A13 near 6.6°S, 77.4°W, with a dark-toned strip indicating the location of MOC NA image M23-00180. The white box indicates the sub-frame of M23-00180 shown in (D), in which a group of stair-stepped layers are outcropping amid talus more than a quarter of the way up the valley wall relative to the layered material on the chasm floor. The Viking image in (C) is illuminated from the right, the MOC image in (D) from the left.

24. Light-toned layered and massive outcrops similar to those of Valles Marineris interior materials exposed in alcoves and amid spurs in Coprates Chasma. (A) Layered material indistinguishable from other layered interior outcrops (e.g., in southern Melas Chasma and eastern Candor Chasma) located about a quarter of the way up the northwestern wall of Coprates Chasma. The white box in (B) indicates the location of image (A), arrows indicate the extent of a lens of light-toned material outcropping in the alcove as known from other MOC NA images (e.g., M20-00380, M21-00693, M22-02472, M23-01561). Image (A) is from M23-01432, (B) is from MOC red WA image M01-00067; both are illuminated from the left and located around 10.3°S, 69.4°W. Pictures (C) and (D) are portions of MOC NA image M20-01760, located near 13.2°S, 64.9°W, on a ridge in central Coprates Chasma. Their context is shown in (E) from red WA image M07-02444; all three pictures are illuminated from the left. Picture (C) shows light-toned material outcropping in a spur of “wall rock” on the Coprates ridge, (D) shows the layered nature of material coming out from under the spur further down the slope, (E)

shows the extent of the lens of light-toned material at this location.

25. Boulders derived from erosion and mass movement in layered volcanic terrain. This example is located in a trough northwest of Arsia Mons, near 3.0°S, 126.7°W, in M07-03574; illuminated from the left.

26. Alternating light and dark bands on the slopes of the large mound in central Ganges Chasma were first seen in Mariner 9 B-frame images, as shown in (A) from Rev. 207, Frame 15 (DAS 9017619). Thought for nearly 30 years to represent layers in the mound, MOC NA images reveal that, while the mound has decameters-thick light-toned layers, the dominant dark features are the result of eroded, superposed mantles. Picture (B) shows a portion of MOC image M04-00323 near 7.4°S, 49.2°W, the white box in (A) indicates the picture in (B), the white box in (B) indicates the expanded view in (C). The MOC image is illuminated from the left.

27. Example of stair-stepped or cliff-bench expression of layering in a western Arabia Terra impact crater at 8°N, 7°W. Illuminated from the left, this view from M18-01349 reveals dozens of layers of similar thickness and geomorphic expression, indicating episodic, repeated changes in deposition pattern over time. These layered materials are considered to be sedimentary rocks [*Malin and Edgett*, 2000b].

28. Layered sedimentary rock units overlain by a massive sedimentary unit (shown here superposed by eolian ripples). These materials are among those described by *Malin and Edgett* [2000b] as ancient sedimentary rock; this example is located in eastern Candor Chasma in M11-02514 near 7.2°S, 69.0°W. Illumination is from the left.

29. Not all repeated-thickness stair-stepped or cliff-bench layered outcrops are confined to the floors of impact craters or large chasm interiors. The layers shown here were preserved from removal by being protected beneath the ejecta of an impact crater on the intercrater plains of west-central Arabia Terra (inset). A portion of the crater ejecta blanket is seen at the upper left and gives the terrain at the upper left a

lobate character. All of the surfaces shown here were subsequently mantled by dust. This is a portion of M08-06185 near 13.5°N, 324.6°W and the inset is a portion of the simultaneously acquired context frame, M08-06186; illumination is from the left.

30. Early views of layers exposed in martian cratered highlands. (A) Layers along stepped scarp in west-central Arabia Terra, SP2-53403, 19.2°N, 353.6°W, illuminated from the left. (B) Layers in the wall of Tinto Vallis in SP1-21506 near 3.4°S, 248.9°W; illuminated from the upper right. (C) Layers the in upper wall at the intersection of an impact crater and a fretted terrain valley in northern Arabia Terra, SP2-46502 near 38.3°N, 320.8°W, illuminated from the right.

31. “Cartoon” sketch portraying a cross section through typical martian cratered highlands upper crust, based upon work presented by *Malin and Edgett* [2000b]. Impact craters up to several hundred kilometers in diameter may form and become completely or partially buried by subsequent deposition of impact, volcanic, and sedimentary material. Craters and cratered, erosional surfaces are preserved within the upper crust, and in some cases have been exhumed or partially exhumed (e.g., in western Arabia Terra). MOC NA images from the Valles Marineris suggest that this layered model may apply to depths of the order of 10 km below the present martian surface in some regions.

32. Viking orbiter view (413S27) of Reull Vallis near 39°S, 249°W, provided pre-MGS evidence for large amounts of exhumation and burial in the martian cratered highlands. In this case, the valley has been superposed on and cut down through the rims of a partly-filled crater (arrows at center-right) and may also have cut through a massif (arrow at left). Superposition of a valley such as this is reminiscent of the imposition of the Susquehanna River upon the Appalachian Mountains of Pennsylvania; these relations imply the previous burial and subsequent re-exposure of the topographic features through which the valley is cut. Illumination is from the top/upper right.

33. Viking orbiter view of craters in various states of exhumation in Noachis Terra between 46.3°S and 50.9°S, 345.2°W and 359.5°W. Crater (A) is completely filled, crater (B) has large pits that separate the filling material from the crater rims and walls, crater (C) appears at this scale to be well-preserved but also exhibits evidence of a remnant of filling material. Finally, the mesa at (D) appears to be a remnant of material that once filled the large crater that it occupies. This picture is from the U.S. Geological Survey's Mars Digital Image Mosaic (MDIM).

34. Long considered to be possible volcanic or periglacial landforms, the large number of isolated and linked mounds, many of which have summit depressions nearly as wide as each mound, appear in MOC NA images to be the result of removal of a layer of material several tens of meters thick from the surface of Isidis Planitia. The mounds and their attendant pits are a combination of old collapse-pit chains and impact craters. Arrows in (A) indicate buttes composed of the material that has been largely removed but still partly-covers craters; arrow 1 in (B) indicates a similar relation, while arrow 2 indicates a crater at the top of a mound that is still partly-filled by yet another layer of material. Both (A) and (B) are illuminated from the left; (A) is from M04-02307 near 13.1°N, 275.6°W, (B) is from M23-00512 near 9.8°N, 271.9°W. Chains of craters atop mounds are common in Isidis Planitia, typical examples are indicated by arrows in (C). A picture from the Hephaestus Fossae of Elysium Planitia in (D) offers a clue as to the origin of the chains in Isidis—the arrows 1 indicate a chain of deep collapse pits common throughout the Hephaestus Fossae, arrows 2 and 3 indicate older pit chains that now appear raised above the surrounding plain. A similar origin is suggested for the chains of mounds and pits in Isidis Planitia. Picture (C) is from M22-02105 near 18.1°N, 268.7°W; picture (D) is from M21-00922 near 19.5°N, 236.4°W; both are illuminated from the left.

35. Exhumation of a heavily cratered surface from beneath layers and lava flows off the east side of the Elysium Rise near 24°N, 206°W. (A) Context image showing a valley, the white box indicates the MOC NA view in (B), the picture is from the U.S.

Geological Survey Mars Digital Image Mosaic. (B) Narrow angle view of upland (top half) and valley floor (lower half) in SP1-21903. Sub-frames in (C) and (D) exhibit differing degrees of mantling on the upland (C) versus valley floor (D). Picture (E) is a close-up of the two craters emergent from beneath the valley's layered north wall. Picture (A) is illuminated from the right, subframes of SP1-21903 (B–E) are illuminated from the lower right.

36. Wind-eroded, light-toned mound in Trouvelot Crater at 16°N, 13°W. (A) Mosaic of (from left to right): M10-03468, SP2-53203, M00-01346. The gap in M10-03468 results from lost data. (B) Viking orbiter mosaic showing Trouvelot Crater in the U.S. Geological Survey MDIM. (C) Sub-frame of SP2-53203 in which a remnant of the light-toned yardang-forming material is seen some distance from the main body of material, indicating that it was once more extensive. Both (C) and (D) also indicate that the light-toned material was deposited on a previously-cratered and eroded surface, (D) shows a pedestal crater emergent from beneath the light-toned material. (E) Light-toned material on the southern wall of Trouvelot indicating that the unit was once much more extensive and perhaps covered much of the basin floor. The MOC views are illuminated from the left.

37. Examples of ripple-like bedforms of light-, dark-, and intermediate-tone. (A) Light-toned bedforms amid dark mantled surface in Terra Sabaea; M02-03360 near 6.6°S, 343.3°W. (B) Typical light-toned bedforms on floors of martian troughs and valleys; example from Nirgal Vallis; M04-00785 near 28.5°S, 41.8°W. (C) Example of dark-toned bedforms in inter-mountain terrain of the northeastern Hellas rim region; M00-01300 near 27.5°S, 281.6°W. (D) Typical bedforms of tone or albedo equivalent to that of the surrounding terrain, interpreted in this case to be mantled by dust; located in Tractus Catena; SP1-26703 near 26.0°N, 101.3°W. (A)–(C) are illuminated from the left, (D) from the lower right.

38. Examples of low-albedo dunes over-riding light-toned ripple-like bedforms. Arrows indicate locations of unambiguous superposition relationship. (A) Nili Patera caldera floor, M10-01512, near 9.1°N, 293.0°W. (B) Far northeastern Syrtis Major,

M11-01038, near 17.1°N, 282.3°W. Both views are illuminated from the lower left.

39. Some of the variety of low albedo dune shapes. (A) Thick sand sheet with drifts behind buttes poking out through the sand covering the floor of western and central Ganges Chasma; M00-00030, near 8.3°S, 51.3°W. (B) Dunes with rounded, rather than sharp, features and no obvious slip face at the present time; M15-01891, southern high latitude crater floor at 67.0°S, 173.3°W. (C) Barchan dunes in the north polar region; M02-02835, near 78.7° N 255.1° W. (D) Barchan dunes with broad stoss and low, small slip faces and stubby horns; M02-00783, near 84.8° N, 26.2° W. (E) Horns of barchan dunes extended downwind (toward lower right) to become seif dunes; M01-00179, near 82.2° N 76.5° W. (F) North polar dunes forming a rectilinear pattern; M02-01917, near 80.1°N, 167.9°W. Illumination is from the left in all examples.

40. Example of search for evidence of eolian dune movement, in this case over a ~11.5 Mars-year interval between a Viking orbiter image from 1978 and MGS MOC image from 1999. Dune slip faces indicate their transport direction is toward the lower left. Limited by the poorer resolution of the Viking image (~17 m/pixel), there is no evidence that the dunes moved (changed position relative to each other and/or substrate landforms) during the interval between the two pictures. (A) Area of overlapping views of dune field; Viking image 709A42 on the left, MOC image M10-02916 on the right. (B) Full Viking image 709A42 with location of overlapping coverage indicated by white box. (C) Close-up view of some of the dunes as seen in the MOC image. The dune field is located in a western Arabia Terra crater at 1.6°N, 351.6°W. Both the Viking and MOC images are illuminated from the left. North is up in the map-projected views of A and B.

41. Examples of avalanching on dune slip faces. (A) Arrow indicates the largest avalanche feature on the slip face that runs diagonally across this scene from an impact crater at 20.1°N, 280.6°W, M11-03072. (B) Dark streaks indicating downslope movement of sediment on dunes in Rabe Crater, FHA-01006, 44.2°S, 325.5°W. (C) Deep avalanche scars on dune in Kaiser Crater, M07-04545, 47.0°S,

340.6°W. (D) Avalanche scars on dune in Rabe Crater, M17-01061, 43.9°S, 325.5°W. North is toward the upper right and illumination from the left in each.

42. Grooved dunes in Herschel Basin, indicating wind erosion of indurated surfaces, M02-01996, 15.8°S, 228.7°W, illumination from the left.

43. Examples of eolian bedforms at high altitude on the Tharsis volcanoes. (A) Bedforms in trough on upper east flank of Olympus Mons, SP1-20805, near 19.1°N, 132.4°W, illuminated from the lower right. (B) Bedforms on flank and in channel on high southern slopes of Arsia Mons, M02-01563, near 8.2°S, 119.6°W, illuminated from the top/upper left.

44. Arrows indicate examples of inferred granule ripples on eolian dune surfaces. Ripples such as these are common on the stoss surfaces of terrestrial dunes [*Sharp,* 1963], but only the largest examples would be visible to MOC with its maximum resolution of 1.5 m/pixel. (A) Ripples in swale between two large, broad dunes in a crater at 20.1°N, 280.6°W, M11-03072. (B) Ripples on dunes in a crater at 47.6°S, 326.2°W, M02-01818. Light-toned materials in the second example are patches of frost. Both views illuminated from the left.

45. Examples of light toned ripple-like bedforms of “megaripple” scale [*Greeley and Iversen,* 1985, p. 154]. In these examples, the bedforms show relations to local-scale topographic features. (A) Bedforms in troughs of Auqakuh Vallis, M12-00991, near 29.2°N, 299.6°W. (B) Bedforms in craters and on plains surrounding craters and buttes of Isidis Planitia, M10-02671, near 18.1°N, 272.4°W. Both views are illuminated from the lower left.

46. Cratered dunes interpreted to be paleo-dunes possibly exhumed from beneath the ridged, yardang-forming material to the immediate north of the dune field in the Apollinaris Sulci region. Two MOC image examples, M03-00006 and M07-05007, are shown. The context view (upper left) is a cropped mosaic of Viking orbiter images 436S03, 436S04, and 436S05. The images are illuminated from the left and cover the area around 12.8°S, 181.9°W.

47. Examples of mantled, cratered, and partly-exhumed ripple-like bedforms. Many of the ripple-like bedforms on Mars appear to be old, inactive, and in some cases indurated. (A) Arrow 1 indicates bedforms completely covered by dark-toned, smooth-surface mantle; 2 shows the light-tone of some of these bedforms when partly exposed from beneath the dark-toned mantle; 3 indicates bedforms partly exhumed from beneath the mantling layer; M19-01045, near 6.1°S, 228.0°W. (B) Partly-mantled bedforms of tone lighter than the overlying material; arrows indicate covered and partly-covered examples; M19-01839, near 13.0°S, 160.8°W. (C) Bedforms poking out from beneath dark-toned mantle and/or dune material. Arrow 1 indicates bedform, arrow 2 indicates one of several boulders superposed on the bedforms and mantle that have come down from adjacent cliffs in Noctis Labyrinthus near 11.2°S, 97.0°W, M19-00561. (D) Light-toned bedforms surrounded by, and probably embayed by, dark-toned mantle in Sinus Sabaeus region. Arrows indicate impact craters superposed on the bedforms, indicating that these features are relatively old and inactive; M17-01225 near 10.8°S, 326.0°W. (E) Cratered bedforms (examples indicated by arrows) on upland near Ius Chasma, M19-02044, 5.5°S, 83.9°W.

48. Wind streak changes observed in 1.1 Mars-year interval between July 25, 1998 (L_s 5°, SP2-44906) and August 10, 2000 (L_s 33.8°, M18-00622), on Tharsis plains northeast of Olympus Mons at 24.2°N, 121.0°W. The SP2 image is illuminated from the right, the M18 picture from the left.

49. Detailed view of a wind streak associated with an impact crater in western Daedalia Planum near 10.1°S, 142.9°W. The surface outside the streak, to the north and south, is covered by a grooved mantle. The streak interior, however, lacks this grooved mantle and might either indicate that the mantling material was not deposited in the streak, or that the mantle has been stripped completely away within the streak. Inset at upper left shows the context of the high resolution view. Context and high resolution images were acquired at the same time; context image is from M08-03123, narrow angle image is from M08-03122; both are illuminated

from the left.

50. Impact craters on the martian northern plains with seasonal wind streaks composed of frost. Crater in upper left is centered at 70.5°N, 93.5°W; crater in lower right is located at 70.0°N, 74.8°W. In 2000, the streaks appeared in early spring before the retreating north polar seasonal frost cap reached their latitude, and, as shown here, persisted after the cap edge had moved farther north. MOC red WA camera image M18-01255, illumination from the left/lower left.

51. Dark wind streaks on or in frost-covered surface during southern spring at 73.6°S, 305.8°W. Streaks follow local topography, with tapered ends pointing downslope. From M07-00243, this scene is illuminated from the lower right.

52. Wind streaks that appear on or in seasonally-frosted surfaces disappear or become indistinguishable when the frost is gone. The two MOC subframes shown here cover the same territory near 87.0°S, 188.4°W. The picture on the left shows a frost-covered and wind-streaked surface in early spring (L_s 196°; August 28, 1999; M04-03806), the picture on the right shows the same surface in late summer after the frost had retreated (L_s 344.8°; May 2, 2000; M15-00118). Both pictures are illuminated from the upper left.

53. Examples of long, thin, filamentary streaks and dust devils caught-in-the-act of creating similar streaks. (A) Typical northern mid-latitude streaks in Utopia Planitia near 53.4°N 274.4°W, M03-04335. (B) Typical southern mid-latitude streaks in Noachis Terra near 55.9°S, 324.9°W, M10-00732. (C) Rare, light-toned streaks (relative to surrounding terrain) in Syria Planum near 13.0°S, 102.8°W, M10-00638. (D) Typical streaks of Argyre Planitia, near 49.4°S, 41.0°W, M09-06457. (E) Typical character of streaks superposed on dunes (distinguish from short streaks on slip faces, which are caused by avalanching) Rabe Crater, near 44.1°S, 325.6°W, FHA-01006. (F) Streaks crossing terrain contact on Argyre Planitia near 48.8°S, 40.2°W, M10-00592. (G) Curled streak in summit caldera of Ulysses Patera near 2.4°N, 121.4°W, M10-00489. (H) Dust devil forming streak in east

Terra Meridiani near 2.6°S, 350.1°W, M09-00193. (I) Dust devil associated with streak in Promethei Terra at 54.1°S, 242.8°W, M10-01267.

54. Examples of dust devils with no surface streak. (A) Dust devil on October 14, 1999, in western Daedalia Planum near 10.0°S, 143.0°W, M08-03122, illumination from the lower left. (B) Dust devil on July 11, 1999, in Melas Chasma near 10.1°S, 74.4°W, M03-01869, illumination from the left/upper left. (C) Red wide angle camera view of multiple dust devils (arrows) on northern Amazonis Planitia on May 17, 1999, near 35°N, 154°W, M01-02267, illumination from the lower left. (D) Red wide angle camera view of dust devils (arrows) in upland southeast of Solis Planum near 31°S, 71°W, on May 18, 1999, M01-02412, illumination from the upper left.

55. Example of changes in long, thin, filamentary streak patterns over time. In this case, streak patterns on low-albedo dunes in a crater at 20.1°N, 280.6°W, are completely different after a 0.94 Mars-year interval between April 1998 (L_s 308°; SP1-23008) and January 2000 (L_s 286°; M11-03072).

56. Example of disappearance of long, thin, dark filamentary streaks after only a 0.2 Mars-year interval near 61.2°S, 332.7°W in Noachis Terra. (A) M15-00685 on May 10, 2000, at L_s 349° (B) M19-01611 on September 23, 2000, at L_s 53°.

57. Example of long, thin, filamentary streak observed in Viking orbiter images that was still present in MOC images more than 10 Mars years later because it results from surface configuration rather than wind vortex/dust devil passage. (A) U.S. Geological Survey mosaic of Viking orbiter images of Proctor Crater at 48°S, 330°W. Arrows indicate one of several prominent, long, thin, filamentary streaks. White box indicates location of MOC image subframe to the right. North is up, illumination is from the right. (B) Subframe of MOC image M03-06827 (illumination from the upper left), showing that the physical nature of the dark streak observed in the Viking images is a product of several combined geomorphic features—the contact between a bumpy plain and a ridged plain of ripple-like bedforms, a ridge

indicated by the arrows (approximately 60 m high in MOLA data), and the presence of patches of dark, smooth-surface material along this ridge. Several additional MOC narrow angle images cross this and other dark, thin, filamentary streaks in Proctor crater (e.g., M02-01510), and they show the same relations. When reduced to the scale of the Viking images, the MOC images show the lineations to have the same width and albedo relative to the surroundings as was observed in the Viking pictures.

58. Examples of pedestal craters observed by the MOC NA camera. (A) Small pedestal craters on lower northwest flank of Apollinaris Patera, indicating removal of a mantle of material from the surface of this volcano; located near 7.3°S, 185.6°W, M12-02590. (B) Crater (left) with blocky ejecta outlined by scarp at 51.9°S, 24.4°W, M15-00485. Additional pedestal craters can be seen in Figure 36. Each is illuminated from the left.

59. Example of terrain in Mangala Valles region. This picture, M07-03611, shows a streamlined landform within the valley. The primary features related to valley formation are not visible at this scale, however, because the surface is completely mantled with a material that has been subsequently eroded by wind to form ridged-and-grooved patterns (yardangs). Box at lower right shows the context within Mangala Valles; it is from red WA image M07-03612. Both pictures are illuminated from the left/lower left and are located near 8.4°S, 154.6°W.

60. Meter- and decameter-scale landforms created by wind erosion. (A) Ridged-and-grooved mantle unit atop lava flows of western Daedalia Planum, M03-00713, near 3.5°S, 133.7°W. (B) Pits developed around boulders on low, rounded hill in Mangala Valles region; pits may have formed by eolian erosion/scour, M11-01809, near 8.8°S, 151.4°W. (C) Triangular-shaped drifts or mantle deposit remnants on lee side of small topographic obstacles on east flank of Olympus Mons, SP1-20805, near 19.1°N, 132.1°W. (D) Triangular-shaped drifts or mantle deposit remnants on lee side of topographic obstacles on northwest flank of Ceraunius Tholus, M04-01565, near 24.5°N, 97.7°W. A, B, and D illuminated from the left, C

is from the lower right.

61. Early view of north polar layers. MOC NA images reveal many more and thinner layers than could be seen in Viking and Mariner 9 pictures. (A) Viking orbiter image 560B60, illuminated from the left, with strip indicating location of MOC NA image SP2-46103, black box indicates location of sub-frame shown in (B) near 79.1°N, 340.8°W. The SP2 image is illuminated from the right.

62. Typical surface morphology of south (A) and north (B) residual caps. (A) The south polar cap exhibits layers, mesas of typically a few meters relief, and many circular features that give the terrain a resemblance to swiss cheese; M09-05133; 87.1°S, 95.4°W. (B) The north polar cap typically appears pitted, with pits of only a few meters depth; CAL-00433; 86.9°N, 207.5°W. To facilitate comparison, both views are shown at the same scale and oriented such that illumination comes from the upper left.

63. Banded slopes on mesa in south residual cap at L_s 306°, M12-02295; 87.0°S, 341.2°W. The bands might be alternating light and dark layers. Illumination is from the upper right.

64. Spring (A) and summer (B) views of the south polar residual cap at 86.5°S, 344.7°W. The darkening of surfaces in the summertime view suggests that the light-toned material—presumed to be CO_2 or H_2O ice—is not very thick. (A) The spring view is at L_s 254° (M10-00093) and the (B) summer view was taken three months later at L_s 320° (M13-01121).

65. Dark lane crossings in (A) north polar cap, M00-02072; 86.0°N, 258.4°W and (B) south polar cap, M08-05817; 86.8°S, 350.8°W. The north polar dark lane is a trough with layers exposed on the equatorward slope, the south polar dark lane is a broad cliff-bench, layered, equator-facing scarp. Illumination is from the upper left in both pictures.

66. Typical layer expressions in the polar terrains: (A) stair-stepped in the south, M13-

00253; 87.0°S, 187.7°W, and (B) ridged-and-troughed in the north, SP2-52406; 86.3°N, 199.2°W. The first picture is illuminated from the upper left, the second from the left.

67. The south polar layered materials exhibit evidence of being competent, including the support of relatively steep slopes in gully walls, the ability to form mesas, and to permit saltation and sand dune transport. South polar layered unit surfaces in planview; (A) gullied surface, M12-00288; 77.9°S, 193.0°W; (B) smooth, mesa-forming units (light-toned), M09-06148; 79.6°S, 298.3°W; (C) typical rugged polar surface, M12-00563, 86.7°S, 264.9°N; (D) eolian dunes traveling across layered terrain surface, M12-00230; 76.7°S, 195.4°W. Illumination is from the upper left in A, C, D, and from the top/upper left in B.

68. Continuity of polar layers over >100 km distance is exhibited in north polar troughs. This series from a single north polar dark lane includes: (A) M00-01754 near 86.5°N, 281.5°W, (B) M00-02100 near 86.4°N, 278.7°W, and (C) M00-02072 near 85.9°N, 257.9°W. All are illuminated from the upper right, all were acquired in northern summer in April 1999.

69. North polar stratigraphy. These two views show at the same scale different slopes in the north polar residual cap located ~280 km from apart. In both cases, a sequence of lighter-toned, thin, horizontal layers lies atop a series of layers that appear broken or jumbled; in both cases the apparent thickness of the units is the same. (A) M02-01676 near 85.4°N, 167.9°W, illuminated from the right. (B) M03-04769 near 85.0°N, 357.7°W, illuminated from top/upper right. Both scenes are partly obscured by late-summer haze.

70. (A) Example of possible angular unconformity among beds of the north polar layered terrain; SP2-44503 near 84.5°N, 113.9°W. (B) Example of possible deformed beds on slope in north polar trough; SP2-44504 near 83.4°N, 123.7°W. Both pictures are illuminated from the right/upper right.

71. Example of possible deformed beds in north polar trough slope (upper 1/4 of

image); M00-01925 near 81.4°N, 273.1°W, illuminated from the upper right.

72. Representative views of frosted dunes in martian polar regions. On the left is a picture of north polar dunes that have brightened relative to surrounding surfaces in early autumn; M04-02215 near 74.7°N, 61.4°W, illuminated from the upper right. The center and right images show the same south polar dunes observed about 14° of L_s apart—the development of dark spots is characteristic of defrosting dunes in late winter and early spring. Center image is from M02-02528, right is from M03-02916, both are illuminated from the upper left and located near 59.2°S, 343.6°W.

73. Example of seasonal frost monitoring on a polar dune field. In this case, portions of 25 MOC NA views of parts of the Richardson Crater dune field at 72.4°S, 180.0°W, are shown covering a period from late winter (L_s 150°) through spring, summer, and into early autumn (L_s 36°) during 1999–2000. The same location could not be imaged each time the MOC flew over the dunes, but the portions of NA MOC images shown here are representative of the whole image in each case. All are shown at the same scale (each picture covers 2.2 by 3.4 km). The last image in the sequence (right most image in lower row) shows the location of each MOC image. The number in the lower left corner of each picture indicates the local time of day; season, L_s, date, and MOC image identification are indicated beneath each view.

74. Comparison of typical polar dunes without frost (A) and with frost (B). Dark spots develop on frosted dunes during the spring; these dark spots exhibit wind streaks indicative of redistribution of dark material and/or directionally-enhanced erosion of frost. These dunes are located in Chasma Boreale near 84.8°N, 26.3°W. (A) Summer view at L_s 151°, M02-00783; (B) early Spring view at L_s 55°, M19-01611. The interval between the images is 0.73 Mars year, both are illuminated from the upper left.

75. Comparison of defrosting patterns in south polar “Inca City” region at 81.5°S, 64.7°W, from one martian year to the next. In each of these four cases, the first image in the pair is a subsection of AB1-07908 acquired at L_s = 247° (late spring)

in 1997. The second image in each pair is a sub-frame of a Mapping Phase image taken earlier in the subsequent late winter/early spring of 1999; they include: (A) M03-03137, (B) M03-04585, (C) M04-00678, and (D) M07-01552. The original AB1 image has a resolution of about 25 m/pixel; the mapping images were acquired at better than 6 m/pixel. All images shown here were stereographic map-projected at a common scale of 10 m/pixel. Inspection indicates that picture A shows a condition in which defrosting is more extensive in the AB1 image than the mapping image. Picture B shows a condition in which the two images are essentially the same. Pictures C and D show more defrosting in the mapping images than in the AB1 image. Thus, defrosting in 1999 occurred about 70° earlier than in 1997.

76. Comparison of early summer red wide angle views of the martian north polar cap acquired exactly 1 martian year apart at L_s 103°. The outlines in the view on the right indicate areas that appeared considerably more defrosted in the second relative to the first year. The extent of defrosting observed in December 2000 and January 2001 was greater than seen at any time during the previous summer in 1999. (A) Mosaic of red wide angle images CAL-00016 through CAL-00113, acquired on March 1, 1999. (B) M23-01.735, acquired on January 15, 2001.

77. The middle west flank of Olympus Mons is characterized by a lack of distinct lava flows; a pattern of leveed channels mantled by wind-eroded material is seen. This is a portion of AB1-02404, located near 19.9°N, 135.5°W, illuminated from the lower left.

78. Lava flows are more common on the lower flanks of Olympus Mons; this example from SP2-41105 is on the lower southwest flank near 16.3°N, 135.6°W. The picture is illuminated from the right.

79. Distinct flows are uncommon on the middle and upper flanks of Olympus Mons, but a few flows do exist, as seen in this example. The west wall of the summit caldera complex is at the right in this portion of SP2-35605 near 18.6°N, 134.1°W. Sunlight is from the right.

80. Among the Tharsis Montes volcanoes, flows and leveed channels are most commonly seen on Ascraeus Mons. This view, SP1-26705, is from the upper east flank of Ascraeus Mons near 11.2°N, 103.5°W; illumination is from the lower left.

81. Pits on the floor of the Ceraunius Tholus caldera; M16-00055, near 24.3°N, 97.4°W; illuminated from the lower left.

82. Platy flows in Marte Vallis around 6.9°N, 182.7°W. Plates indicate formation and subsequent break-up of a crust on material that flowed from bottom toward top of these pictures. Picture (A) is from SP2-38804, and is illuminated from the right. The location of Picture (B) is indicated in (A) as a white box; this is a portion of M07-01249 and is illuminated from the left. Note that the difference in dark- and light-toned surfaces in the SP2 image resolves into a difference in decameter-scale surface texture in the higher-resolution Mapping Phase image. These materials are attributed to voluminous flood volcanism.

83. Flows similar to those in Marte Vallis found in southern Amazonis, emergent from beneath yardang-forming material (seen at lower right corner) in FHA-01428 near 11.3°N, 161.1°W; illumination is from the upper left.

84. Platy flow material in (A) Echus Chasma/southern Kasei Valles near 6.4°N, 79.6°W, in M09-03515 and (B) Kasei Valles near 24.3°N, 63.5°W, in M07-05848. Both images are shown at the same scale and illuminated from the lower left.

85. Small valleys in Tharsis plains. (A) Channels and flows on plain southeast of Olympus Mons, SP2-43004, 16.0°N, 129.2°W. (B) Valleys and channels of Olympica Fossae; the large deep valleys appear to have formed via collapse; SP2-41306, 24.7°N, 114.9°W. Both images are illuminated from the right.

86. The genesis of valley networks on northwestern flank of Alba Patera may be impossible to determine from orbiter images because the valleys are completely covered by roughened mantle material. (A) Cropped mosaic of Viking orbiter images 252S65 and 252S67. (B&C) MOC NA views from SP2-46803. All views are

illuminated from the lower right and located near 48.8°N, 110.1°W.

87. The surface of the volcano, Apollinaris Patera (inset from M07-04624), has been exhumed from beneath a yardang-forming material. This example is from M00-01038 near 9.3°S, 186.1°W; illumination is from the upper left.

88. The platy flow surfaces of southern Elysium Planitia and southern Amazonis Planitia have relatively few impact craters, leading *Hartmann and Berman* [2000] to conclude that these are among the youngest volcanic materials on the planet. However, the southern margins of both plains exhibit exhumation relations such that the platy flow materials appear to be coming out from underneath yardang-forming material of dozens to hundreds of meters thickness. (A) Examples from the southern Elysium/Cerberus plains, M19-00226, 4.0°N, 209.9°W. (B) Example from southern Amazonis, M03-06170, 13.1°N, 159.9°W. The pictures are all illuminated from the left.

89. Test of *Lucchitta* [1987] “recent mafic volcanism” hypothesis to explain nature and configuration of dark patches along fault scarp at the base of the northern Coprates Chasma wall. (A) A portion of Viking orbiter image 081A04, as was used in the paper by *Lucchitta* [1987], white box indicates location of MOC image in (B), which is a sub-frame of AB1-08105 near 11.6°S, 66.3°W. The authors have seen no unequivocal evidence for volcanism (e.g., flows, vents) in MOC NA images of locations within the Valles Marineris. The dark materials along the lower wall of Coprates Chasma appear to be a combination of dark talus derived from the fault scarp long known to occur there, wind-worked dark material in the form of ripples, and, as in other parts of Valles Marineris, dark mantles of unknown source or origin.

90. Features proposed as small volcanoes prior to the MGS mission. (A) Small vent in Tempe Terra at 36.2°N, 85.1°W; at top is Viking context image 627A28, below is MOC image SP2-50704; both views are illuminated from the left. (B) Small cone with summit depression on west upper flank of Pavonis Mons near 0.8°N,

113.3°W; on left is a portion of Mariner 9 camera B frame 31, from Rev 111 (DAS 5563953), on right is a part of MOC image M19-02048; both views illuminated from the left. (C) Circular depression at summit of deeply-gullied rise in Terra Cimmeria at 20.0°S, 187.2°W; on left is Viking-based MDIM view for context (illuminated from uppe right); on right is a portion of MOC image M07-01737.

91. Small shield volcano in the Arsia Mons caldera; M10-03730, 9.2°S, 120.3°W, illuminated from the left.

92. Very few boulders (arrows in B) are visible on streamlined landforms behind obstacles in the martian outflow channels, indicating that if boulders are present, most of them are smaller than can be resolved in 1.5 m/pixel images. (A) Context in Viking orbiter image 366S06, illuminated from the right. (B) Sub-frame of 1.5 m/pixel image M00-02029, illuminated from the upper left and located near 16.8°N, 33.6°W.

93. Outflow channel surfaces on the Chryse and Acidalia plains typically have a pitted and ripple-textured surface (A), while surfaces in the main channels lack these features (B). These examples are from Ares Vallis and illuminated from the left; (A) M04-01924, near 20.0°N, 35.4°W; (B) FHA-00547, near 16.5°N, 31.9°W; (C) Context in Viking orbiter-based MDIM.

94. Lobate forms in Kasei Valles interpreted as possible mudflows. Bouldery-surfaced flow lobes in (A) are shown in expanded view in (B); these are from SP2-41705 near 15.6°N, 77.7°W, and illuminated from the right. (C) Retreated flow fronts in M15-01873 near 17.0°N, 76.5°W, illuminated from the left, suggest that the flow material is less competent than hardened lava.

95. Valley in the Nanedi Valles system with inner channel exposed in meander near upper right. Illuminated from the left, the inner channel appears to be leveed. Very few images of the Nanedi Valles exhibit inner channels such as this. Picture is from AB1-08704, located near 5.0°N, 48.4°W.

96. Narrow, leveed channel occurs within a wider channel at the center of a portion of Nirgal Vallis. The southern wall of Nirgal is visible in the top quarter of this view from M07-00752 near 29.3°S, 39.2°W (illuminated from the right). Like Nanedi Valles, inner channels are not exposed along the entire length of the valley system; even here the channels have ripple-like bedforms superposed upon them.

97. Valley network with inner channels and streamlined forms in Terra Sirenum, M15-01887, near 35.9°S, 155.3°W; illuminated from the left.

98. The valleys of the Warrego Valles are not all connected to each other, and their genesis is difficult to decipher because primary erosional features are covered by rugged, “scabby” mantling material. (A) Viking orbiter MDIM context for MOC image M02-04864 (inset), showing one of the better branching valley networks within the Warrego Valles; the white box outlines the location of (B), which is a portion of M02-04864 near 42.9°S, 91.7°W.

99. Typical mid-latitude gullies of the type initially described by *Malin and Edgett* [2000a] as resulting from seepage and run-off of a fluid (most likely, water) confined to specific layers within a few hundred meters of the martian surface. These are usually found most often on pole-facing slopes and are characterized by three basic landforms: a channel, an alcove that formed above the channel, and an apron of debris that appears to emanate from each channel. Channels commonly begin at the same layer in a crater or trough wall, the limited extent of aprons indicates that there is a limit as to the amount of material that has flowed through the channels. Picture (A) shows the context within an impact crater for the gullies in picture (B). These are from image M17-00423, illuminated form the upper left and located near 39.1°S, 200.7°W.

100. Locations (white dots) of all known mid-latitude gullies, through January 2001, of the type shown in Figure 99 and described by *Malin and Edgett* [2000a]. Clustered points, as in the Gorgonum Chaos/Newton Basin region, may indicate the location of regional aquifers or paleo-aquifers. Map is a simple cylindrical projection

incorporating shaded relief derived from MGS MOLA and relative albedo from MGS MOC red WA Geodesy Campaign images.

101. Gully aprons superposed on bedforms in Nirgal Vallis indicate the relative youth of the gullies; M19-00386, near 28.4°S, 41.7°W, illuminated from the upper left.

102. Dark-toned, arborescent and braided channels and gullies on a slope within a pit in Noachis Terra near 47.8°S, 354.8°W, in M12-00595. The braiding and junctions between channels suggest liquid flow; the dark tone suggests relative youth because light-toned dust has not mantled these surfaces. Illumination is from the upper left.

103. Meandering and banked channels and light-toned aprons in a crater east of Gorgonum Chaos at 37.4°S, 168.2°W, in M15-01466, illumination from the upper left. Multiple lobes of material, and a shift in channel course from deposition toward lower right to deposition toward the lower left of apron in (B) are evident.

104. Gullies emergent from the same subsurface layer in troughs and crater in Gorgonum Chaos near 38.1°S, 170.3°W, in M15-00538, illuminated from the upper left. These relations are strongly suggests of the presence of a specific layer to which a liquid volatile (i.e., water) is confined and through which this fluid percolates only a few hundred meters below the surface at this location--an aquifer by terrestrial analogy.

105. Typical fretted terrain lineated valley floor landforms in the transition zone between northern Arabia Terra’s cratered highland and the martian northern plains. Brain or corn-like pit-and-mound textures and patterns (C, D) are common when viewed at or near full MOC NA resolution (1.5–3.0 m/pixel). The MOC NA image is SP2-52106 (A, C, D) is located near 40.5°N, 306.1°W and illuminated from the lower left; the Viking context (B) is from 233S12 and illuminated from the right.

106. Southern hemisphere mid-latitude valley and crater floors exhibit landforms similar to those in northern hemisphere mid-latitude fretted terrains. (A) Northern

hemisphere example from Coloe Fossae fretted terrain valley floor, SP2-52106, 40.6°N, 306.2°W, illuminated from the lower left. (B) Southern hemisphere example from Reull Vallis floor, FHA-00591, 41.6°S, 252.9°W, illuminated from the upper left.

107. Circular features on fretted terrain lineated valley floor indicate that the lineated and pitted material has not moved differentially along the trend of the lineations since these circular landforms were created. All of the circular features are assumed to be degraded impact craters. This is a portion of M08-08042, located near 35.1°N, 343.2°W, and illuminated from the lower left.

108. Floors and slopes in closed and open-ended fretted terrain valleys are similar, suggesting that down-valley flow is not a factor in genesis of the basic fretted terrain lineated and pitted floor morphologies. (A) MOC NA example from a closed valley floor, M03-01119, near 36.7°N 335.2°W. (B) Example from an open-ended valley floor, M08-05953, near 36.2°N, 344.3°W. (C) Viking-based MDIM context for closed valley in A; (D) Viking-based MDIM context for open-ended valley in B. All pictures are illuminated from the left/lower left.

109. Fretted terrain valley, crater, and trough walls differ on poleward and equatorward slopes; equatorward slopes tend to be mantled by material that appears smooth at MOC NA scales, poleward slopes usually appear to have less material covering them and in some cases exhibit the local bedrock. Pictures from FHA-00457, near 37.3°N, 325.4°W, illuminated from the lower left.

110. Movement of material from fretted terrain valley walls is suggested by close correspondence between valley wall planitmetric pattern and the planimetric pattern of subjacent lineated material. The example shown here is on a broad slope in a northern Arabia fretted terrain valley near 34.3°N, 303.0°W. Arrows indicate where a crater in the wall appears to have influenced the position of ridges in the valley. Illuminated from the right, this is a portion of SP2-41205.

111. Fretted terrain valleys may have widened by retreat of valley walls. In this example

a crater and its ejecta appear to have been undermined along the valley wall. Debris derived from the valley wall is evident along its base. The lineated, pitted, and bumpy valley floor material appears to be superposed by material that has come from the valley wall, indicating that the two phenomena may be unrelated. This is a portion of M03-03238, located near 37.7°N, 325.3°W, illumination is from the lower left.

112. Outcrops of relatively thin, stair-stepped, layered bedrock may contribute to the lineated character of mid-latitude fretted terrain valley floors and concentric crater floor materials. The three pictures shown here are presented at the same scale. (A) shows stair-stepped layering at equatorial latitudes in a crater at 8°N, 7°W, in image M09-01840. (B) shows similar features on a shallow slope at the base of a fretted terrain valley wall mid-latitude near 38.7°N, 320.8°W, in M19-00517. (C) shows a wavey pattern expressed either by deformed layers or layers exposed on a non-uniform slope (as in A) in a north polar trough at 83.5°N, 122.5°W; SP2-44504. Figures (A) and (C) show known layer outcrop expressions, (B) is proposed to also be an expression of layers.

113. Layers in impact craters at mid-northern latitudes. (A) Roughened, fretted terrain-like textures on a terraced mound in a crater at 23.6°N, 289.9°W in SP1-26603. (B) and (C) Layered mesas in two craters on the northern plains at 35.4°N, 277.0°W, both from SP2-43304. All three pictures are illuminated from the right.

114. Comparison of concentric crater interior materials with north polar layers. (A) Layers expressed as resistant ridges and less-resistant troughs in concentric crater interior material, M03-03019, 35.9°N, 284.5°W, illuminated from the left. (B) North polar layers expressed as resistant ridges and less-resistant troughs, M18-00804, 86.7°N, 282.9°W, illuminated from the lower left.

115. Traverse of fretted terrain apron in Deuteronilus Mensae by image SP1-20504 at 40.2°N, 337.6°W. (A) and (B) show the context in a Viking orbiter-based MDIM view, (C) is a MGS MOLA profile acquired at the simultaneously with the SP1

image and correlated using spacecraft event time, (D) through (L) show sub-frames of the SP1 image starting on the mesa surface and going south to the dark plains beyond the apron boundary.

116. Circular features (arrows) on fretted terrain apron suggest that the material differential motion within the apron has not occurred since the craters were formed; today the craters' morphology is sufficiently altered as to call into question the processes that created them. (A) M10-02711, 42.6°N, 333.3°W, illuminated from the right; (B) Viking orbiter image 267S24, illuminated from the lower right.

117. Beneath the surface of the northern plains may lie an older, heavily cratered surface. This example is from Utopia Planitia; M02-04189 near 48.0°N, 228.1°W, illuminated from the lower left.

118. Buried and partly-buried craters on the northern plains often exhibit small dark spots on their rims and sometimes in the location of their buried ejecta. These are interpreted to be boulders that have perhaps worked their way to the surface and/or were never covered by the thin northern plains surface mantle; M03-04941 near 68.2°N, 257.9°W, illuminated from the lower left.

119. Rings of boulders (small dark dots) indicating buried or partly-buried crater rims on the martian northern plains; M02-01076, 50.7°N, 292.3°W; illuminated from the lower left.

120. Thinly-buried northern plains impact crater and rayed ejecta near 47.2°N, 227.8°W; M09-05353, illuminated from the lower left.

121. Example of bouldery knob protruding from northern plains; M09-00978 at 50.3°N, 194.0°W, illuminated from the lower left.

122. Cluster of craters on the martian northern plains that have been exhumed and exhibit remnant layered mesas on their floors; M15-00944, near 36.3°N, 281.9°W, illuminated from the lower left.

123. Examples of martian periglacial features in the form of patterned ground at middle and high latitudes. (A) Patterned ground/polygons near the Viking 2 lander site, M03-07241, 48.0°N, 225.6°W, illuminated from the left. (B) Polygons on crater floor at 65.7°N, 231.8°W, M00-00602, illuminated from the lower left. (C) Polygons outlined by dark boulders on Lyot Crater ejecta surface, M19-01493, 54.5°N, 326.9°W, illuminated from the lower left. (D) “Basketball” textured surface of evenly-spaced mounds amid north polar dunes at 78.5°N, 215.7°W, M01-00063, illuminated from the upper right. (E) Striped pattern of mounds on northern plains near 72.4°N, 252.6°W, M02-04009, illuminated from the lower left.

124. Example of MOC NA camera test of pre-MGS northern plains coastal landform hypothesis, keyed specifically to shoreline features proposed by *Parker et al.* [1993] in their Figure 2a. (A) Portion of Viking orbiter image 129A32, illuminated from the left, at the northwestern edge of Acheron Fossae. The is the same image as used by *Parker et al.* [1993]. White box indicates the location of MOC NA image M11-02987 near 39.6°N, 140.4°W. (B) Portion of M11-02997 indicated by the black box in (A). (C) Expanded view of a part of M11-02997 as indicated by white box in (B). Illumination in M11-02997 is from the lower left. *Parker et al.* [1993] noted a series of subtle, parallel bands on the upland separating the plains in the northwest corner of from the southeastern two-thirds of (A). These bands were proposed to indicate former coastlines similar to those seen in aerial photographs of Pleistocene Lake Bonneville in Utah. However, MOC image M11-02987 shows that the contacts between the bands are expressed as low escarpments that face toward the upland of Acheron Fossae—in other words, the scarps face the opposite direction that a scarp cut by coastal erosion would exhibit. The units marked 1, 2, 3, in (C) are the subtle bands, each resolves into a relatively thin layer of differing surficial textures.

125. Example of a MOC NA image test of martian northern plains coastal landform hypothesis. Picture (A) is from Viking orbiter image 076B84 and is the same as the picture used by *Parker et al.* [1993] in their Figure 2b to describe a similarity to

landforms in Pleistocene Lake Bonneville. The white box inset indicates the location of MOC NA image M19-01289, which covers a portion of a knob on the northern plains at 45°N, 186°W. Pictures (B) and (C) present the MOC image in increasing resolution; the white box in (B) is the location of the image in (C). All of the images are illuminated from the left. Each knob in (A) was observed by *Parker et al.* [1993] to have a series of terraces around their lower slopes; these were proposed to be wave-cut features. The higher resolution of the MOC NA image shows that the terraces or concentric striations surrounding the knob photographed in M19-01289 are subtle, discontinuous undulations expressed in (or through) a relatively smooth mantle that covers the lower slopes of the knob.

126. Craters with flat, bouldery rims poking through or thinly-covered by plains-forming material are common at middle and high latitudes in both martian hemispheres, suggesting that ocean sedimentation is not a primary contributor to the processes that have covered and obscured these landforms on the northern plains. This example presents a crater on the northern plains (left) and two in the southern highlands (right; located several kilometers above the martian datum) at the same scale. Both are at latitude 50°. The geomorphic expressions of the craters and surrounding plains are similar in the two locations despite being in different hemispheres , in different geologic settings, and at different altitudes (Δ altitude = 3 km). (A) M03-03063, near 50.3°N, 315.5°W, illuminated from the lower left. (B) M18-00069, near 50.5°S, 315.6°W, illuminated from the upper left.

127. While rings of boulders indicating the presence of thinly-buried impact craters are common on the northern plains (e.g., Figures 118, 119), excellent examples are also found at middle and high latitudes in the southern hemisphere at elevations several kilometers above the martian datum. Because of the topographic difference between the southern highlands and northern plains, these landforms in the south suggest that ocean sedimentation may not be responsible for the burial of craters in the north. This southern hemisphere example is located in south Aonia Terra near 67.4°S, 100.2°W; this example is from M11-00590, illuminated from the

upper left.

128. Large, dark boulders transported down slopes in troughs and valleys in volcanic regions provide an example of one of the forms of mass movement on Mars. This is an early MOC example from image AB1-02003 in the Elysium Fossae troughs near 26.1°N, 223.64°W. The picture is illuminated from the left.

129. Examples of boulder tracks on martian slopes. (A) Schiaparelli south rim, 5.9°S, 343.6°W, AB1-11104, illuminated from upper left; (B) Crater wall at 34.7°S, 151.7°W, in M19-00080, illuminated from the upper right; (C) trough wall in Noctis Labyrinthus, 7.2°S, 95.4°W, M12-02743, illuminated from the lower right; (D) trough wall in east Candor Chasma, 6.5°S, 69.2°W, M12-01405, illuminated from the right.

130. Large landslide surface. (A) Full-resolution MOC NA view of boulders on landslide in Ganges Chasma, FHA-00485, 8.6°S, 45.0°W, illuminated from the upper left; (B) location of the MOC image relative to the entire landslide as seen in U.S. Geological Survey Viking orbiter-based MDIM.

131. Large landslides do not exhibit evidence for liquid flow or “dewatering” of the materials out beyond the terminus of the deposit. (A) Landslide and terminus in Ganges Chasma, M02-02906, 8.2°S, 44.9°W, illuminated from the left. (B) Landslide and terminus in Ophir Chasma, M12-02556, 4.3°S, 71.6°W, illuminated from the lower left.

132. Light- and dark-toned slope streaks together in central Arabia Terra near 13.8°N, 323.8°W, in M12-02375, illuminated from the lower left.

133. Appearance of 4 new dark slope streaks (compare features at arrows in B and C) after a 0.92 Mars year interval. (A) and (B) are subframes of AB1-11304 acquired February 1, 1998; (C) is from M09-04872, obtained November 18, 1999. These are located in a crater at 6.0°S, 183.8°W. All three views are illuminated from the lower left.

134. Dark slope streak with apex intersected by long, thin, faint dark streak. Located on the northwestern basal scarp of Olympus Mons, this picture suggests that a passing dust devil may have created the long, thin, faint streak (A) and triggered the motion that created the broad, downslope-widened dark streak (C). The intersection is indicated in the inset at (B). This is from M10-00662 near 23.4°N, 136.4°W, and is illuminated from the upper left.

135. Rampart crater with terminal ridge, at the contact between Tharsis plains and the lower east flank of Ascraeus Mons at 9.5°N, 102.4°W. Under the nomenclature recently proposed by Barlow et al. [2000], this crater is classified as “single-layer ejecta rampart sinuous”. As with all MOC NA images of craters exhibiting rampart or what we have called “fluidized” ejecta, there are no small channels on the ejecta or on the adjacent plains that would indicate fluid flow beyond the ejecta margins (e.g., “dewatering”) as might occur if these were emplaced as mudflows. MOC image M19-01972, illuminated from the left; the context picture (upper left) is from Viking orbiter image 892A34, illuminated from the right.

136. Impact crater in northern Elysium Planitia at 33°N, 238°W. None of the martian craters exhibit evidence of fluid flow beyond the margins of the primary ejecta blanket, placing at least a qualitative limit on the amount of liquid volatile that may have been involved in their emplacement. Picture is from SP2-43704, illuminated from the right.

137. Examples of small, relatively fresh rayed impact crater ejecta. (A) Impacted into a dust-mantled surface is a 30 m diameter rayed crater on the southeastern summit of Ulysses Patera, M08-01170, 2.4°N, 121.3°W, illuminated from the left. (B) Rayed crater with multiple light- and dark-toned ejecta facies (possibly indicating penetration through light- and dark-toned layers), Cerberus/Elysium plains, M19-01991, 0.4°N, 187.1°W, illuminated form the upper left. (C) Rayed crater example in northern Crommelin Crater, M14-02051, 5.6°N, 10.0°W, illuminated from the lower left. (D) Large, dark, rayed ejecta in north-central Tharsis at 17.2°N, 113.7°W, M10-02045, illuminated from the lower left; the context frame is from

Viking orbiter image 516A55; no MOC NA image of the crater cavity for the latter was obtained through M23.