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An overview of the 1985–2006 Mars Orbiter Camera science investigation

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Abstract

Background: NASA selected the Mars Orbiter Camera (MOC) investigation in 1986 for the Mars Observer mission. The MOC consisted of three elements which shared a common package: a narrow angle camera designed to obtain images with a spatial resolution as high as 1.4 m per pixel from orbit, and two wide angle cameras (one with a red filter, the other blue) for daily global imaging to observe meteorological events, geodesy, and provide context for the narrow angle images. Following the loss of Mars Observer in August 1993, a second MOC was built from flight spare hardware and launched aboard Mars Global Surveyor (MGS) in November 1996. The spacecraft began orbiting Mars on 12 September 1997 and operated until 3 November 2006.

Results: From launch until the end of the mission, the MGS MOC returned 243,668 images, 97,097 of which were acquired by the narrow angle camera. By mission's end, the narrow angle images covered 5.45% of the planet's surface at better than 12 m/pixel, and ~0.5% of Mars at better than 3 m/pixel. The MGS Mars Relay (MR) antenna utilized the MOC buffer to return data from landed spacecraft on Mars. In particular, the MR system relayed mission–critical Entry, Descent, and Landing data from the Mars Exploration Rovers (MER) in real time in January 2004. In total, the MR, through the MOC buffer, returned 7680.26 Mbits of telemetry and science data from the MERs. Major science results of the MOC investigation include recognition of exposures of water-lain sedimentary rock; evidence of persistent water flow across the Martian surface and ponding in a body of standing water; the discovery of gullies that might indicate the presence of liquid water in the recent past and possibly at the present time; observation of rapid geomorphic change, perhaps indicating on-going climate change, in landforms composed of solid carbon dioxide at the Martian south pole; geomorphic evidence for ancient rainfall in the form of inverted hillslope rills and first-order streams; documentation of the present-day Martian impact cratering rate—a first for any body in the Solar System; observation of a planet–encircling dust event and recognition that there really are no truly global dust storms; and documentation of the repeatability of Martian weather events from year to year (which has a direct impact on the ability to predict future conditions for spacecraft that will enter the Martian atmosphere). MOC was used to support every U.S. mission to Mars for a decade; activities included imaging of candidate landing sites, monitoring weather during orbiter aerobraking periods, observation of weather at landing sites, imaging of landed hardware, the search for missing landers, and relay of data through the MR system.

Conclusions: The scientific success of the $44 million, 20.5 year MOC investigation hinged upon a combination of factors, including how the instrument was operated (by a small, dedicated team that frequently discussed the results, posed hypotheses, and used the cameras to test those hypotheses); the high spatial resolution (relative to previous missions) of the narrow angle camera; the multiple extensions of the mission, resulting in 4.04 Mars years of systematic observation of meteorological events and greater areal coverage and opportunities for repeated imaging by the narrow angle camera; and the addition of off-nadir and higher down-track spatial sampling capabilities during the extended mission.

Introduction

The Mars Orbiter Camera (MOC) science investigation revolutionized our collective view of the geologic diversity and nature of the modern meteorological conditions of Mars. Selected in 1986 for the Mars Observer (MO) mission, and then re-flown on Mars Global Surveyor (MGS) after MO was lost, the MOC consisted of three instruments: a narrow angle camera that typically acquired images of spatial resolution between 1.5 and 12.0 m per pixel and two wide angle cameras (one with a red filter, the other blue) for 0.24 to 7.5 km per pixel imaging of the Martian surface and atmosphere. The MOC was also an integral part of the Mars Relay (MR) system, as the 12 MB RAM buffer within the MOC was used to store data relayed to Earth from landed hardware through the MR UHF antenna.

The MGS MOC returned 243,668 images to Earth. In addition, 7680.26 Mbits of telemetry and science data were received after relay from the Mars Exploration Rovers (MER) through the MR and MOC buffer. Over the course of the MGS mission, the MOC wide angle cameras returned 62,571 systematic, daily global image swaths (31,123 red; 31,448 blue) for meteorological investigation nearly every day for a period of 4.04 Mars years; these were interrupted by solar conjunction periods, spacecraft contingency and safe mode upsets, and occasional Deep Space Network (DSN) coverage/downlink issues, but otherwise form a nearly continuous record. The narrow angle camera images, which totaled 97,097, covered 5.45% of the planet's surface by the time the mission ended in early November 2006 at a resolution higher than 12 m/pixel, and ~0.5% at a resolution higher than 3 m/pixel.

The purpose of this paper is to summarize the MOC investigation, instrument, and major results. We recognize that describing the overall scientific results of the investigation will require hundreds of pages and hundreds of illustrations; further, a detailed description of all aspects of the instrument development and operation would likewise fill many dozens of pages. To that end, the authors began work in 2007 on a comprehensive MOC final report that we anticipate will take several more years to complete. In the meantime, we decided to publish the present, shorter report so that MOC data users and others would not have to wait for the final report.

Science objectives

The Mars Observer mission was designed to last one Martian year so that a full Mars year of atmospheric and surface-atmosphere interaction (*e.g.*, dust-raising) observations could be acquired. Mission goals centered on a combination of atmospheric science, surface mineralogy and elemental composition, and global mapping of gravity, topography, and magnetic fields (Palluconi and Albee 1985).

The science objectives of the MOC investigation, as it was proposed in 1985, were to address two broad research categories: meteorology/climatology and geoscience. Clouds, dust, variable surface features, and wind patterns were part of the former, while observations of the geomorphology (*e.g.*, channels, volcanoes, layered materials, craters) and their implications for the understanding of environmental phenomena (*e.g.*, atmospheric and fluvial sediment transport) were part of the latter category. As such, these two broad topic areas addressed key Mars Observer science goals to "determine the time and space distribution, abundance, sources, and sinks of volatile material and dust over a seasonal cycle," and to "explore the structure and aspects of the circulation of the atmosphere" (NASA 1985). The broad MOC science objectives were unchanged as the mission transitioned from Mars Observer to Mars Global Surveyor after the former was lost in 1993.

Meteorology and climatology

Meteorology and climatology are intimately related, as meteorology is regarded as the present, dynamic expression of climate. MOC objectives focused on monitoring cloud patterns, dust storm activity, changes in surface albedo patterns, and seasonal variations in the polar caps over the course of a full Martian year (Malin et al. 1992). All of these phenomena serve as proxies for aspects of atmospheric circulation, interaction between the surface and atmosphere, and the present Martian H_2O and CO_2 cycles.

Geoscience

MOC geoscience objectives centered on geomorphic forms that have implications for the past and present climate, including the nature of fluvial landforms, eolian features, polar layers, polar ice caps, and the modification of impact craters and volcanic landforms (Malin et al. 1992). The high spatial resolution of the MOC narrow angle camera was intended to bridge the gap between what can be seen in the highest resolution Viking orbiter images and the panoramic views obtained by the Viking landers (Danielson 1989). This increase in spatial resolution—relative to Viking orbiter images—was intended to permit better understanding of both ancient and modern landforms by focusing attention on the details of processes involved; for example, it was considered that boulders transported by catastrophic floods or in mudflows would permit computation of the physical properties of the flowing material at the time of emplacement, and fine details in layers exposed in the Valles Marineris and in the polar regions would help resolve questions about their deposition and, in the polar case, their relation to obliquity cycles. The high resolution images were intended also to examine the sedimentological nature of eolian wind streaks and bedforms, features which result from interaction between the circulating atmosphere and loose clasts on the planet's surface. Finally, high resolution images of Mars were anticipated to contribute to studies of future landing sites and assist in the engineering design of future landed missions, although this was not considered a NASA priority at the time the Mars Observer payload was selected.

Instrument description

The nominal orbit for MO (and later, MGS) was to be nearly circular, with an average altitude of about 378 km. The orbit

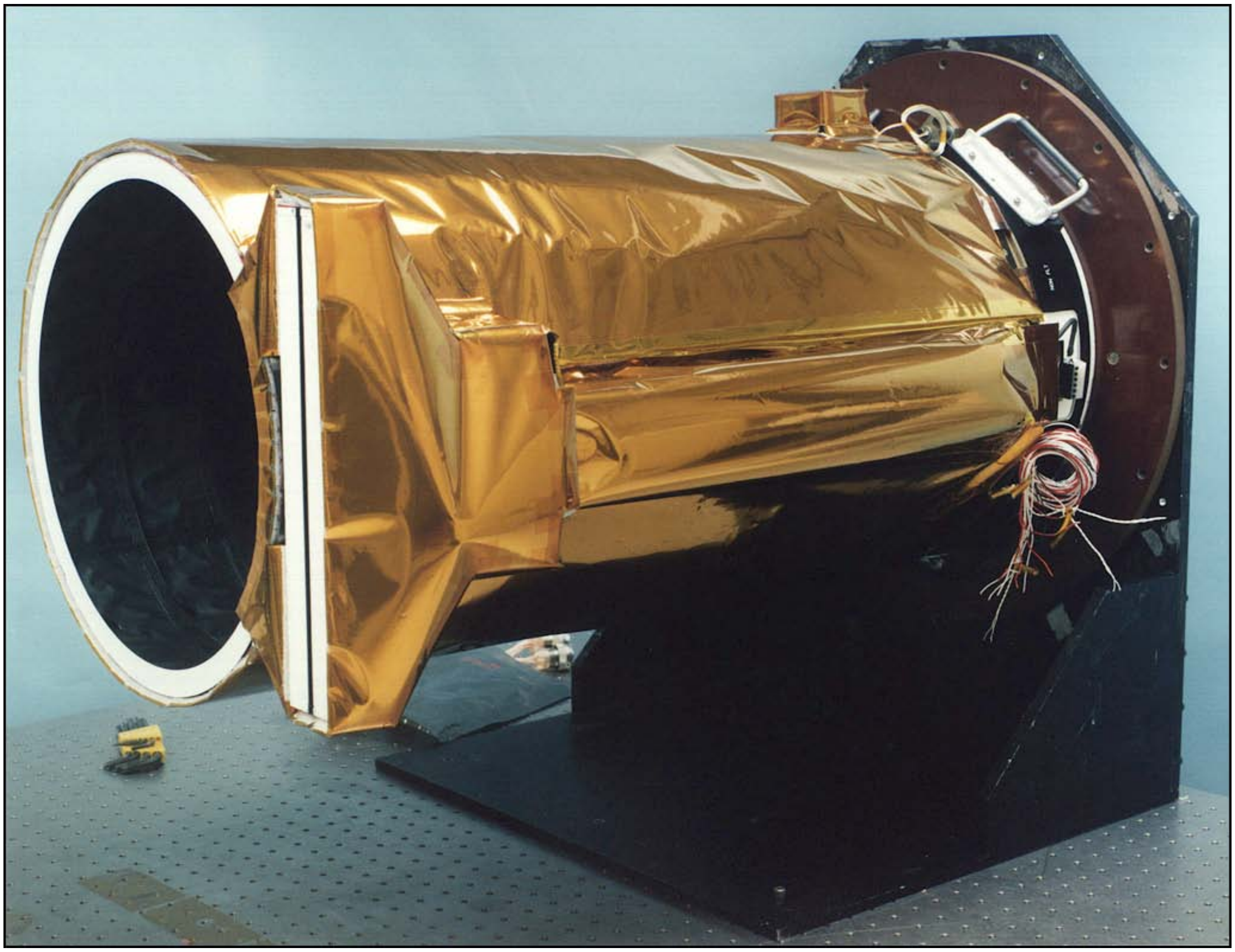

Figure 1. The Mars Global Surveyor Mars Orbiter Camera. The telescope cylinder measures 80 cm long by 40 cm in diameter (figure1.jpg).

was to be nearly polar, with an inclination of 87° (which became 93° with the change in MGS mission plan resulting from a modified aerobraking effort in 1997–1998), with an equator crossing on the day side of the planet near 2 p.m. local time, and a repeat cycle of 7 Martian days (Palocz 1991, Albee et al. 1992). The spacecraft would orbit the planet 12 to 13 times per day (every ~117 min).

To address the objectives to obtain one Mars year of global meteorological observations plus targeted views of specific surface-atmosphere and polar volatile interactions, the MOC team proposed to fly two wide angle cameras that had a sufficient field of view and a sufficient number of cross-track pixels to cover the planet from limb to limb and terminator to terminator. In addition, the instrument was required to have sufficient onboard storage space to acquire the data. These wide angle images could be returned with spatial scales from ~230 m/pixel resolution to at least 7.5 km/pixel scale from the nominal orbit. With 12–13 orbits per day, 12–13 red/blue wide angle image pairs would provide complete daily global coverage to meet the meteorological objectives. To address the investigation's geoscience objectives, the team proposed a narrow angle camera capable of 1.4 m/pixel imaging from the nominal orbit.

Malin et al. (1991) and Malin et al. (1992) described the MOC instrument and science investigation. In addition, Myers et al. (1987), Telkamp and Derby (1990), Scharton (1990), Scharton (1991), Applewhite and Telkamp (1992), Telkamp (1992), Cushing and Applewhite (1992), Brylow and Soulanille (1992), and Ravine et al. (2003) described various detailed aspects of the instrument development and testing effort.

The MOC had a single cylindrical structure of about 80 cm length and 40 cm diameter that housed the narrow angle camera to which the two wide angle cameras were attached. Figure 1 shows the MGS MOC and Figure 2 shows a cut-away view with key structural components labeled.

Each camera was a "push broom" type with each custom charge-coupled device (CCD) detector consisting of a single line array. The ~3 km per second ground track velocity of the orbiting spacecraft, the physical size of the pixels on the detector, and the focal length of each of the three sets of optics determined the line exposure time: 0.4421 msec for the narrow angle camera and 80.48 msec for the wide angle instruments.

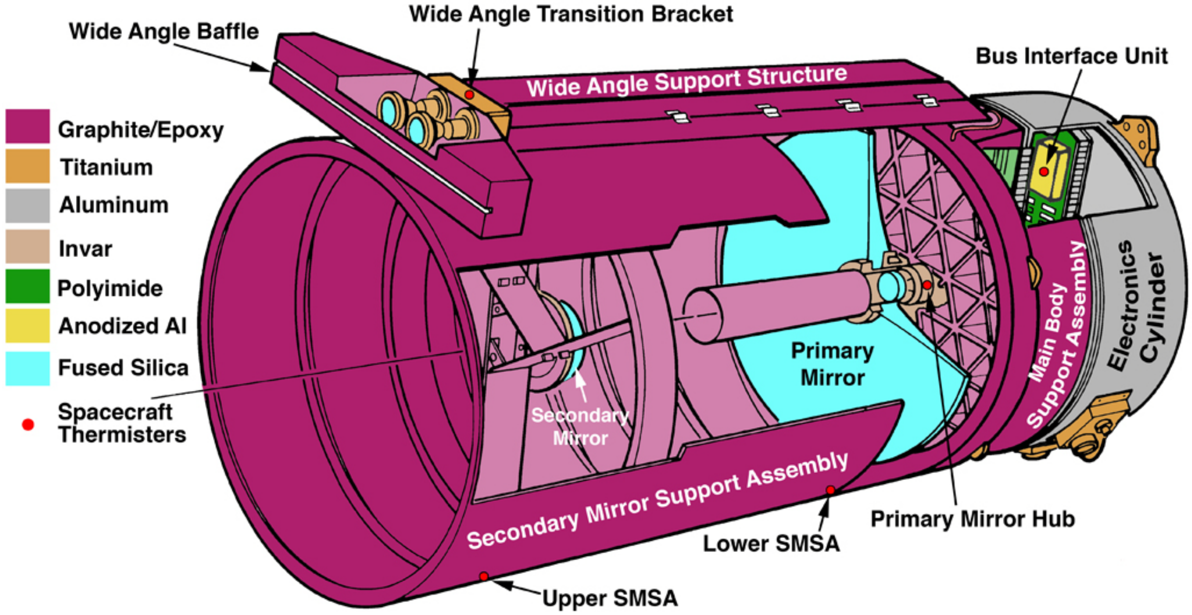

Figure 2. Cutaway drawing showing main structural elements of the MOC and the materials of which the MOC was constructed. The telescope cylinder measures 80 cm long by 40 cm in diameter (figure2.jpg).

The narrow angle camera was a 35 cm diameter aperture, 3.5 m focal length (f/10) Ritchey-Chrétien telescope. The detector was filtered for a panchromatic bandpass covering 500–900 nm. The CCD consisted of 2048 × 1 elements with 13 µm-sized pixels. The narrow angle camera instantaneous field of view was 3.7 µrad, and when coupled with the 2048 element line array, narrow angle images could cover about 3 km in the cross-track dimension from the nominal MO and MGS orbit.

One wide angle camera had a blue filter (400–450 nm), the other had a red filter (575–675 nm). Both cameras had a 140° field of view for limb-to-limb imaging at the MO and MGS nominal altitude, and each had a CCD consisting of 3456 × 1 element composed of 7 µm pixels and could obtain full-resolution images of about 230 m per pixel at nadir and 1.5 km per pixel at each planetary limb. The blue wide angle camera had a focal length of 11.4 mm (f/6.3) and the red camera focal length was at 11.0 mm (f/6.4).

The MOC electronics reflected late 1980s state of the art capabilities for spaceflight hardware. The electronics were block redundant, with each completely independent half system consisting of a 32-bit radiation-hard Sandia SA 3300 microprocessor operating at 10 MHz and about 1 million instructions per sec, a 12 MB buffer consisting of 96 1-Mbit, 120 ns dynamic random access memory (DRAM) chips, and three 11,000-gate and one 8,000-gate application-specific integrated circuits (gate arrays) operating on 50 ns clocks. The block redundant half systems were cross-strapped to allow operation of both narrow angle and wide angle cameras by either set of electronics; each half system controlled a separate narrow angle detector. All three cameras were capable of operating simultaneously.

The MOC had considerable capabilities to perform on-board image processing and compression by summing (which traded spatial scale for down track length), sub-frame imaging (by specifying cross track dimensions and by permitting virtual camera operations of the wide angle system—see Malin et al. (1992)), and by lossless and lossy compression algorithms.

Historical narrative

MGCO and Mars Observer

Following the success of the Viking Program, NASA and the planetary science community found difficulty in generating interest in follow-on Mars missions. Almost four years were spent looking at alternatives, with little consensus on what should be proposed. Even before the new Reagan Administration began efforts to cut space science funding (Norman 1981, Waldrop 1981), delays in preparing for the first launch of the Space Shuttle and its cost over-runs had made it clear that funding for planetary exploration would be severely challenged in the 1980s.

Owing to the pending budget cuts, the Solar System Exploration Committee (SSEC) was established to keep the Galileo Jupiter mission from being cancelled, advance the cause of an imaging radar mission for Venus, and to attempt to focus future planetary missions on lower cost alternatives. The SSEC's recommendations for Mars, after two years of deliberations, advocated an orbiter with science investigations focused on climatology and geoscience (Waldrop 1982, Morrison and Hinners 1983, SSEC 1983).

The Mars Geoscience/Climatology Observer (MGCO) was not planned to carry a camera. The SSEC chairmen described the Mars science community view, saying, "High-resolution imaging is not a part of this mission. The Viking orbiters have already given us excellent maps of Mars," (Morrison and Hinners 1983).

The MGCO mission was re-named Mars Observer (MO) and received a new start from Congress in October 1984 (fiscal year 1985). At the time, the plan was to launch MO from the cargo bay of a Space Shuttle in August 1990. In 1985, NASA issued an Announcement of Opportunity to solicit proposals for MO science investigations (NASA 1985). The announcement did not preclude the possibility of proposing imaging systems. However, it was clear that resources to add a camera would be very tight. When the MOC was proposed, therefore, we required that it would use no more than 10% of any given resource (*e.g.*, < 10 kg mass, < 10 W power, < 1.6 MB/day data volume, < 150 bits/s data rate, < $10 Million cost) relative to the baseline science payload described in the announcement.

MOC proposal and selection

The MOC proposal was submitted in August 1985. Selection of MO investigations was expected to occur by the end of the year. As with many such NASA selections, the decision was then delayed until late January 1986 and the loss of the Space Shuttle Challenger on 28 January 1986 resulted in a further postponement.

Two different—but not mutually exclusive—stories describe the selection of the MOC investigation. One, the official history of the Mars Observer mission through 1988 (Polk 1990), describes the selection process from the Jet Propulsion Laboratory's (JPL) perspective, mostly up through January 1986. The other, developed initially around anecdotal comments but later researched and published as an Internet article by author Andrew Chaikin, outlines the selection from the Principal Investigator's (PI) perspective, covering the time after January 1986 (Chaikin 2000).

After the MO investigation proposals were reviewed by NASA panels and categorized, NASA requested that the MO Project at JPL assess the impact of oversubscribing the payload selection. The Project determined that selecting eight instruments would definitely impact the available resources (mass, dollars, power), which had been sized to support a seven-instrument suite. Fourteen instruments emerged as leading candidates for selection from the independent review process. These were grouped into 60 possible 8-instrument suites, plus a number of 7-instrument suites, the former all oversubscribing the available resources. The MO Project highlighted four 8-instrument example payloads in their report to NASA Headquarters. With the Project resource groupings and assessments, and the science review recommendations, the NASA Space Science and Applications Steering Committee (SSASC) met in late January 1986 to review and recommend a payload to the NASA Associate Administrator responsible for space science (Polk 1990).

Events affecting the selection of the MOC between late January and early April are not as well documented. Anecdotal comments heard by the PI, Malin, after selection, subsequently confirmed in part by Chaikin (2000), suggest that the MOC was not part of the initial selection. The delay in announcing the selected investigations gave the NASA Associate Administrator for Space Science and Applications, Burton I. Edelson, time to assess the importance of imaging on planetary spacecraft during the Voyager 2 encounter with Uranus in January 1986 and the encounters with Comet P/Halley by the USSR Vega and the ESA Giotto spacecraft in March 1986. Faced with selection letters for a Mars Observer payload that did not include a camera, he commented, "I can't see sending a spacecraft back to Mars without a camera," (Chaikin 2000).

On 8 April 1986, the payload selection was announced, and the MOC PI was informed of conditional circumstances accompanying the selection described in the letter shown in Figure 3—essentially, the camera was the last on and would be the first off, should accommodation or resource constraints require removing an instrument.

Mars Observer development, launch, cruise

Eight MO investigations were selected for accommodation study; these included the MOC, Thermal Emission Spectrometer (TES), Visual and Infrared Mapping Spectrometer (VIMS), Gamma Ray Spectrometer (GRS), Radar Altimeter and Radiometer (RAR), Pressure Modulator Infrared Radiometer (PMIRR), Ultrastable Oscillator/Radio Science (USO/RS), and the Magnetometer/Electron Reflectometer (MAG/ER) investigations (Polk 1990). To cut projected mission costs, NASA later removed the VIMS from the payload in 1988 (rather than MOC, the removal of which, projections showed, would have saved less money) and changed the RAR to the Mars Observer Laser Altimeter (MOLA) (Polk 1990, McKinley 1991). Komro and Hujber (1991) and Albee et al. (1992) described the final Mars Observer payload configuration.

Meanwhile, in 1987 the MO launch date was slipped to 1992 and the launch vehicle was changed to a Commercial Titan III rocket with a Transfer Orbit upper stage. In addition, discussions with France and the USSR in 1987 and 1988 led to addition of the Mars Balloon Relay (MBR) antenna provided by the Centre National d'Etudes Spatiales (CNES). The MBR would relay data from balloons planned to be deployed at Mars by France and Russia on a USSR mission to launch in 1992 (Blamont 1990). (The 1992 Russian launch was eventually slipped to 1994, and then to 1996—and with no balloons aboard—but the mission was still intended to deploy landed payloads that would relay their data through the MBR). The MBR would use the large MOC buffer to pass data along for relay to Earth. In part because of its role in the MBR system, the MOC went from the "last on first off" status of the conditional 1986 selection to being a "launch-critical" payload element on 2 September 1992.

Mars Observer was launched from Cape Canaveral aboard its Titan III rocket on 25 September 1992 (Esposito et al. 1994). During the cruise to Mars, the MOC was turned on several times to acquire images of stars and Jupiter (and Galilean satellites) for focus testing and calibration. Nearly a month before the planned orbit insertion, on 27 July 1993, MOC acquired two narrow angle images and attendant red/blue wide angle pairs of Mars as it approached the planet

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: EL

APR 8 1986

Dr. Michael C. Malin
Department of Geology
Arizona State University
Tempe, AZ 85278

Dear Dr. Malin:

I am pleased to inform you that, after the review and evaluation of proposals submitted for the Mars Observer mission, your investigation, "Mars Observer Camera" (proposal number MO-026), has been selected for the Investigation Accommodation Phase of this mission. You are hereby appointed to membership on the Mars Observer Project Science Group (PSG). The PSG will hold its first meeting in the near future at the Jet Propulsion Laboratory (JPL), Pasadena, CA. You will be notified soon as to the exact date and time.

As specified in the Mars Observer Announcement of Opportunity (AO No. OSSA-2-85), this selection does not constitute a commitment by NASA to ultimately include your investigation on the Mars Observer mission. Final selection and confirmation of all investigations will be made at the end of the Investigation Accommodation Phase, which will last for approximately six months.

You should be particularly aware of the fact that we are not at all certain at this time that it will actually be possible to accommodate the Mars Observer Camera on the mission. Preliminary studies we carried out during the selection process suggested that adding the camera will, in fact, cause us to exceed important mission and program constraints which have been placed on mass, power, data handling capability and funding. For these reasons we seriously considered rejecting your proposal. However, because of the scientific importance of having an imaging capability as part of our Mars Observer payload, we felt that it would be premature to close out the opportunity at this time and so we are inviting you to participate in the Investigation Accommodation Phase.

At the end of the Investigation Accommodation Phase, if your investigation is selected for development for flight, you will be appointed a Principal Investigator on the Mars Observer, and you will continue your activities on the PSG.

As described in the AO, the purpose of the Investigation Accommodation Phase is to provide an opportunity to evaluate all tentatively selected investigations in detail for cost, compatibility with the capabilities

Figure 3. First page of the official selection letter for the Mars Observer Camera. The letter differed from all other Mars Observer investigation selection letters by inclusion of the text highlighted here in red (it was not highlighted in the original letter). This text describes the ground rules by which the MOC would be evaluated for accommodation by the Mars Observer Project. It can be summarized by saying that the MOC was the last on and would be the first off if a mission descope was required (figure3.jpg).

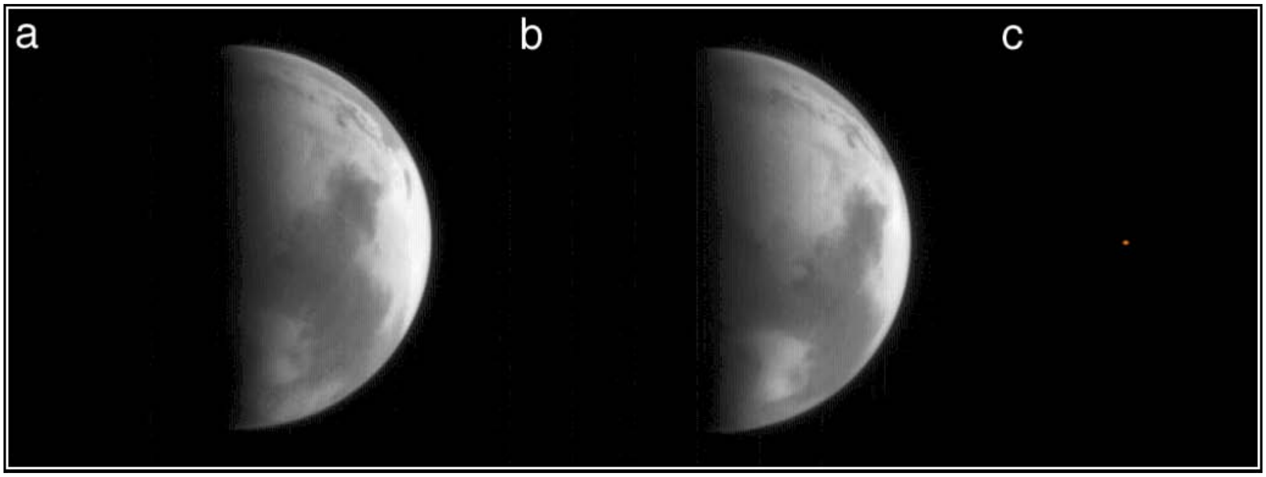

Figure 4. The Mars Observer Camera images of Mars. These approach pictures were taken on 27 July 1993, twenty-eight days before the planned orbit insertion. **(a)** Narrow angle image obtained at 03:52:41 UTC (sub-frame of Mars Observer MOC image C12-3). **(b)** Narrow angle image obtained 1 hour later; features have rotated toward the right (sub-frame of MO MOC image C12-6). **(c)** Wide angle camera view, in which Mars covered a single pixel. This is a color composite of MO MOC images C12-4 and C12-5 (figure4.png).

(Figure 4). These were the only images of Mars acquired by the Mars Observer Camera. The spacecraft was lost when the propellant system necessary for Mars Orbit Insertion was being pressurized on 22 August 1993, three days before arrival (Cunningham 1997). The loss occurred during a planned communication outage. As no further information was received from the spacecraft, the review boards that investigated the loss had to deduce several possibilities, the primary among them being rupture of a fuel line when fuel and oxidant accidentally came into contact with each other during the preparation for orbit insertion (Coffey et al. 1993, Stephenson et al. 1993).

Mars Global Surveyor

After considering whether a replacement mission could be prepared in about a year for launch during the 1994 Mars launch period, and after examining a range of options for re-flying the MO instruments during subsequent launch periods in 1996, 1998, and beyond, NASA decided in 1994 to re-fly a sub-set of the MO science payload on a new orbiter to launch in 1996, the Mars Global Surveyor (MGS). Selected for flight were the MOC, TES, MOLA, USO/RS, and MAG/ER (Albee 1996). Two other instruments, PMIRR and GRS, were to fly on successive orbiters to be launched in 1998 and 2001, respectively. The MGS orbit and mission plan were grossly similar to those of MO (Cunningham 1996, Dallas 1997). Albee (1996) and Palluconi and Albee (1997) described the revised science objectives.

For the MGS mission, the MO Mars Balloon Relay (MBR) became the Mars Relay (MR), as the French balloons were no longer planned for launch to Mars. As noted by Cunningham (1996), the MR system was expected to relay data from Russia's Mars-96 landed hardware—this included two small stations and two penetrators (Linkin et al. 1998, Surkov and Kremnev 1998)—but Mars-96 re-entered Earth's atmosphere shortly after launch in November 1996. In addition, the MR was planned to be the primary downlink pathway for the Deep Space 2 Mars Microprobes (DS2) that were to be launched in January 1999 with the Mars Polar Lander (Smrekar et al. 1999). Following the MGS Primary Mission, NASA anticipated a "Relay Phase" during which the MR system would be available to relay future lander or rover data through at least February 2003 (Dallas 1997).

MGS MOC development

The MGS MOC was built mostly from flight spare hardware produced during the fabrication effort for the MO MOC. The development of the second MOC followed a substantially different arc than that of the first camera, because the time to prepare the instrument for delivery was much shorter, much of the hardware already existed, and the financial resources available were much smaller. However, the electronics consisted of assembled but untested boards which in many cases had been set aside during MO MOC development because of problems, the available detectors had lower performance than those used for MO or had never been characterized, and many of the integration and test procedures had been only incompletely documented in the final stages of MO MOC development. This led to a development flow for the MGS MOC that required more work effort than if a ready-to-fly spare had existed; some of the significant problems encountered during the development effort included:

1) Most of the integrated circuits on the analog boards had been stressed by a defective soldering iron at the assembly subcontractor (during the MO MOC development effort) and had to be replaced.

2) During the 500-hour burn-in of the MOC electronics in March 1995, one of the wide angle subsystems failed. Subsequent investigation showed that its rigid-flex circuit board had a manufacturing flaw that trapped solvents within the board layers, eventually causing a short.

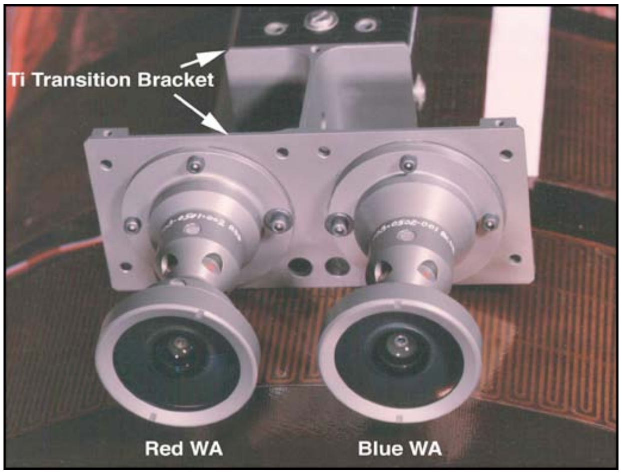

Figure 5. The MGS MOC wide angle camera heads prior to enclosure within the baffling structure. Compare with Figures 1 and 2 for scale (figure5.jpg).

3) On occasion, the primary side electronics failed to power up correctly. This problem occurred several times before and after the spacecraft integration and even in functional testing while the spacecraft was on the launch pad. The cause of the problem was never understood. However, despite real time monitoring of every MOC turn-on during the MGS mission, the problem never occurred in flight.

4) A controller error during instrument thermal-vacuum testing in August 1995 caused the instrument to briefly exceed its design temperature, but no damage resulted.

5) During calibration in October 1995, the team found that the blue wide angle camera CCD had almost no in-band response. The CCD was replaced with a spare.

6) After delivery of the instrument to the MGS spacecraft manufacturer, Lockheed Martin Astronautics (LMA; near Denver, Colorado), in November 1995, a connector between one of the wide angle camera focal planes and the main electronics was found to be broken and had to be repaired.

7) Final checkout of the MOC at LMA showed that one edge of the red wide angle field was obscured; this was found to result from the omission of an alignment step during final assembly. As the impact of this was considered to be relatively minor, the instrument was flown in this state.

8) While integrating the instrument with the MGS spacecraft, the wide angle baffle sustained impact damage caused by the handling fixture; the baffle was thus replaced in August 1996.

Figure 5 shows the integrated wide angle camera heads without the wide angle baffle that obscures them from view in Figure 1. Figure 6 shows the MOC, MR and other hardware on the MGS nadir instrument deck during assembly at LMA.

MGS launch, cruise, and aerobraking

MGS was launched from Cape Canaveral by a McDonnell Douglas Delta II 7925 rocket on 7 November 1996. Shortly after launch, spacecraft engineers determined that a solar panel deployment damper had failed, resulting in damage to one of the spacecraft's two solar panels (Lyons 1997).

The MOC acquired images on seven occasions during the MGS cruise to Mars. Most of these were images of stars to calibrate MOC focus heater settings. However, on 2 July 1997, MOC obtained a narrow angle image of Mars from a distance of about 17.2×10^6 km to support weather prediction for the 4 July Mars Pathfinder landing, and on 19–21 August 1997, MOC obtained a series of approach images as a contingency against spacecraft failure before data could be acquired from orbit. Following Mars Orbit Insertion (MOI) on 12 September 1997, MOC was powered-up and obtained its first images from orbit on 15 September.

MGS began aerobraking on 17 September, and MOC continued to acquire contingency data on nearly every orbit. Owing to the broken solar panel damper (Lyons 1997), the spacecraft suspended aerobraking on 13 October when it encountered too much pressure on the affected solar panel (Cunningham 1998). Following analysis, a less vigorous aerobraking effort began on 7 November; this led to a one-year delay of the start of the MGS Primary Mission, from March 1998 to March 1999 (Esposito et al. 1998, Lyons et al. 1999, Albee et al. 2001). Meanwhile, MOC acquired images of Mars into February 1998, then again during the new Science Phasing Orbits period of April–September 1998. During these orbits, several close encounters with the Martian satellite, Phobos, provided opportunities for high resolution observations.

MGS primary and extended missions

MGS attained its near-polar, near-circular mapping orbit in February 1999 following a second aerobraking period during which MOC was not operated. In late February 1999,

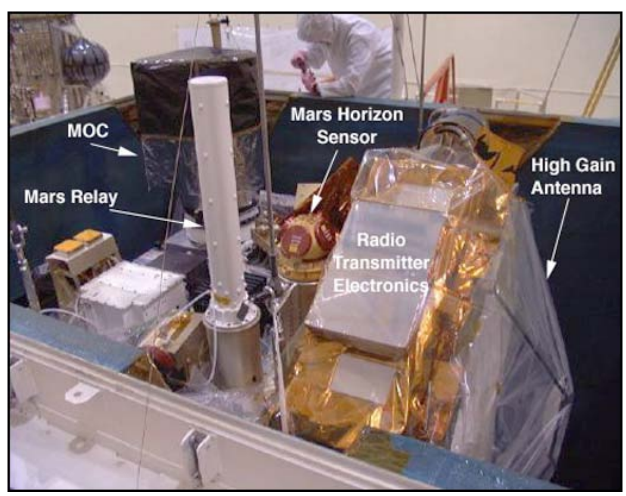

Figure 6. MOC (beneath a protective cover) and the Mars Relay antenna on the Mars Global Surveyor instrument deck during spacecraft testing in 1996. Note the person for scale (figure6.jpg).

calibration data for the MOC were acquired—particularly for focus heater settings, flat fields, dark current, and initial information on camera gain and offset settings. The Mapping (Primary) Mission began on 9 March with several weeks of observations acquired while the MGS High Gain Antenna (HGA) was in a fixed position (owing to concern that the deployment of the HGA might fail and end the mission (Cunningham 1998)). The HGA was successfully deployed on 29 March 1999 and normal operations began at that time. Shortly thereafter, the HGA gimbal experienced a problem that limited its range of motion. This constraint led to the development of a communications workaround known as "beta supplement"—this approach became operative in early May 1999 (and was necessary for some part of each Martian year until the HGA obstruction problem was discovered to have cleared during a spacecraft safe mode entry in August 2005).

The MGS Primary Mission period closed at the end of January 2001 and was immediately followed by the start of the first Extended Mission (Albee et al. 2001). The Extended Mission consisted of one additional Mars year of observing and was followed by two more extensions, covering two additional Mars years. During this time, the MR system—which required use of the MOC buffer and was operated by the MOC operations team at Malin Space Science Systems (MSSS)—was used to relay critical Entry, Descent, and Landing (EDL) data in real time from the two Mars Exploration Rovers in January 2004 (Esposito et al. 2004). The MR system was further used to relay data from the rovers during the months that followed.

In mid-2006, NASA approved a fourth mission extension for MGS. In terms of U.S. federal fiscal year funding cycles, the fourth extension began on 1 October 2006. The MOC acquired data 1–17 October, then the camera was turned off as Mars passed behind the Sun, relative to Earth, for the fifth solar conjunction to occur since MOI.

Loss of MGS and final MOC activities

Following the 2006 solar conjunction, the MOC was successfully turned on during orbit 34201 on 2 November 2006 at 21:19 UTC. However, no image data were returned to Earth from MOC before contact with the spacecraft was lost on orbit 34203 on 2 November 2006 at 23:45 UTC.

A complex sequence of events is considered to have led to the failure of the MGS spacecraft (Perkins et al. 2007). During analysis in December 2006, small solar array panel attitude errors were found that traced back to a memory location write command that was radiated to the spacecraft in June 2006. The June commands were intended to synchronize the two spacecraft computer states (a minor mismatch was seen after recovery of spacecraft computer lockup anomalies encountered in July–September 2005). The commands were unintentionally written to the wrong memory address location and over-wrote the solar array panel motion soft-stop protection and thus defined a poor communication attitude for the HGA when in Contingency Mode. Then, a routine command to offset the angle of the two solar array panels by 10° was radiated on 2 November 2006 on the same orbit as the MOC turn-on. The offset caused one solar panel to try to exceed its hard stop on the following orbit, producing error messages that were received on the ground. The spacecraft went to backup commanding and cleared the errors. The same problem happened on the next orbit, however, so the spacecraft locked the problem solar array panel and went into Contingency Mode. MGS communication with Earth was then lost due to the accidentally-commanded poor attitude of the HGA in Contingency Mode (Perkins et al. 2007). The spacecraft attitude in this Contingency Mode would have preserved power on the problem solar panel, but was also likely at an unfortunate angle that exposed one of the two spacecraft batteries to direct sunlight. The battery is thought to have subsequently overheated (within about 6 orbits) and failed, resulting in loss of the spacecraft.

The MOC operations team supported the MGS recovery efforts through January 2007 by standing ready to resume MOC operations, which included creation of documentation for quick reference if the recovery period was excessively long (6 months), attending daily spacecraft team recovery teleconferences, reporting the recovery status to the MOC science operations team, and reviewing the spacecraft team anomaly event timeline and fault tree, including the final MOC turn-on and commanding files.

Following the loss of MGS, the MOC operations team closed-out the investigation by preparing this report; completing nominal archiving of MOC data as well as re-archiving the full MOC data set in calibrated and map-projected form, including repair of data corrupted by ground data systems prior to arrival at MSSS; reassessment of pointing and navigational information to improve the placement of MOC data on standard maps of Mars; and the initial efforts toward completion of a lengthy (hundreds of pages) final report.

Science team

Table 1 lists the members of the MOC science team. In 1986, the team was small and consisted of the PI and four Co-Investigators. Sadly, in August 1990, Co-Investigator Harold Masursky passed away. Laurence Soderblom, of the same institution as Masursky (U.S. Geological Survey, Flagstaff) was added to the team. The science team was expanded to ten members in 1992 by NASA's selection of five Participating Scientists through a competitive proposal and review process. A few additional investigators who were part of the MO and MGS effort as Interdisciplinary Scientists (or Participating Scientists affiliated with an Interdisciplinary Scientist) also contributed to the investigation; in particular these were Michael H. Carr (Interdisciplinary Scientist) and Kenneth E. Herkenhoff (Participating Scientist). Young research scientists and graduate students affiliated with these team members also conducted data analyses during portions of the mission. Team member Davies passed away in April 2001 and the MOC Instrument Manager, Danielson, passed away in December 2005.

Table 1. The MOC science team.

Name	Role	Institution	Responsibilities
The team at selection in 1986			
Michael C. Malin	PI	Arizona State University (until 1991)	Overall responsibility for the MOC investigation
G. Edward Danielson, Jr.	CoI	California Institute of Technology	MOC Instrument Manager
Andrew P. Ingersoll	CoI	California Institute of Technology	Atmospheric science; meteorology
Harold Masursky	CoI	U.S. Geological Survey, Flagstaff, Arizona	Geology, geomorphology, landing sites
Joseph Veverka	CoI	Cornell University	Surface/atmosphere interaction
The team at MO launch in 1992 and MGS launch in 1996			
Michael C. Malin	PI	Malin Space Science Systems (from 1991)	Overall responsibility for the MOC investigation
G. Edward Danielson, Jr.	CoI	California Institute of Technology	MOC Instrument Manager
Merton E. Davies	PS	RAND Corporation	Geodetic control network of Mars
William K. Hartmann	PS	Planetary Science Institute, Tucson, Arizona	Crater, geomorphology, climate record
Andrew P. Ingersoll	CoI	California Institute of Technology	Atmospheric science; meteorology
Philip B. James	PS	University of Toledo, Ohio	Clouds and polar ice/frost
Alfred S. McEwen	PS	U.S. Geological Survey, Flagstaff (until 1996) University of Arizona, Tucson (from 1996)	Color and albedo variations
Laurence Soderblom	CoI	U.S. Geological Survey, Flagstaff, Arizona	Mars geology
Peter C. Thomas	PS	Cornell University	Eolian sediment, seasonal change, topography
Joseph Veverka	CoI	Cornell University	Surface/atmosphere interaction

PI = Principal Investigator, CoI = Co-Investigator, PS = Participating Scientist

Operations and MOC toolkit

The MOC Ground Data System (GDS) was designed to use as much automation as possible while still preserving the ability to acquire high-quality science data from Mars, such that the instrument could be operated with a minimal staff. During most of the Primary and Extended Missions of MGS, for example, staffing levels consisted of about ~5 FTE (full time equivalent) professional instrument operations staff, 2–4 science personnel (~3 FTE), and about 1.3 FTE for software support. The MOC operations staff commanded the instrument, logged and archived the data, participated in MGS Project teleconferences several times a week, and worked with the spacecraft team to implement special activities such as off-nadir imaging of Mars and other targets; they were also responsible for operation of the MR system. The MOC science staff focused on selecting image targets, weather reporting based on the daily global images, interaction and planning of targets with the MOC science team, scientific data analysis, and preparation and release of captioned images for the public. Caplinger (1993) and Caplinger (1994) described the basic attributes of the MOC GDS and commanding process, though these were modified operationally throughout the MGS mission, particularly to enable much more interactive target selection by the scientists than had been anticipated prior to the start of the Primary Mission. Malin and Edgett (2001) briefly described the operations activities of the Primary Mission.

The MOC cameras, compression schemes, and summing capabilities provided a very versatile system that could be adapted by the science user to select imaging parameters appropriate to a given combination of image science goal, downlink availability, and onboard MOC buffer space. Table 2 briefly describes the full MOC toolkit of options that the team exercised during the course of the MGS mission. Throughout the Extended Mission, off-nadir pointing of the MGS instrument deck to obtain targeted MOC images became routine, but prior to that time, images were obtained largely from a nadir viewing position. Having the off-nadir capability greatly enhanced the ability to compile mosaics of interesting surface features, obtain stereopair coverage where desired, repeatedly monitor targets anticipated to change, and image targets of high science interest sooner than would be possible without a pointing capability.

The MGS guest observer and MOC public targeting programs

The MOC investigation had three pipelines by which suggestions for narrow angle targets came in to the science and operations team. The first, which was available throughout the entire investigation, was to tell a member of the MOC team of a target of interest. In some cases the MOC team sought specific advice from members of the science community, particularly for targets in the north polar region and Hellas, both of which had very limited periods each Mars year when imaging conditions were ideal. The other sources of narrow angle targets were the MGS Guest Observer Program and the Public Targeting Program.

In late 2000, NASA instituted the MGS Guest Observer Program to provide funded opportunities for selected scientists—who were not already a member of one of the MGS science investigation teams—to acquire and study data using MGS instruments. Only one investigator, Ronald Greeley of Arizona State University, was selected for MOC guest observing research. Several narrow angle images of eolian features that had been imaged previously by MOC were acquired under the Guest Observer program to look for changes indicative of wind action.

Following that effort, and starting in August 2003, the MOC team began soliciting broad public and science community suggestions for MOC narrow angle camera targets through an interface available on the Internet. The MOC Public Targeting Program resulted in a total of 4,636 requests, 1,086 of which were satisfied by acquisition of one or more narrow angle images (and, usually, a red wide angle context frame)

Table 2. The MOC toolkit.

Narrow Angle Camera	
Full-resolution imaging	Approximately 1.5 m/pixel imaging of selected targets.
Non-square aspect ratio pixels	Images of > 1.0 aspect ratio for longer down-track imaging at the expense of some down-track spatial resolution. Typical images had an aspect ratio of 1.5.
Summed imaging	Summing of 2, 3, 4, 5, 6, 7, or 8 to cover greater downtrack distance at the expense of spatial resolution; often traded against science objectives and available space in the MOC buffer for a given image. Summing also improved signal-to-noise performance in images anticipated to be noisy (*e.g.*, near terminator, hazy conditions).
Repeat imaging	Acquired to monitor changes and for stereo.
ROTO imaging	Roll-Only Targeted Observations (ROTOs); acquired by rolling MGS up to 30° off-nadir to build mosaics, obtain stereo pairs, and target features of high science interest sooner than could be accomplished by waiting for ground track to pass over the feature. Obtaining ROTOs became a routine activity starting in February 2001.
cPROTO imaging	Compensated Pitch and Roll Targeted Observations (cPROTOs); involved complex pitch and roll maneuvers of MGS to obtain images of < 1 m/pixel scale in the downtrack dimension; used extensively for high resolution views of landing sites and various geomorphic features; became a routine activity in December 2003.
Constant roll imaging	When MGS orbit walk was near 0 or ground tracks were otherwise repeating on timescales of weeks to several months, MGS was rolled off the nominal ground track for several weeks to months to permit MOC imaging of targets outside the repeating ground track area.
Twilight imaging	Clear atmospheric conditions near the terminator in late winter, especially in the southern hemisphere, permitted imaging before sunrise. This was especially important in June 1999 to provide the first detailed looks at candidate Mars Polar Lander landing sites; the technique was also used routinely to fill downlink during high data rate periods.
Off-planet imaging	MOC focus calibration was determined by imaging stars at least once per Earth year. MOC also acquired images of spacecraft and other Solar System bodies (*e.g.*, Phobos, Earth). These activities required pointing the MGS instrument deck off of Mars and toward the object of interest.
Guest observer and Public imaging	The MGS Guest Observer Program (2000) and Public imaging effort (2003–2006) provided pathways for the science community and general public to suggest MOC targets that had not already been suggested to the MOC team previously.
Autonomous imaging	In the event that MOC was powered-up, its buffer was empty, and it had not received a command from Earth, the system was capable of acquiring narrow angle images at full resolution of random Martian terrain.
Wide Angle Cameras	
Daily global map imaging	Daily global images were built from 12–13 red and 12–13 blue wide angle image swaths acquired from terminator to terminator on every orbit; typical swaths had a spatial scale of 7.5 km/pixel, some special campaigns were conducted with imaging at 3.75 km/pixel.
Context imaging	Many narrow angle camera images were acquired with a simultaneous red wide angle 480 by 480 pixels image of ~230 m/pixel scale; it was also possible to acquire a blue context image (which was done occasionally).
Targeted imaging	Like the narrow angle camera, selected wide angle images were targeted and summed 1, 2, or more times (depending on decisions to trade between spatial scale, MOC buffer space, and science goals); these were commonly acquired to monitor seasonal frost, albedo changes, and weather conditions at specific locations on Mars.
Autonomous imaging	In the event that MOC was powered-up, its buffer was empty, and it had not received a command from Earth, the system was capable of acquiring red wide angle context images and daily global image swaths autonomously.

Table 3. Mars Orbiter Camera investigation cost in real year dollars, May 1986 – June 2008.

Cost Element	MO	MGS	Total
Hardware development	$21.57 M	$3.27 M	$24.84 M
Science & MOS/GDS development	$2.13 M	$2.36 M	$4.49 M
Subtotal, Phase A–D	$23.70 M	$4.48 M	$28.18 M
Phase E: MO&DA	$2.60 M	$12.47 M	$15.07 M
Closeout costs	—	$0.57 M	$0.57 M
subtotals	$26.30 M	$17.51 M	$43.81 M
		Total	$43.81 M

MO = Mars Observer; MGS = Mars Global Surveyor; M = million; MOS = Mission Operations System; GDS = Ground Data System; MO&DA = Mission Operations and Data Analysis

by the time of the abrupt end of the MGS mission. About a quarter of the public requests came from members of the Mars scientific community, but this resource was generally underutilized by Mars scientists. A little more than half of the requests came from a single individual, a member of the general public. Some of the science community requests resulted in publications, including research by Bandfield et al. (2004), Fassett and Head (2005), Mouginis-Mark and Christensen (2005), Schneider and Hamilton (2006), Tournabene et al. (2006), McDowell and Hamilton (2007), and Weitz et al. (2008). One member of the public who participated in the target request effort expressed his experience in a letter to the Planetary Society's *The Planetary Report*, saying, "For two years, I made suggestions and received many pictures back from Mars. It was one of the most exciting ventures I've ever attempted. It was like a football fan being able to run a few plays in the Super Bowl," (Secosky 2007).

Programmatic summary

The Mars Orbiter Camera investigation spanned 20.5 years, from May 1986 through November 2006 (or 23 years if one includes the writing of the MOC proposal in 1985 and the contract closeout period which ended June 2008). As shown in Table 3, the investigation cost about $44 million in real year dollars, of which 53% went into the design, fabrication, and testing of an engineering model, two flight units, and a flight spare. The second instrument was mostly paid for as the flight spare during the development of the first mission, and the third (the MGS spare) was mostly paid for during the development of the second mission.

The cost of the MOC investigation at the time it was proposed was estimated to be 5–6 million dollars. By the time Mars Observer was launched, the cost was nearly $24 million. Figure 7 shows the history of the estimated cost to complete, annotated by key factors that contributed to the cost growth. Note that these are not all the factors affecting cost, but represent the larger changes that occurred during development of the MOC. Table 4 gives a generalized description of the primary influences on the cost increases.

Figure 7 and Table 4 show that the final Mars Observer MOC cost was about a factor of four more than its original proposal cost, that is, the original cost was about 25% of the final cost. Of the remaining 75% of the final cost, 15% is attributable to inexperience and not understanding the job we

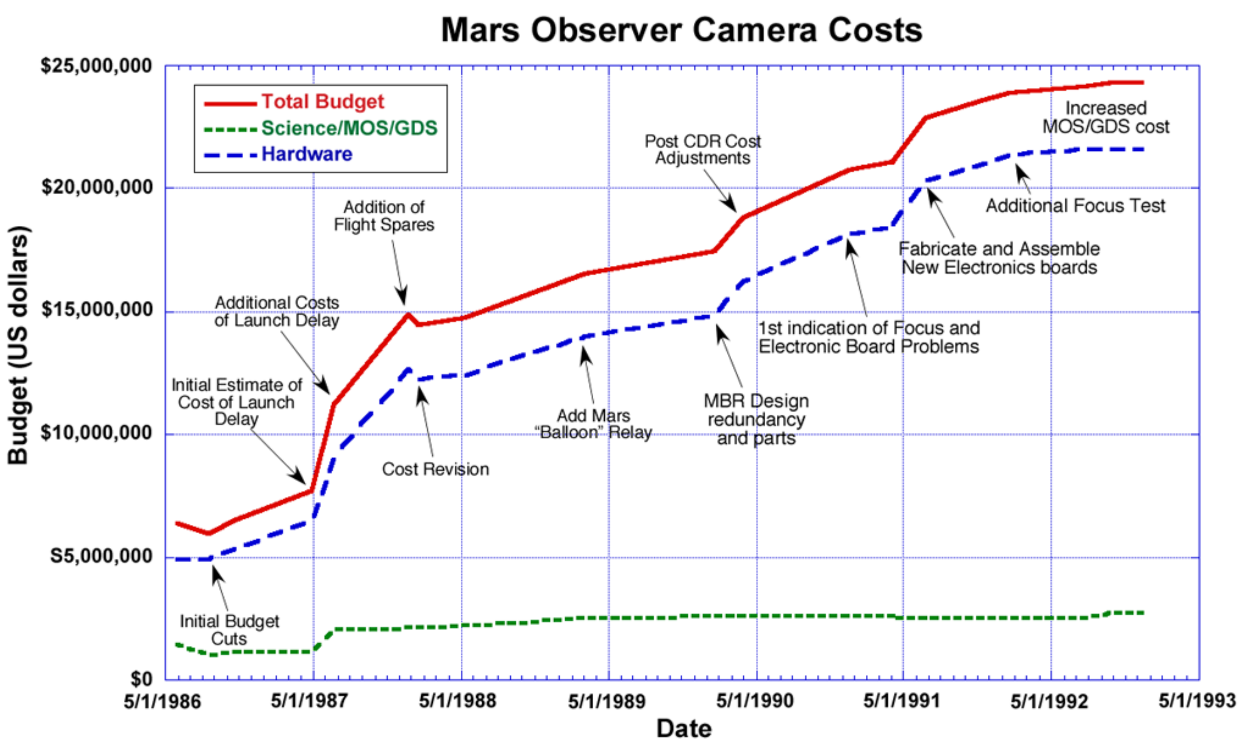

Figure 7. Cost history for the Mars Observer Camera. MOS is Mission Operations System; GDS is Ground Data System (figure7.png) (figure7.txt).

Table 4. Categories and examples of cost growth factors for the Mars Observer Camera.

	Original	Better Understanding	Problems	Upgrades	Mistakes	NASA	JPL Project	Contractor Problems	Total
Total cost, each category	$4,935 K	$2,221 K	$2,467 K	$2,345 K	$1,272 K	$3,410 K	$3,044 K	$1,876 K	$21,569 K
Percent of original cost	—	45%	50%	48%	26%	69%	62%	38%	337%
Percent of final price	23%	10%	11%	11%	6%	16%	14%	9%	100%

Better Understanding	Changes in parts screening requirements; responding to modeling results; change in Caltech overhead cost.
Problems	Analog board rebuild; focus problem and solution.
Upgrades	Build a flight spare; additional parts screening; use better parts.
Mistakes	Change in overhead costs at Caltech and Arizona State Univ.; bookkeeping errors; left out cost of a Co-I.
NASA	Capability to launch on expendable vehicle or Space Shuttle; launch delay and inflation; additional quality assurance; addition of Mars Balloon Relay (MBR).
JPL/MO Project	Move to nadir; additional quality assurance requirements; qualification testing.
Contractor Problem	Solder iron shorted electronics boards; bonding failures during test of optics/structure.

K = thousand

wanted to do, 10% from true upgrades to the instrument (whether our choice or imposed on us), 20% came from problems we encountered, and 30% from changes in the requirements and ground-rules by JPL and NASA.

Both the MO mission and the rest of the science payload experienced similar cost growth, which at several points threatened the mission. Cost growth is inevitable and every such mission experiences it. It stems from each of the categories noted in Table 4, and from optimism when the project is initially proposed. Other instruments on MO similarly overran their proposed costs. Of the eight components of the payload that launched on MO, only six were instruments for which cost bookkeeping was similar (*i.e.*, the MOLA was developed at Goddard Space Flight Center before full-cost accounting was implemented and the MBR was contributed by France). Of the six instruments, MOC was the third least expensive instrument (the Radio Science Ultrastable Oscillator, a commercial device, was the lowest cost and the Magnetometer/Electron Reflectometer was the second lowest cost).

Cost performance for MGS MOC development and operations was significantly better than for MO, between 15–19% of the MO MOC costs. Given that fewer outside influences affected the hardware development, estimated-cost-to-complete growth was only about 10%, reflecting solutions to problems discovered during the MO cruise activities. In the end, the MGS MOC instrument—as was the case on MO—was the third least expensive of the MGS science investigations (again, the Radio Science Ultrastable Oscillator and the Magnetometer/Electron Reflectometer were lower cost).

During the operational phase of the MGS effort (one month after launch through the end of the mission), Malin Space Science Systems consistently under-ran its estimated cost to complete/contract value owing to several factors. These included personnel and cost sharing with subsequent missions, pro-ration of work hours to 40-hour work weeks, conservative hiring practices (*e.g.*, don't hire until the spacecraft is in orbit), and nearly fixed indirect costs. Operational cost efficiency improved by ~5% per year, attaining a final level nearly 50% less than the initial year cost. The operational cost under-run was almost $2 million (about 10%) of the contract value.

Data

MO MOC data

In flight, the Mars Observer MOC only acquired data during the cruise phase of the mission. Cruise data included the images of Mars shown in Figure 4. The MO MOC cruise data were not archived with the NASA Planetary Data System (PDS), as there was no requirement to do so and the PDS elected not to receive these data.

MGS MOC data

All MGS MOC data have been archived with the NASA PDS. From launch through the end of the MGS mission, 254,796 MOC image acquisitions were commanded and 243,668 images were received. This amounted to 250 Gb of compressed image data received on Earth. Table 5 shows the number of images of each type acquired by MOC, plus data received through the MR system, for the entire mission.

Figure 8 shows the number of images by type (daily global swaths, wide angle context images, targeted wide angle images, narrow angle images, MR data) received as a function of mission subphase. Figure 9 shows the total decompressed data volume received as a function of data type and mission subphase. Data compression was used extensively by MOC. Typically during real time orbits (on which data were transmitted back to Earth as they were

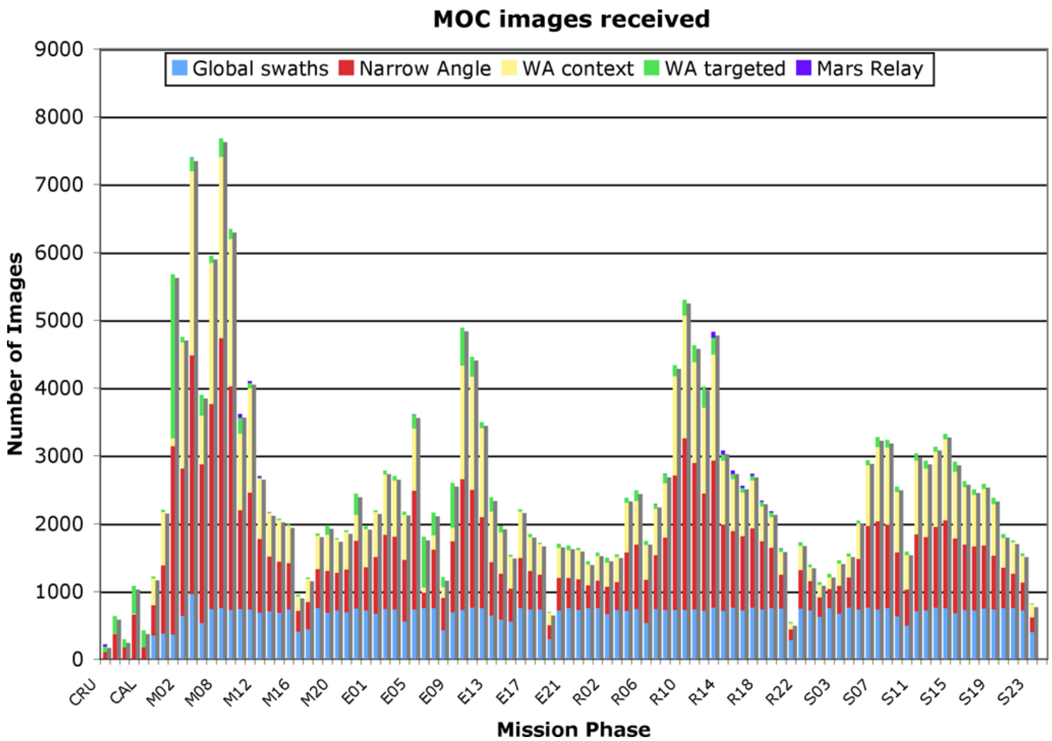

Figure 8. Total number of MOC images and MR data collections received as a function of mission subphase from cruise (CRU) through the end of the mission, November 1996 – November 2006. The number of images received is a direct function of data playback rates and downlink availability (figure8.png) (figure8.txt).

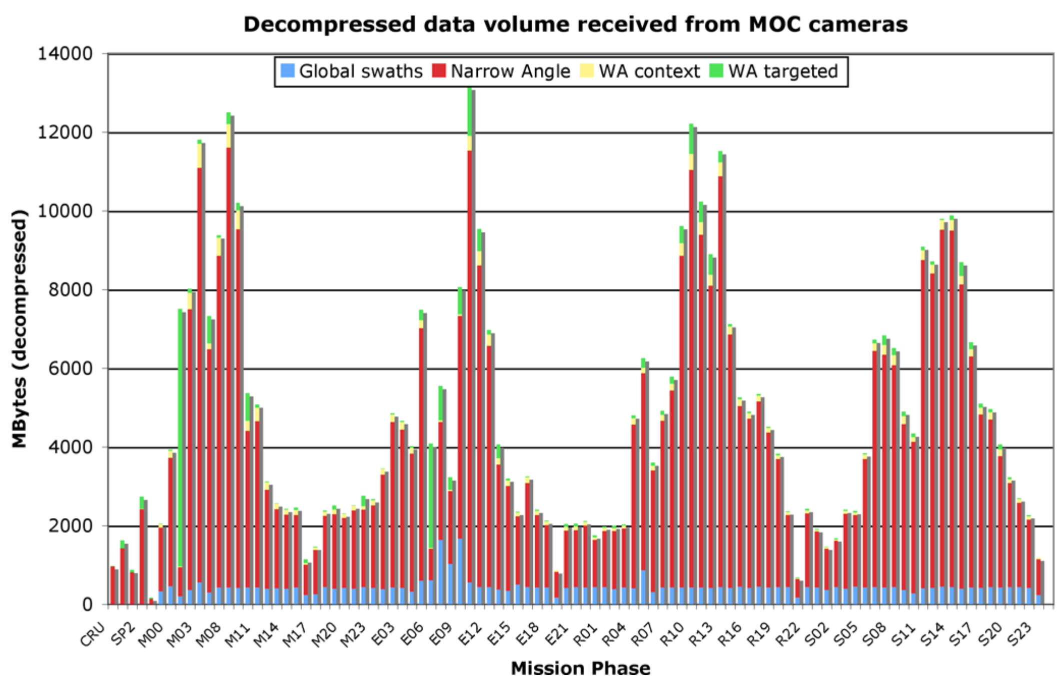

Figure 9. Volume of decompressed MOC and MR data received as a function of mission subphase from cruise (CRU) through the end of the mission. Except during the 2001 planet-encircling dust event, data volume was a direct function of data playback rates and downlink availability, with more data received during high data rate periods near Mars opposition (relative to Earth) and less data received during low data rate periods, which occur near Mars solar conjunction (relative to Earth). Note that the volume of the daily global image swath data was maximized during the 2001 planet-encircling dust event (figure9.png) (figure9.txt).

Table 5. MGS MOC images and MR data collections commanded and received, launch through the end of mission, November 1996 – November 2006.

Image type	daily global swaths	wide angle context	targeted wide angle	narrow angle images	Mars Relay (MR)	mission total images	mission total images + MR
commanded	64,681	74,292	14,468	101,355	530	254,796	255,326
commanded received	62,559	70,137	13,848	97,081	505	243,625	244,130
autonomous received	12	15	0	16	0	43	43
corrupted	4,589	2,042	2,498	19,497	87	28,626	28,713
Total Received	62,571	70,152	13,848	97,097	505	243,668	244,173

acquired), narrow angle images were losslessly compressed and wide angle images (including daily global images) were uncompressed. During periods of high and medium data rate, the same applied on record orbits (on which data were recorded onboard MGS after acquisition and played back later, typically the following day), except for daily global swaths—these were usually compressed when transitioning through medium data rate from low to high. During low data rate periods, most narrow angle images were compressed using DCT (Discrete Cosine Transform) compression, as were the daily global swaths. To prevent degradation of image quality, cPROTO images were losslessly compressed, regardless of the data rate and downlink availability.

Operationally, the MOC investigation experienced both data loss and data corruption. Data loss is defined as images for which commands were submitted by the MOC team, but no part of the image was received. Table 5 shows that 11,171 images commanded were never received. That is, ~4% of the images commanded were lost before reaching Earth. The majority of these losses occurred because of spacecraft or camera upsets (Contingency Mode, Safe Mode, MOC reboots) or problems at the receiving DSN station (antenna not available because of a problem with another spacecraft, heavy snow cover, severe storms, hardware or software problems). Some images were lost when, by human error, the commands to take the images were not sent to the spacecraft by the spacecraft real time operations staff. In addition to entire images being lost, Table 5 shows that about 12% of the received data (including MR data) were corrupted by data packet loss.

MGS Mars Relay data

The Mars Relay (MR) was the primary and only pathway for downlink of data from the Deep Space 2 Mars microprobes (DS2), which reached the planet on 3 December 1999. Likewise, the MR system was the only pathway available for real time downlink of telemetry from the two Mars Exploration Rovers (MER) as they descended toward the planet's surface in January 2004 (Entry, Descent and Landing, EDL). No signals were ever received from the DS2 probes and the MR was subsequently employed December 1999–March 2000 to seek signals from the missing Mars Polar Lander (MPL), again to no avail.

The MR system did successfully receive signals from each MER as it was landing in January 2004. Mars Odyssey performed as the primary relay pathway for most of the MER surface science (post-EDL) data because, unlike MGS, the relay system was provided as a spacecraft system function for which relay data collection did not come at the expense of orbiter science. In addition, MER data packets were lost every 16 seconds due to the hand shake protocol employed on MGS; Mars Odyssey did not have this problem. Owing to the limited size of the MOC buffer, MR data acquisitions came at the expense of MOC imaging: through and beyond the primary MER mission (January–July 2004), the MGS MR and MOC system was employed to relay some of the science data from the rovers. Thereafter, the system was exercised once again in February 2006 to demonstrate readiness as a backup to the Mars Odyssey relay system in the event of a problem with that spacecraft. Table 6 describes the timing and amount of data returned through the MR/MOC system from the MER rovers. These data were passed along immediately to the MER science team and the original received MR data, per agreement with the NASA PDS, were delivered to the Navigation & Ancillary Information File (NAIF) group at the Caltech JPL for safekeeping. Copies of the MR data were also stored at MSSS.

Table 6. Data from MER allocated and returned through the MGS MR system.

MOC sub-phase	Date	Spirit (MER-A)		Opportunity (MER-B)		MER-A + MER-B	
		Allocated (Mbits)	Received (Mbits)	Allocated (Mbits)	Received (Mbits)	Allocated (Mbits)	Received (Mbits)
R13	Jan 2004	2070.28	692.28	572.13	327.45	2642.41	1019.73
R14	Feb 2004	1622.02	784.18	1665.27	1275.21	3287.29	2059.38
R15	Mar 2004	1690.83	1274.77	1681.00	1424.29	3371.83	2699.06
R16	Apr 2004	1327.10	847.28	1258.29	428.15	2585.40	1275.43
R17	May 2004	471.86	42.30	865.08	129.98	1336.93	172.28
R18	Jun 2004	0.00	0.00	983.04	175.15	983.04	175.15
R19	Jul 2004	0.00	0.00	550.50	220.23	550.50	220.23
S15	Feb 2006	0.00	0.00	58.98	58.98	58.98	58.98

Mission event summary

Table 7 describes the events that occurred during the MGS mission, as they pertain to the conduct of the MOC investigation. These details are valuable for understanding when and why certain MOC data were acquired and the limitations that the team was working under at any given time during the mission.

Mission support

The MGS MOC and the MR were used to support other missions to Mars from the first images acquired of the planet in July 1997 to some of the last images obtained in October 2006 for candidate Phoenix and Mars Science Laboratory landing sites. Table 8 details the mission support activities conducted by the MOC team. Narrow angle images provided the first views of human artifacts on the surface of Mars (Malin 2005), particularly the Viking 2 backshell (Figure 10) and the MER hardware and rover tracks (Figure 11). MOC also captured views of the Mars Odyssey and Mars Express spacecraft as they orbited the planet (Figure 12).

Science results

The MOC narrow angle and wide angle cameras were used to address the full array of scientific topics that can be addressed by imaging from Mars orbit. Each image target was considered by a person who selected targets 3–5 days prior to its acquisition. Imaging efforts were typically conducted with the intent to address a specific hypothesis formulated about a given subject.

This section summarizes what we consider to be the twelve most important results of the MOC investigation. Other results were summarized elsewhere. For example, early (*i.e.*, data acquired before the Primary Mission) science results were described by Malin et al. (1998), Malin and Carr (1999), McEwen et al. (1999), Hartmann et al. (1999), Thomas et al. (1999), and Malin and Edgett (1999). Other early results included (but were not limited to) analysis of images of Phobos (Thomas et al. 2000), polar studies (James et al. 2000, Thomas et al. 2000), cratering studies (Hartmann and Berman 2000, Hartmann and Neukum 2001), valley networks (Carr and Malin 2000), eolian features (Edgett and Malin 2000), and volcanic landforms (Keszthelyi et al. 2000). MOC results from the Primary Mission were summarized by Malin and Edgett (2001), Caplinger and Malin (2001), Carr (2001), Cantor et al. (2001), Sullivan et al. (2001), James et al. (2001) and James and Cantor (2002). Finally, cPROTO imaging efforts were briefly discussed by Malin and Edgett (2005).

The choice of results summarized here, and the description of those results, is a "snapshot in time" that reflects the views and perspectives of authors Malin, Edgett, and Cantor as they stood at the time of the unexpected end of the MGS mission in late 2006. As this section is simply intended to be a summary of the major results of the MOC investigation, we do not address in detail the research of others as it relates to the major findings presented here. We remind the readers, as noted in the Introduction, that a much longer and more detailed volume is being prepared which will cover these and many other MOC science results.

Layered crust, cratered volume, and interbedded craters and valleys

Examination of MOC narrow angle camera images and images from previous and concurrent Mars orbiters (particularly Viking and Mars Odyssey) show that the upper crust of Mars is layered and interbedded within these layers are filled and buried impact craters, valleys, and other landforms that were once located at the Martian surface. In some regions, formerly buried landforms have been exhumed or partially exhumed (Figure 13). Craters of greater than 100 km diameter have been buried and exhumed. Ancient fluvial valleys in some places are inverted (*i.e.*, stand today as ridges of material that represent the former valley floor sediment or subsequent material that filled or partly filled the valley but were more resistant to erosion than the walls of that depression); in others they are discontinuous, with segments either buried or cut through rock that was long ago eroded away. Some of the light-toned layered rocks exposed within the Valles Marineris are examples of material—some of which once filled and buried impact craters—that were buried beneath the plains through which the chasms were later cut. Hard rocks retain small impact craters better than soft rocks, and thus in some places the younger rocks are those that have the most craters. The burial, exhumation, and destruction of impact craters challenges the utility of crater counting to date surfaces unless these observations are taken into account. Most of these general concepts were outlined by Edgett and Malin (2004) and discussed by Malin and Edgett (2000), Edgett and Malin (2002), and Edgett (2005). The sketches in Figure 14 portray the basic idea in a very simplified form and compares the "cratered volume" view with the pre-MGS perception, a view that was derived from a simplistic understanding of the nature of the upper crust of the Moon (Mars was generally viewed as a Moon-like, heavily-cratered body on which were superimposed valley networks, outflow channels, polar caps, eolian features, and a greater variety of volcanic landforms).

Sedimentary rocks

Layered rocks composed of clasts—and in some cases, perhaps precipitates—are common on Mars. Despite much discussion of sediment and "layered deposits" following the Mariner 9 and Viking orbiter missions, there was very little discussion of "sedimentary rock". The first comprehensive discussion of sedimentary rocks on Mars (*e.g.*, Figure 15) is found in Malin and Edgett (2000) and was only possible because of the documentation of hundreds of occurrences of these layered rock outcrops provided by the MOC narrow angle camera (Figure 16). A variety of bedding styles and erosional expressions are represented in the images. In some locations, hundreds of layers (or packages of layers) of repeated thickness have been exposed at the Martian surface; these indicate a repetition of sedimentation conditions in

Table 7. Mars Global Surveyor MOC mission event summary.

Subphase		Dates	Events and Activities
Cruise (C*xx*) and Mars Orbit Insertion (T*xx*)			
C01	1996	7 – 22 NOV	MGS launch occurred on 7 November. MOC was not operated.
C02	1996	22 NOV – 19 DEC	Earth/Moon calibration imaging. Earth/Moon not seen in narrow angle images but present in wide angle images. Star focus calibration imaging (Pleiades, M45). Mars Relay (MR) system health checks.
C03	1996/1997	19 DEC – 13 JAN	Earth imaging during Mars Orbiter Laser Altimeter (MOLA) Earth scans. Earth not seen in narrow angle images but present in wide angle images.
C04	1997	13 – 27 JAN	Star focus calibration imaging (Pleiades, M45). Thermal bake-out to remove moisture from the MOC instrument structure.
C4A	1997	28 JAN – 17 FEB	Post-bake-out star focus calibration imaging (Pleiades, M45).
C05	1997	17 FEB – 20 MAR	Star focus calibration imaging (Pleiades, M45).
C06	1997	20 MAR – 21 APR	MOC was not operated.
C07	1997	21 APR – 27 JUN	MGS entered Safe Mode on 8 May, recovered on 25 May. MOC and MOLA were going to point at Earth but this was cancelled owing to the Safe Mode entry.
C09	1997	27 JUN – 11 AUG	C08 was cancelled owing to Safe Mode entry and recovery in C07. In C09, the first MOC narrow angle images of Mars were obtained to support Mars Pathfinder landing site weather prediction.
C10	1997	11 – 25 AUG	Star focus calibration (Omega-2, Omega–1, and Beta-1 Scorpius). Approach imaging of Mars at 45° longitude increments through 1 rotation of the planet.
C11	1997	25 AUG – 2 SEP	MOC was not operated.
T01	1997	2 – 13 SEP	MOC was not operated. Mars Orbit insertion on 12 September.
T02	1997	13 – 15 SEP	MOC was not operated.
Aerobraking (AB*x*), Science Phasing Orbits (SP*x*), Calibration (CAL)			
AB1	1997/1998	15 SEP – 27 MAR	AB1 for "Aerobraking 1". Early imaging; narrow angle camera not in focus. First images on 15 September. Aerobraking began 17 September; suspended 13 October; resumed 7 November; continued to 27 March. MOC operated until 5 February, then turned on again 13–18 February for 0°-phase angle imaging.
SP1	1998	28 MAR – 28 APR	SP1 for "Science Phasing Orbits 1". Aerobraking suspended until 13 September. MOC turned on 28 March for imaging which included targeted observations of landforms in Cydonia ("the face on Mars") and the Viking and Mars Pathfinder landing sites. Narrow angle camera not in focus.
Solar Conjunction	1998	29 APR – 1 JUN	MOC was not operated.
SP2	1998	2 JUN – 13 SEP	SP2 for "Science Phasing Orbits 2". Additional pre-Mapping Phase imaging of Mars with narrow angle camera not in focus. Targeted imaging of Phobos on 7, 19, and 31 August and 12 September.
AB2	1998/1999	13 SEP – 28 FEB	AB2 for "Aerobraking 2". MOC was not operated.
CAL	1999	28 FEB – 8 MAR	CAL for "calibration". Calibration imaging of stars (Omega-2, Omega–1, and Beta-1 Scorpius) and Mars. Imaging at sub-Earth latitude (15.6°N) corresponded with Hubble Space Telescope Wide Field Planetary Camera (WFPC2) imaging for cross-calibration of the MOC cameras.
Primary Mission (M*xx* for "Mapping")			
FHA	1999	9 – 27 MAR	FHA for "Fixed High Gain Antenna" operations. Contingency science prior to High Gain Antenna (HGA) deployment, in event of failure and loss of spacecraft during the deployment. Narrow angle camera was focused; initial survey at ~1.5 m/pxl and 3 m/pxl of Martian terrain. Partial daily global coverage (interrupted on orbits where MGS had to rotate to point HGA at Earth for communication).
HGA deployment	1999	27 MAR – 2 APR	HGA deployment. MOC was not operated.
M00	1999	2 APR – 5 MAY	Nominal imaging activities until 16 April when MGS went into Contingency Mode and MOC was automatically turned off. The HGA azimuth gimbal had encountered an obstruction. This ultimately led to changes in how MGS was operated until the obstruction was determined to be cleared in September 2005. Fixed High Gain-like operations were conducted (with MOC on) starting 28 April.

Table 7. (continued)

Primary Mission (continued)			
M01	1999	5 MAY – 4 JUN	Nominal spacecraft operations resumed on 6 May, permitting daily global coverage by the MOC wide angle cameras. MGS Orbit Trim Maneuver-1 (OTM-1) to alter ground track walk to 59 km at equator suspended owing to thruster plume impingement on the HGA. MOC conducted Science Campaign A, the Geodesy Campaign, described by Caplinger and Malin (2001). First Mars Polar Lander (MPL) candidate landing site images.
M02	1999	4 – 30 JUN	Completion of Geodesy Campaign on 5 June; continued imaging of MPL landing site candidates; nominal imaging activities. MGS Orbit Trim Maneuver-2 (OTM-2) to change orbit walk to 59 km separation at the equator on 10 June.
M03	1999	1 JUL – 10 AUG	Nominal imaging activities. MR system test for readiness to relay data from Deep Space 2 (DS2) probes in December. MGS slewed across the north and south pole for MOLA observing and MOC acquired images during these slews.
M04	1999	10–31 AUG	MGS Orbit Trim Maneuver-3 (OTM-3) to change ground track repeat cycle to 50 km at equator on 11 August. Science Campaign B covered nearly the entire planet at ~1 km/pixel with both wide angle cameras at equinox. First MOC spontaneous reboot (some data lost, other data impacted).
M07	1999	SEPTEMBER	There was no M05 nor M06 subphase; the MOC subphase naming convention was readjusted to correspond with Earth months. MOC late August spontaneous reboot recovery. Science Campaign B completed. Dark current images acquired on 2 orbits per week for the month. Real time downlink available to MGS increased after Mars Climate Orbiter lost upon arrival on 23 September.
M08	1999	OCTOBER	MOC spontaneous reboots on 3, 5, and 18 October resulted in some data lost and other images affected. MOC team began sending instrument initialization commands for every orbit to minimize further impacts resulting from spontaneous reboots. Dust storm activity and dust haze affected the quality of narrow angle images.
M09	1999	NOVEMBER	MGS transitioned from high to medium data rate on 18 November. MOC spontaneously rebooted on 4 and 23 November, resulting in some minor loss and impacts to images acquired. MR operational readiness tests for DS2 were conducted 4 and 30 November.
M10	1999	DECEMBER	The MR was used to attempt relay of data from the DS2 probes 3–8 December, to no avail. MR was then employed to listen for communication from MPL, again with no contact resulting from these efforts. Science Campaign C began 13 December to collect a full-resolution red wide angle geodesy map (stereo) of the south polar region. MGS was rolled off nadir so that MOC could image the MPL landing site to search for the missing hardware. An image of the Mars Pathfinder site was also attempted (but missed). MOC spontaneous reboots occurred on 3 and 26 December.
M11	2000	JANUARY	Off-nadir imaging to seek MPL continued. Efforts to find MPL using MR also continued. An off-nadir targeted image of the Mars Pathfinder site was obtained, for comparison with the MPL site images. Science Campaign C concluded.
M12	2000	FEBRUARY	Final off-nadir imaging to search for MPL and to image the Viking 1 lander site. Low data rate period began on 6 February. On 7 February, MGS began communicating in beta-supplement mode for the first time (owing to the HGA gimbal obstruction); this would continue for many months. A spacecraft commanding error led to filling of the MOC buffer and loss of some data 17–18 February and a few days thereafter. Search for signals from MPL using the MR continued.
M13	2000	MARCH	MGS slewed off-nadir over the poles for MOLA topographic observing on 5 March—the north pole was in darkness but MOC imaged south polar terrain on these passes. To facilitate Radio Science observing over the south polar region, the instrument deck pointed off of Mars for communication with Earth for about 8 hours for 3–4 days starting on 6 March, but this led to several problems and the effort was abandoned. Use of MR to search for MPL signals ended on 6 March. A star focus calibration image (Pleiades, M45) was obtained 31 March.
M14	2000	APRIL	Star focus calibration (Pleiades, M45); south polar off-nadir imaging near the pole during slews designed for MOLA topographic observations on 8–9 April. A MOC spontaneous reboot occurred on 25 April. Around 17 April, MOC red wide angle camera sensitivity began to degrade and lasted until May 2001.
M15	2000	MAY	Science Campaign D began during the month; the main focus was on acquiring red wide angle images of Hellas because the Geodesy Campaign images of Hellas were hazy. MOC acquired 1 image of south high latitude terrain during an off-nadir slew for MOLA polar observations. MGS bistatic radar observations limited MOC narrow angle imaging on 14 May.

Table 7. (continued)

Primary Mission (continued)			
M16	2000	JUNE	Science Campaign D (Hellas imaging) concluded. Some MOC data lost owing to Deep Space Network (DSN) problems on 6 June. An incorrect commanding of a MOC capability to inhibit data retrieval from the instrument by the spacecraft caused a 3-day outage of MOC followed by a commanded reboot of the camera. MOC acquired some autonomous images just prior to turn-off at the start of solar conjunction.
Solar Conjunction	2000	22 JUN – 13 JUL	MOC was not operated.
M17	2000	JULY	MOC turned on 13 July and returned several autonomous images because the imaging command file was radiated late. The rest of the month consisted of nominal imaging activities.
M18	2000	AUGUST	Nominal MOC imaging activities. MOC commands were radiated late on 12 August and thus, on 13 August, MOC returned a single autonomous image before resuming normal operations.
M19	2000	SEPTEMBER	Back-to-back MOC spontaneous reboots occurred twice on 8 September, resulting in some images lost and a few others affected. Star focus calibration images (Pleiades, M45) were obtained 18 September – 3 October. Science Campaign E was conducted; this effort focused on acquiring a springtime (near L_s 50°) wide angle red (summed 2) and blue (summed 4) map of the north polar region between 60°N and 90°N.
M20	2000	OCTOBER	MOC had a spontaneous reboot on 2 October. A star focus calibration image (Pleiades, M45) was acquired on 3 October. Nominal imaging occurred throughout the month, including clear-atmosphere imaging of Hellas basin.
M21	2000	NOVEMBER	A spontaneous reboot occurred on 12 November. Data rate increased from low to medium on 26 November. Nominal imaging activities were conducted.
M22	2000	DECEMBER	The MOC operations team detected error messages in the camera's daily health reports that indicated a sensor that measures focal plane assembly temperatures was stuck from 18 December until the team commanded a reset for the sensor on 20 December. The sensor subsequently became stuck again between 25 and 28 December; this was again cleared by commands radiated to the spacecraft. There was no loss of data but the image headers for these periods received an incorrect value for this sensor. A modeled value was replaced in these headers for PDS (NASA Planetary Data System) archiving of the affected images. Science Campaign F began; it involved acquisition of red and blue wide angle images covering Mars between 90°N and 56°S at ~1.5 km/pixel and a series of evenly-spaced (in latitude and longitude) narrow angle views at about 5 m/pxl to sample the variety of Martian terrain.
M23	2001	JANUARY	Science Campaign F concluded. Imaging of candidate Mars Exploration Rover (MER) landing sites began. MOC completed 1 Mars year of daily global imaging.
First Extended Mission (E*xx* for "Extended")			
E01	2001	FEBRUARY	ROTO imaging became routine; the first ROTO images since the MPL search in early 2000 were acquired. MOC did a spontaneous reboot on 7 February. Data rate transitioned from medium to high on 15 February.
E02	2001	MARCH	A major emphasis during the month was on north polar narrow angle imaging, as conditions were ideal (minimal frost, minimal atmospheric obscuration). For 8 hours on 23 March, MGS was pitched 22° off nadir such that MOC was facing backward relative to the northward motion of the spacecraft on the day side of Mars. This 22° pitch, or "Relay-22" was a test designed to place MGS in an attitude that would align with the gravity gradient and thus save fuel, yet still provide an orientation necessary to relay data from landed spacecraft such as the planned 2004 MER rovers. The results of this test later evolved into the Relay-16 (for 16° pitch) approach that was adopted by the MGS Project. MOC acquired images during the Relay-22 test, including one that repeated a previous nadir narrow angle image for stereo. Also during the month, the MOC team conducted a series of focus heater imaging tests.
E03	2001	APRIL	Star focus calibration images (Omega-2, Omega-1, and Beta-1 Scorpius) were obtained 26 April – 2 May.

Table 7. (continued)

First Extended Mission (continued)			
E04	2001	MAY	MGS went into Contingency Mode on 2 May and the MOC automatically turned off. MOC was returned to service following Contingency Mode recovery on 9 May. However, a late uplink of MOC commands on 9 May affected 21 images. Following the 9 May turn-on, the MOC team found that the original sensitivity of the red wide angle camera had been restored. On 15–16 May, a test of the MR system was conducted by sending a signal from Earth and then returning it through the MR/MOC system. This was the first in a series of tests planned to support the MER Project, and the MR capability was tested in the Relay-16 attitude.
E05	2001	JUNE	MGS transitioned from beta-supplement to nominal communications on 21 June. Another MR test was conducted 26–28 June using UHF signals sent from Earth. Large, regional dust storms began to appear the end of the month. The MOLA laser stopped functioning on 30 June.
E06	2001	JULY	Large, regional dust storms led to a planet-encircling cloud that obscured most of the planet from the MGS MOC vantage point. The atmosphere over the south polar region remained relatively clear, as did the highest elevations on the Tharsis volcanoes; thus, these were the main narrow angle camera targets for the month. As the dust activity continued, wide angle images, including images of the sunward limb, were increasingly acquired to provide views of the dust and for use as possible flat field calibration data. MOC did a spontaneous reboot on 3 July.
E07	2001	AUGUST	Planet-encircling dust activity continued through the month. MOC daily global image swaths were acquired at 3.75 km/pxl instead of the nominal 7.5 km/pxl to view the dust activity and to help fill downlink that could not be utilized by the narrow angle camera. Narrow angle images acquired to repeat 1999 coverage of the south polar residual cap showed that scarps had retreated ~3 m. Five planned ROTO images were acquired without a slew because the off-nadir maneuvers were cancelled. On 16 August at 00:44 UTC the MGS was pitched to 16° off nadir (Relay-16 orientation) as the new nominal orientation. Repeat imaging of areas observed in nadir images permitted stereopairs to be acquired without conducting a ROTO maneuver. On 20 August, the MOC operations team detected error messages that indicated a sensor that measures focal plane assembly temperatures was stuck. The team commanded a reset for the sensor, which was stuck 18–21 August. There was no impact to the data but the image headers received incorrect values; modeled values were placed in the affected image headers during PDS archiving.
E08	2001	SEPTEMBER	Planet-encircling dust activity continued, thus the imaging strategies of July and August continued through the month, with narrow angle imaging emphasis on the south polar region. A spontaneous reboot occurred on 1 September, affecting a few images. MGS entered Contingency Mode on 6 September and MOC automatically shut down. The instrument was powered up again on 11 September; after returning only 8 images, MOC locked up into an unknown state on 12 September while it was running a command to inhibit transfer of data to the spacecraft (a strategy used because of limited DSN coverage/downlink opportunities). In an attempt to clear the problem, a software reboot was commanded on 17 September; this was unsuccessful and suggested that the problem centered on a hypothesis that the maximum number of commands the MOC could receive had been exceeded. A hardware reboot command was sent on 18 September and that cleared the problem; normal operations were resumed. Although commands to inhibit MOC data transfer were successfully used 40 times since March 2000, the MOC operations team subsequently ceased this strategy.
E09	2001	OCTOBER	Dust storm activity subsided and the planet-encircling dust haze began to thin. The MOC team began taking summed narrow angle images of terrain outside the south polar region and Tharsis; the summing, usually ≥ 4x, was done to improve signal-to-noise performance when viewing terrain through a dust haze. Star calibration images (Pleiades, M45) were obtained 8–16 October. MGS went into Contingency Mode on 19 October; the spacecraft was quickly recovered and MOC powered up on 21 October. Mars Odyssey entered Mars orbit on 24 October, and MOC aerobraking support for Mars Odyssey (daily weather observations) began. A spontaneous reboot occurred on 27 October.
E10	2001	NOVEMBER	The post-planet-encircling dust event imaging strategy of acquiring narrow angle images of summing ≥ 4x continued through the month as the haze slowly dissipated. Daily global imaging resumed at 7.5 km/pixel after > 2 months at 3.75 km/pixel. Off-nadir (ROTO) imaging was suspended out of concern that star tracking associated with the ROTO slews had caused the Contingency Mode entries in September and October; the MGS Project did not want the spacecraft to have an upset during the Mars Odyssey aerobraking support period. Two spontaneous MOC reboots occurred: 5 and 6 November.

Table 7. (continued)

First Extended Mission (continued)			
E11	2001	DECEMBER	MGS data rate transitioned from high to medium on 13 December. Mars Odyssey aerobraking support, including the moratorium on ROTO imaging, continued. The atmosphere returned to near-normal clarity and nominal narrow angle imaging resumed. A MOC spontaneous reboot occurred on 28 December.
E12	2002	JANUARY	A MOC spontaneous reboot occurred on 13 January. Mars Odyssey aerobraking support ended on 17 January and ROTO imaging resumed. The red wide angle camera was used to begin acquiring a full-resolution (~240 m/pxl) map of the summer south polar residual cap to complete the Geodesy Campaign effort.
E13	2002	FEBRUARY	Full-resolution red wide angle mapping of the south polar residual cap was completed. MGS entered Contingency Mode on 27 February and MOC automatically powered off.
E14	2002	MARCH	MGS was recovered from Contingency Mode and MOC was powered up on 6 March. MGS communication strategy switched to beta supplement on 15 March and the data rate went from medium to low on 21 March.
E15	2002	APRIL	MGS entered Contingency Mode on 1 April and MOC powered down. It was recovered a week later and MOC was powered up on 8 April. ROTO imaging was suspended for the rest of the month pending better understanding of the cause of the Contingency Mode entry.
E16	2002	MAY	A minor number of off-nadir images were permitted—2 ROTOs and 5 star focus calibration images (Pleiades, M45).
E17	2002	JUNE	The MGS star catalog and ROTO processing software were updated and then ROTO imaging resumed in earnest with 26 ROTO images commanded during the month.
E18	2002	JULY	On 10 July, MOC acquired 24 autonomous images owing to a Deep Space Network problem and late arrival onboard of MOC commands. MOC rebooted on 17 July. MOC was turned off on 31 July for solar conjunction.
Solar Conjunction	2002	31 JUL – 19 AUG	MOC was not operated.
E19	2002	AUGUST	MOC was powered up on 19 August and nominal imaging activities resumed.
E20	2002	SEPTEMBER	Nominal MOC imaging activities were conducted throughout the month. A major emphasis was on red wide angle full-resolution (~240 m/pxl) mapping of Hellas Planitia, as Hellas exhibits the clearest atmospheric conditions each Mars year between about L_s 55° and 85°.
E21	2002	OCTOBER	Nominal imaging activities and the Hellas red wide angle mapping effort continued.
E22	2002	NOVEMBER	Operations and imaging activities were nominal. The Hellas mapping campaign concluded and narrow angle imaging focused on the north polar region as northern summer began on 4 November.
E23	2002	DECEMBER	Nominal imaging activities continued, with an emphasis on north polar targets.
Second Extended Mission (R*xx* for "Relay")			
R01	2003	JANUARY	The data rate rose from low to medium on 9 January. Nominal imaging activities were conducted, with continued emphasis on the north polar region.
R02	2003	FEBRUARY	Nominal imaging activities with an emphasis on north high latitude narrow angle targets.
R03	2003	MARCH	Nominal imaging activities with an initial emphasis on north polar targets; dust storm activity increased in the north polar region and narrow angle imaging there was reduced. A spontaneous reboot occurred on 23 March.
R04	2003	APRIL	MGS data rate rose from medium to high on 3 April. Star focus calibration (Omega-2, Omega-1, Beta-1 Scorpius) images were acquired 24 April – 3 May. A spontaneous reboot occurred 18 April. As southern spring approached, the first south polar residual cap images were acquired and the wide angle cameras monitored for the annual spiral clouds in the Arsia Mons caldera.
R05	2003	MAY	A star focus calibration image (Omega-2, Omega-1, Beta-1 Scorpius) was acquired on 3 May. On 8 May, MGS was slewed to point MOC and image Jupiter and Earth/Moon, both in the same part of the sky. The first two test Pitch and Roll Targeted Observation (PROTO) images were obtained (these did not have the compensation, the "c" in "cPROTO" for the rotation of Mars); the PROTO images covered the Viking 1 and Mars Pathfinder landing sites. MGS conducted a 1-week test of the constant roll technique 8–14 May with a roll of 0.53° east of nadir. A spontaneous reboot occurred on 15 May.

Table 7. (continued)

Second Extended Mission (continued)			
R06	2003	JUNE	On 1 June, MGS slewed to point MOC to image Phobos over the Martian limb. MGS entered Contingency Mode on 11 June and MOC was automatically shut off. Following recovery, MOC was returned to service on 17 June. Constant roll imaging was conducted throughout most of the month: 5–11 June at 5° west, 12–18 June at 4° west, 19–21 June at 3° west, 22 June – 2 July had no roll. Three MOC spontaneous reboots occurred: 8 June, 20 June, 24 June.
R07	2003	JULY	Constant roll imaging continued: 3–9 July at 4° west, 10–16 July at 3.4° west, 17–23 July at 5° west, 24–31 July at 2° west. To begin preparing to do real time relays of MER Entry, Descent, and Landing (EDL) data in January 2004, the MR system was exercised by collecting UHF signals sent from Earth on 1–3 July.
R08	2003	AUGUST	Constant roll imaging throughout the month: 1–7 August at 1.3° west, 8–14 August at 0.9° west, 15–21 August at 2.0° west, 22–28 August at 4.7° east, 29–31 August at 5.0° east. The MOC team began collecting MOC target suggestions from the general public through an internet web site on 20 August. End-to-end MR testing, using UHF signals sent from Earth, occurred 26–29 August. A spontaneous reboot occurred on 27 August. A third test PROTO image (Olympica Fossae) was acquired; from this it was recognized that compensation for planetary rotation would be necessary.
R09	2003	SEPTEMBER	Constant roll operations were conducted 1–4 September at 5° east, then the nominal Relay-16 orientation was resumed. Beta supplement communications ended on 11 September. The first narrow angle image and red wide angle context frame suggested by a member of the general public was acquired on 4 September. A MOC spontaneous reboot occurred on 24 September.
R10	2003	OCTOBER	On 3 October, MGS performed an Orbit Synchronization Maneuver (OSM–1) to begin positioning the spacecraft to relay data during the MER-A (Spirit) descent scheduled for 3 January 2004. Owing to uncertainty as to whether OSM-1 would place the spacecraft into the correct orbit, the MOC team acquired semi-random narrow angle images for several days thereafter, in the event that desired targets would be missed. Off-nadir imaging was suspended for the OSM-1 period, too. OSM-1 was sufficiently successful that OSM-2 and OSM-3 were not needed. Three MOC reboots occurred: 4 October, 8 October, and 10 October.
R11	2003	NOVEMBER	The first two cPROTO images were acquired and nominal imaging activities were conducted throughout the month.
R12	2003	DECEMBER	The MOC team began regular targeted wide angle imaging and frequent reporting of weather conditions at the MER and Beagle 2 landing sites. A reboot of the MOC was commanded on 4 December to demonstrate that the command was functional and to prepare for the possibility of needing to induce reboots of MOC before MER EDL support in order to reduce the likelihood of a spontaneous reboot that would result in loss of MR data collection from the MERs. The MER Project later determined that commanded reboots would not be necessary for MER support. cPROTO imaging became part of nominal MOC imaging activities on 19 December. Daily housekeeping telemetry from the MR system began to be collected on 30 December to support relay from the MERs.
R13	2004	JANUARY	The MR system, which included the MOC buffer, was heavily used to receive critical Entry, Descent, and Landing (EDL) data from the two MERs. The MR was used throughout the rest of the month to relay some of the MER science data. Spirit (MER-A) landed on 4 January and Opportunity (MER-B) on 25 January. Following the MER-A landing, MGS executed OSM–4 on 4 January to place the spacecraft in position to relay MER-B EDL data. OSM–5 and OSM–6 were cancelled because of good performance on OSM–4. On 5 January, the MOC team began acquiring images to look for the missing Beagle 2 lander. The team also executed 3 cPROTOs; the first two attempted to image the MER-A hardware on the ground and was fully successful in the second image; the third cPROTO attempted to image MER-B hardware but missed the target. Three MOC spontaneous reboots occurred: 2, 12, and 31 January.
R14	2004	FEBRUARY	MOC acquired a ROTO image (1 February) and a cPROTO image (6 February) showing the MER-B hardware on the ground. MGS data rate transitioned from high to medium on 6 February. Some imaging efforts focused on ROTO views of the final Beagle 2 landing ellipse. The MR system was used throughout the month to relay MER data to Earth.
R15	2004	MARCH	Additional ROTO images of the Beagle 2 site were obtained and 5 cPROTOs were targeted to view the MER landing sites. The fifth cPROTO image, R15-02643, was the first to show rover tracks (MER-A) on the Martian surface. The MR system continued to be used throughout the month to relay MER data.

Table 7. (continued)

Second Extended Mission (continued)			
R16	2004	APRIL	On 1 April, MGS data rate switched from medium to low. Efforts were continued to search for Beagle 2; this included acquisition of 2 cPROTO images targeted to a candidate Beagle 2 impact site (which turned out to be a windblown dune or drift). Other cPROTO imaging included the MER-B site and an attempt to image the Viking 2 lander site. The MR system was used throughout the month to relay MER data to Earth. A spontaneous reboot occurred on 24 April. Star focus calibration images of M45 (Pleiades) stars were executed on 29 and 30 April.
R17	2004	MAY	The star focus calibration effort continued with 3 images obtained through 10 May. MGS performed OSM-7 on 27 May to stop the orbital drift in Mars local mean solar time that resulted from the earlier OSMs. The MR system relayed MER data throughout the month; on 28 May, relay from MER-A was ended.
R18	2004	JUNE	Nominal MOC imaging efforts, including acquisition of cPROTOs and ROTOs, were conducted. The MR system operated throughout the month to relay MER-B data.
R19	2004	JULY	The ideal time of year to image Hellas Planitia (L_s 55°–85°) opened near the start of the month and thus a campaign to acquire key narrow angle images in Hellas was initiated. MGS transitioned from nominal to beta-supplement communications mode on 22 July. Owing to the low data rate and beta-supplement communications, plus an upcoming solar conjunction, the MR system was used only through 19 July to relay MER-B data. After that, the MR acquired health-check data only, once per day through 28 July to assess MR effects on power consumption. Two MOC spontaneous reboots occurred: 16 and 18 July.
R20	2004	AUGUST	Hellas Planitia narrow angle imaging efforts continued through the month. Routine efforts to image the candidate Phoenix Mars Scout landing sites began. A final health check of the MR system occurred on 5 August; then the MR was turned off. A MOC spontaneous reboot occurred on 22 August.
R21	2004	SEPTEMBER	MOC was powered off on 7 September for solar conjunction, and powered back up on 25 September. Imaging of the Phoenix landing site candidates continued.
Solar Conjunction	2004	7–25 SEP	MOC was not operated.
R22	2004	OCTOBER	Vigorous efforts to obtain narrow angle images of north polar targets began as MOC started its fourth Mars year of daily global imaging. Polar targets centered on stratigraphic relations of layered materials, cPROTO imaging of polar dunes, layers, and residual ice cap surfaces, and documentation of dunes being exhumed from within polar layers. Imaging of candidate Phoenix landing sites continued.
R23	2004	NOVEMBER	Narrow angle imaging continued to emphasize north polar targets and Phoenix landing site candidates. A new commanding procedure was introduced on 1 November for ROTO and cPROTO imaging; it permitted off-nadir slews to occur during orbits that MGS would be communicating in real time with Earth. In these cases, the motion of the HGA would be frozen and communication severed while MGS slewed to acquire an image, then communication would be re-established after the slew. This greatly enhanced the number of opportunities for targeting ROTO and cPROTO images.
Third Extended Mission (S*xx* for "Science" and "Support")			
S01	2004	DECEMBER	High resolution imaging of north polar landforms and Phoenix landing site candidates continued throughout the month. Nominal ROTO and cPROTO imaging continued. On 22 December, MGS went into Contingency Mode and MOC was automatically powered off. Following recovery of the spacecraft, MOC was powered up on 27 December to resume its activities.
S02	2005	JANUARY	Off-nadir slews were resumed on 6 January, following a short hiatus resulting from the Contingency Mode entry in December. The normal, expected increase in dust storm activity at north high latitudes led to targeting of fewer and fewer north polar and Phoenix landing site images. Imaging to support Phoenix landing site surveys was suspended at the end of the month because cloud cover (and, eventually, winter darkness) obscured the sites until the following late winter season. Nominal imaging activities, including ROTO and cPROTO acquisitions, were continued throughout the month. On 27 January, MGS transitioned from low to medium data rate.

Table 7. (continued)

Third Extended Mission (continued)			
S03	2005	FEBRUARY	MGS underwent multiple angular momentum dumps (AMDs) during the month that resulted from a change made by the spacecraft operations team to move the solar panel offset angle from 10° to 35° (to reduce excess electrical power production). Unanticipated AMDs resulted in a degradation of predicted orbital ground tracks, thus resulting in MOC narrow angle images that missed their targets. The spacecraft team solved the problem by setting one solar panel at +10° and the other at −10°. Although some narrow angle images missed their targets because of the AMDs, the net result was development by the Lockheed Martin Astronautics group of an improved angular momentum control scheme for positioning the HGA to counteract momentum buildup; this led directly to extremely accurate predictions of MOC ground tracks for the remainder of the MGS mission.
S04	2005	MARCH	Southern spring began during the month; with it came increased narrow angle imaging of the south polar seasonal and residual caps. Nominal imaging, including ROTOs and cPROTOs, continued through the month.
S05	2005	APRIL	The MGS data rate changed from medium to high on 22 April. On 21 and 22 April, MGS was slewed so that MOC could obtain narrow angle images of Mars Express and Mars Odyssey, respectively. Also on 21 April, the MOC team attempted cPROTO imaging of a candidate Mars Polar Lander hardware site, but that image was saturated white owing to seasonal frost and a poor assumption about the needed gain and offset settings.
S06	2005	MAY	The MGS operations team modified cPROTO commanding to permit access to terrain at more latitudes than previously possible; narrow angle imaging included the first cPROTO views of the south polar residual cap. A spontaneous reboot occurred on 1 May. Between 12 and 21 May, 5 star focus calibration images (Omega-2, Omega-1, and Beta-1 Scorpius) were obtained.
S07	2005	JUNE	Owing to Earth–Mars geometric relations and a requirement that Earth be above the limb of Mars to maintain communications through the MGS HGA, spacecraft operators began on 16 June to move MGS in both roll and yaw orientations on the Martian day side. This resulted in a continuous roll-yaw offset with a pre-set maximum roll angle relative to the nadir ground track. During this period the roll angle was changed continuously along the day-side ground track to a specific maximum that was periodically determined by MGS operators. The first maximum angle, set on 16 June, was 2°. The angle changed to 4° on 23 June and 5° on 30 June. The MOC operations team received predicted ground tracks that included both the effects of changing roll and yaw, thus there was no impact to the ability to select MOC targets, nor was there an impact to the ability to obtain ROTO and cPROTO images. MOC rebooted on 21 June. Several regional dust storms obscured large portions of Mars in June; as a result, ROTO imaging was suspended for 1 week and cPROTO imaging for 2 weeks.
S08	2005	JULY	Continuous roll-yaw offset maneuvers continued, starting with a maximum roll of 5° and changing to 6° on 6 July, 7° on 14 July, and 8° on 21 July, where it remained for the rest of the month. Four spontaneous MOC reboots occurred: 2, 15, 23, and 24 July. The atmosphere remained hazy following the June dust storms; narrow angle imaging was focused on dust-free regions such as the south polar seasonal and residual cap and high elevations in Tharsis. A second cPROTO attempt was made to investigate a candidate for Mars Polar Lander hardware but the target was missed in the image. On 30 July, the spacecraft primary computer (SCP1) experienced a functional lockup anomaly during a MOC command uplink to both SCPs and switched to the backup (SCP2); no MOC science data were lost but this was the start of a problem that would lead to data loss in August.
S09	2005	AUGUST	Continuous roll-yaw offset maneuvers were set to a maximum of 8° all month. The atmosphere continued to clear following the June 2005 dust events. The number of ROTO and cPROTO images commanded was limited owing to spacecraft recovery efforts following the SCP1 and SCP2 problems; only 1 cPROTO image was obtained—another attempt to find candidate Mars Polar Lander hardware, which again missed the target by a few hundred meters. MGS entered Safe Mode for the first time since Cruise on 26 August. MOC was automatically powered off at the Safe Mode entry. The Safe Mode occurred when SCP2 encountered a lockup anomaly, also during a MOC uplink to both SCPs; this caused the spacecraft to switch to SCP1, which had been purposefully placed in Safe Mode by the spacecraft team as part of SCP1 recovery efforts from the problem that occurred in July.

Table 7. (continued)

Third Extended Mission (continued)			
S10	2005	SEPTEMBER	MGS was recovered from Safe Mode and MOC powered up on 7 September. At this time MGS operators found that the HGA cleared the obstruction that it had encountered in April 1999; beta-supplement communications was suspended and never needed again; continuous roll-yaw maneuvers were also no longer necessary. The MOC team changed its uplink strategy such that MOC commands would only be uplinked to the active SCP (not both) to help alleviate the lockup anomaly that occurred twice in the previous two months. Three more cPROTO images were attempted to investigate candidate MPL hardware; the final image hit the target on 27 September (and showed no hardware). On 21, 24, and 28 September, the MGS instruments were pointed toward Earth to attempt using MOLA to receive a laser communication signal; for the 24 and 28 September Earth scans, the MOC team attempted to obtain images of Earth but these missed their targets owing to timing uncertainties. Meanwhile, MOLA did receive a signal from Earth on the third attempt. Owing to a problem with the commanding of recorded data playbacks in the MGS background sequence, ~75% of recorded MOC data were lost each day between 29 September and 5 October.
S11	2005	OCTOBER	The spacecraft record playback problem that began 29 September persisted to 5 October and resulted in some MOC data loss. A campaign to obtain 240 m/pixel blue wide angle images of north mid-latitude slopes was undertaken to search for seasonal frost, as frost is seen at the south mid-latitudes in the corresponding season. Imaging efforts also included a cPROTO view of the MER-B rover at the crater informally named Erebus. Near the end of the month, dust storm activity increased and began to limit the areas targeted by the narrow angle camera. Two MOC spontaneous reboots occurred: 20 and 27 October. Nominal imaging, including ROTOs and cPROTOs, continued.
S12	2005	NOVEMBER	Narrow angle imaging was somewhat inhibited by dust storm activity and haze that spread across the planet during the month, but otherwise nominal imaging, including ROTO and cPROTO acquisitions, were conducted. The MGS operations team conducted tests 28–29 November to determine whether the HGA obstruction had indeed cleared during the August 2005 Safe Mode period. To maintain real time communication with MGS during these tests, the spacecraft was maneuvered in a manner similar to the continuous roll-yaw offset activities of June–August 2005. However, because of uncertainty as to whether the spacecraft would encounter a problem during the tests, MOC was commanded to take narrow angle images of unspecified targets during the 28–30 November period (the 30th was reserved by the MGS operators as a period for additional tests, if necessary). The test confirmed the lack of an obstruction.
S13	2005	DECEMBER	The MOC science operations team noted that the MGS ground track was repeating every 377 orbits (about once per month) for the past several months; a mission change request was submitted to conduct constant roll imaging. Narrow angle imaging of candidate Phoenix landing sites was resumed although the targets were covered with seasonal frost. The MOC operations team began a new strategy to include MOC initialization commands to recover more quickly from MOC spontaneous reboots, thereby reducing the number of uplinks required to command the instrument. Nominal imaging, including ROTOs and cPROTOs, continued as north high latitude targets (with seasonal frost) came into view.
S14	2006	JANUARY	The mission change request to conduct constant rolls was approved and MGS was rolled to 3° west, per MOC science team advice, on 12 January. Narrow angle imaging of candidate Phoenix landing sites continued and a new campaign was begun—using the red wide angle and the narrow angle cameras—to find impact craters that had formed on Mars between the May 1999 Geodesy Campaign and early 2006. A MOC reboot occurred on 30 January. Also on 30 January, the MR was powered up and MOC returned two housekeeping telemetry acquisitions from the MR. These showed that the MR was functioning nominally and could still be used to relay data from the MER rovers.
S15	2006	FEBRUARY	On 1 February, the MR and MOC were used to relay data from MER-B, then the MR was turned off to conserve power. This was the first in a planned series of quarterly collections to demonstrate MGS readiness to relay data from the MERs in the event of an upset on the primary relay spacecraft, Mars Odyssey (however, the remaining 3 MR collections in 2006 were waived because of spacecraft power constraints). On 10 February, MGS was slewed to point MOC at the Mars Express spacecraft, which was imaged by the narrow angle camera. A MOC spontaneous reboot occurred on 11 February. Constant roll imaging continued—the month began at 3° west as set in January; this was changed to a 2.7° west roll on 9 February on the basis of MOC science team analysis. Imaging of candidate Phoenix landing sites continued and MOC daily global image swaths and meteorological experience began to be used to support the upcoming aerobraking effort for the Mars Reconnaissance Orbiter (MRO).

Table 7. (continued)

Third Extended Mission (continued)			
S16	2006	MARCH	The MOC ground track position improved during February and, thus, the constant roll effort was ended on 2 March. MOC reboots occurred on 8 and 22 March. On 9 March, the MGS operations team implemented a new data playback scheme so that MOC daily global image swaths could be returned to Earth earlier than usual, so as to be used to advise the MRO aerobraking effort of Martian weather conditions. MRO went into orbit on 10 March. The MGS data rate was reduced from high to medium on 16 March. On 24 March, MOC took wide-angle images coordinated with MRO Context Camera (CTX) and Mars Color Imager (MARCI) instrument check-out imaging obtained the same day. Deep Space Network coverage of the launch of NASA's Space Technology (ST-5) microsatellite mission resulted in loss of 22 MOC images and decisions not to command other targeted data during the month. As northern spring progressed on Mars, the science team began an effort to document layer unconformities in the north polar region. Phoenix landing site candidate imaging continued.
S17	2006	APRIL	Daily weather reporting in support of MRO aerobraking efforts continued, as did imaging of candidate Phoenix landing sites. Five star focus calibration images of stars in M45 (Pleiades) were obtained starting on 20 April. MOC spontaneous reboots occurred on 2 and 26 April.
S18	2006	MAY	A final star focus calibration image was obtained on 3 May. MOC support for Phoenix landing sites and MRO aerobraking continued. The Hellas Planitia L_s 55°–85° clear atmosphere period began and Hellas was a major focus of narrow angle camera targeting efforts. On 30 May, a month-long moratorium on cPROTO imaging began because of lowered availability of solar power as Mars approached aphelion (cPROTO maneuvers would otherwise interrupt opportunities to collect solar power; aphelion would occur 26 June).
S19	2006	JUNE	MOC support for Phoenix landing site imaging and MRO aerobraking continued, as did the Hellas narrow angle campaign. An attempt was made on 12 June to image Deimos but the target was missed. The moratorium on cPROTOs continued through the month.
S20	2006	JULY	Imaging of candidate Mars Science Laboratory (MSL) landing sites began as efforts to support the Phoenix landing sites, MRO aerobraking, and Hellas campaigns continued. A narrow angle image of Deimos was acquired on 10 July. On 12 July, the MOC operations team detected error messages in the MOC daily health report telemetry that indicated a sensor that measures focal plane assembly temperatures was stuck. The team commanded a reset for the sensor and it was only stuck for portions of 11 and 12 July; there was no loss of data but some MOC image headers contained incorrect information that was replaced with a modeled value in the archived data products. A gradual degradation in red wide angle camera sensitivity began this month near L_s 83°; this was not fully recognized until data analysis efforts were conducted in April 2007. This degradation continued for the remainder of the MGS mission.
S21	2006	AUGUST	Imaging and support for MRO aerobraking and the MSL and Phoenix landing site candidates continued through the month. Successful tests were conducted on 6 and 18 August for new approaches to spacecraft maneuvers to acquire ROTO images; these resulted in fewer spacecraft commands to specify the maneuvers (meaning that more ROTO and cPROTO images could be taken once the approach was to be fully implemented in November 2006) and allowed the spacecraft to maintain communications lock with Earth during off-nadir slews on communication orbits. MRO aerobraking ended on 30 August and MOC daily meteorological support for MRO ended on 31 August.
S22	2006	SEPTEMBER	On 7 and 9 September, MGS tested two approaches that made it possible to do 2 ROTO slews on a single orbit. These tests were successful, and were expected to lead to fully implemented capabilities in November 2006. Attempts were made (on short notice) to image the MRO spacecraft on 7 and 14 September, but these missed their targets. The second attempt included an accidental command to freeze HGA motion (freezing solar panel motion had been the intent); this resulted in loss of part of the MOC image in which MRO might have appeared. North high latitude narrow angle imaging was a major focus during the month, as were candidate Phoenix and MSL landing sites. MRO MARCI and MGS MOC both acquired daily global image swaths, about 1 hour apart, starting on 27 September. A 58th (and final) MOC spontaneous reboot occurred on 14 September.

Table 7. (conclusion)

Third Extended Mission (continued)			
S23	2006	OCTOBER	MRO MARCI and MGS MOC continued simultaneous daily global imaging until 5 October. On 1 October, MOC acquired images of Amazonis dust devils coordinated with 1 hour later observations by MARCI and CTX. On 3 October, MOC obtained a cPROTO image of the MER-B site, the same day that MRO HiRISE imaged the rover. Phoenix and MSL candidate landing sites were also imaged. Narrow angle imaging continued to 14 October and daily global imaging to 17 October, then the camera was powered off for solar conjunction.
Solar Conjunction	2006	17 OCT – 2 NOV	MOC was not operated.
Fourth Extended Mission (X*xx* for "eXtended" and "10 years" in Roman numerals)			
X01	2006	NOVEMBER	MOC was powered up and image commands were uploaded on MGS orbit 34201 on 2 November. No image data were returned to Earth before contact with MGS was lost on orbit 34203 a little more than 4 hours later. There was no subsequent contact with MGS thereafter.

Table 8. MOC mission support activities.

Mission	MOC Support Activities
Mars Pathfinder (MPF)	• 1997: Narrow angle image < 2 days before landing to document weather at landing site. • 1998 – 2003: Targeted narrow angle images of landing site, including May 2003 cPROTO view and attempted identification of MPF hardware (Malin 2005).
Mars Global Surveyor (MGS)	• 1997 – 1998: Aerobraking support during Aerobraking 1 mission subphase via acquisition of summed red and blue wide angle images covering much of the day side of the planet following each periapsis pass.
Mars Climate Orbiter (MCO)	• 1999: Plans were in place to use MOC daily global images to advise the MCO aerobraking effort on Martian weather conditions during that time. However, the spacecraft was lost upon the orbit insertion attempt on 23 September 1999.
Mars Polar Lander (MPL)	• 1997 – 1998: Initial candidate landing site imaging, with sites covered by seasonal frost, during Aerobraking 1 mission subphase. • 1999: Imaging of landing site candidates which led to MPL science team selection of the final and backup landing ellipses; further imaging of these ellipses using narrow angle camera to document the sites' geomorphology. • 1999 – 2000: After Mars Climate Orbiter (MCO) loss, efforts were made in November 1999 to use MGS Mars Relay (MR) as a backup to the MPL direct-to-Earth capability; this system was then used to search for the missing MPL in December 1999 – March 2000. • 1999 – 2000: After MPL loss, MGS Project authorized targeted roll imaging using MOC narrow angle camera to search the MPL landing ellipse for the missing hardware. • 2005: After seeing landed hardware in MOC cPROTO images of the MER landing sites, a candidate location for MPL was identified by Malin (2005) and, after 6 attempts, the site was imaged with the cPROTO technique and found not to be the lander hardware. MOC did not find MPL.
Deep Space 2 (DS2)	• 1999: By design, the primary and only pathway to transmit data from the DS2 microprobes, which reached Mars the same day (3 December 1999) as MPL, was through the MGS MR system, which utilized the MOC buffer to relay the data. The DS2 probes were to operate for only 1 day. No signals were received through the MGS MR/MOC system and attempts were abandoned on 8 December, the day that the DS2 batteries were assumed to have failed.
Mars Surveyor 2001 lander	• 1999 – 2000: Before the mission was cancelled after the loss of MPL, MOC was used to acquire narrow angle images of ~60 candidate landing sites proposed at a June 1999 workshop; further imaging of the top 5 and then the top 2 sites followed a workshop in October 1999. Imaging of the top 2 sites, Libya Montes and Meridiani Planum, continued until the mission was cancelled in the first half of 2000.
Mars Odyssey (ODY)	• 2001 – 2002: MOC daily global images and the observation of the repeatability of Martian weather events from the first to second Mars year of MGS operations were used to both predict and report weather conditions to the atmospheric science group that advised the ODY aerobraking effort between late October 2001 and mid-February 2002. • 2005: On 21 April, the MOC narrow angle camera imaged ODY twice during the same orbit.
Beagle 2	• 2001 – 2003: While no formal agreement to image the Beagle 2 landing site existed between NASA and the European Space Agency (ESA), the MOC team imaged portions of the Isidis Planitia landing ellipse as buffer space and downlink capabilities allowed. • 2002 – 2004: The MOC team predicted in 2002 the weather conditions expected in Isidis Planitia at the time of landing—a dust storm was predicted to occur within 2 weeks of landing, and, indeed, a dust storm occurred 13 days before the event. Weather reporting for the Beagle 2 site using daily global images and specially-targeted wide angle images was conducted from late November 2003 through January 2004. • 2004 – 2006: No formal agreement between NASA and ESA existed to search for the missing landed hardware, but narrow angle images were acquired over much of the final landing ellipse. One candidate site was identified and imaged using the cPROTO technique in April 2004 but this turned out to be a patch of dark, windblown sand in a small impact crater.
Mars Express (MEX)	• 2005: On 21 April, MOC imaged the MEX spacecraft twice on one orbit. However, the spacecraft was too far away for details to be seen. • 2006: MEX was imaged again by MOC on 10 February 2006.

Table 8. (continued)

Mission	MOC Support Activities
Mars Exploration Rovers (MER)	• 2001 – 2003: The narrow angle camera and ROTO technique were used to acquire images of ~30 candidate landing sites proposed at a January 2001 workshop. Six top choices emerged from a workshop in October 2001, and these were further imaged by MOC. A third workshop in March 2002 narrowed the list to 3 sites plus 2 "low wind" sites which were then imaged by the narrow angle camera. The final 2 landing sites, at Gusev Crater and Meridiani Planum, were ultimately covered by 93 and 67 narrow angle images, respectively, prior to the January 2004 landings. • 2002: Wide angle daily global images and experience from the previous Mars year of MOC daily global imaging were used in March 2002 to predict weather conditions at the top four landing site candidates; the prediction found dusty and unsettled conditions at the time of the MER-A landing for all sites but Gusev Crater. • 2003 – 2006: Daily global images, targeted wide angle views of the Meridiani and Gusev landing sites, and limb observations were used to report and predict weather conditions at the landing sites to first inform the landing day events and second to inform solar power conditions. Reports were made available to the public until July 2004, then reports were sent directly to the MER team thereafter. • 2004, 2006: The MGS MR and MOC buffer were used as the primary and only pathway through which telemetry transmitted by each MER during its entry, descent, and landing activity was relayed to Earth. For each landing, this relay occurred in real time. While ODY provided the primary science data relay capability for MER, the MR system was then used to relay science data from MER-A until 28 May 2004 and MER-B until 19 July 2004. Additional MER-B data were relayed on one occasion in February 2006 to demonstrate readiness to assist in the event of an ODY upset or failure. • 2004 – 2006: Narrow angle images, including cPROTO images, were acquired which showed the landed hardware and rover tracks on the Martian surface. These sites were imaged from time to time throughout the rest of the MGS mission to also document changes caused by eolian processes.
Mars Reconnaissance Orbiter (MRO)	• 2006: As with ODY, the MOC team used daily global images and multiple Mars years of experience with Martian meteorology to report and predict weather conditions that might impact the MRO aerobraking effort which occurred April – August 2006. • 2006: Attempts were made on 7 and 14 September to image the MRO spacecraft, but the target was not in the images received. • 2006 – 2007: MOC image targets that were not obtained because of the loss of MGS were passed along to the MRO CTX and HiRISE investigations to acquire, and sites that were monitored for changes (wind streaks, slope streaks, dunes, ripples, seasonal frost, dust devils, etc.) using the MOC narrow angle and wide angle cameras became CTX monitoring sites.
Phoenix Mars Scout (PHX)	• 2004 – 2006: Narrow angle imaging of candidate landing sites selected by the PHX science team began in August 2004. Imaging was suspended at the end of January 2005 because of increasing storm activity and cloud cover. Imaging resumed near the end of December 2005 as the candidate sites emerged from winter darkness and from beneath the polar hood. Imaging continued into October 2006 when the last MOC data were acquired. • 2004 – 2007: MOC daily global images and several Mars years of experience with the repeatability of weather events were used by the MOC team to make predictions for the PHX team regarding conditions expected at the landing site during the mission.
Mars Science Laboratory (MSL)	• 2006: Following the first MSL landing site workshop in May–June 2006, more than 80 narrow angle images (plus context frames) were acquired for ~25 candidate landing sites. This activity continued into October 2006, when the last MOC data were obtained.

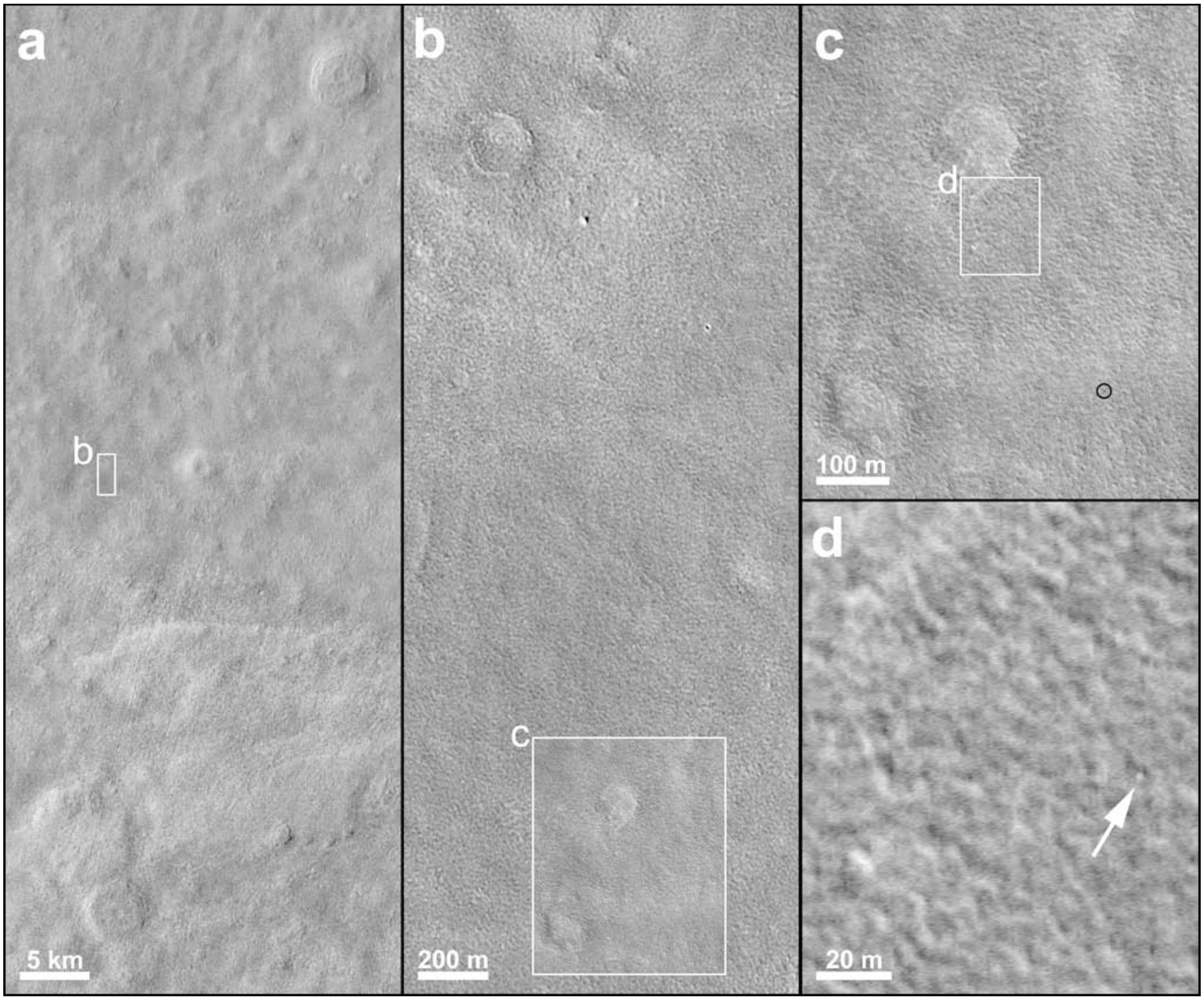

Figure 10. Best determination, using the MOC narrow angle camera, of the Viking Lander 2 location near 48.0°N, 225.8°W, as described by Malin (2005). North is up. **(a)** Mosaic of sub-frames of Viking 2 orbiter images 009B14, 009B15 and 009B16. **(b)** Sub-frame of MOC image E02-02726, showing area near the landing site. **(c)** Sub-frame of MOC cPROTO image R18-01139. The area inside the white box includes the feature identified by Malin (2005) as the Viking 2 lander. The black circle indicates the actual location of the lander as determined in November 2006 from MRO HiRISE image PSP_001501_2280. **(d)** Expanded view of a portion of MOC image R18-01139; the white arrow indicates the feature believed (until the HiRISE image was acquired) to be the lander. The HiRISE image showed that this feature is the lander's backshell (Parker et al. 2007) (figure10.png).

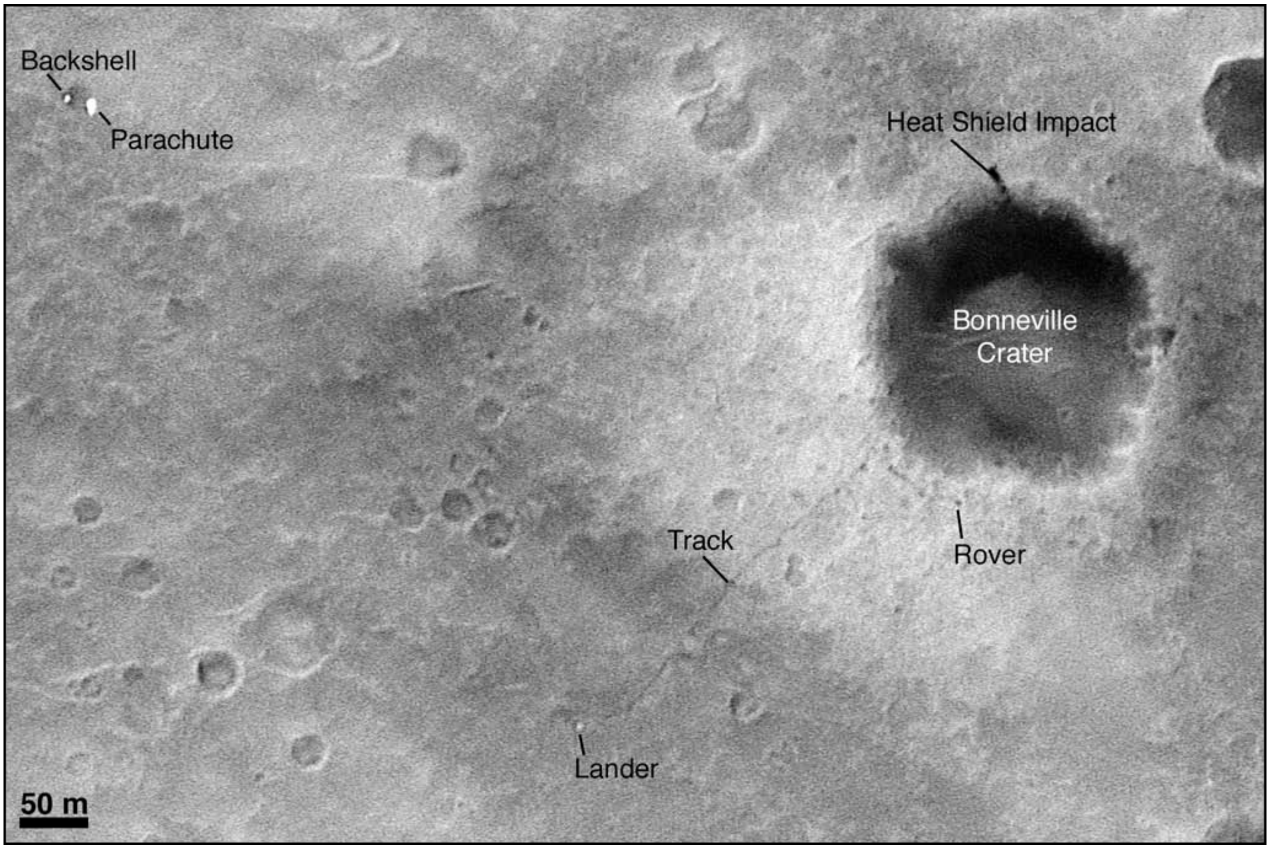

Figure 11. Sub-frame of MOC cPROTO image R15-02643, showing the track made by the Spirit (MER-A) rover during its first 85 sols on Mars. The image was acquired on 30 March 2004 (figure11.png).

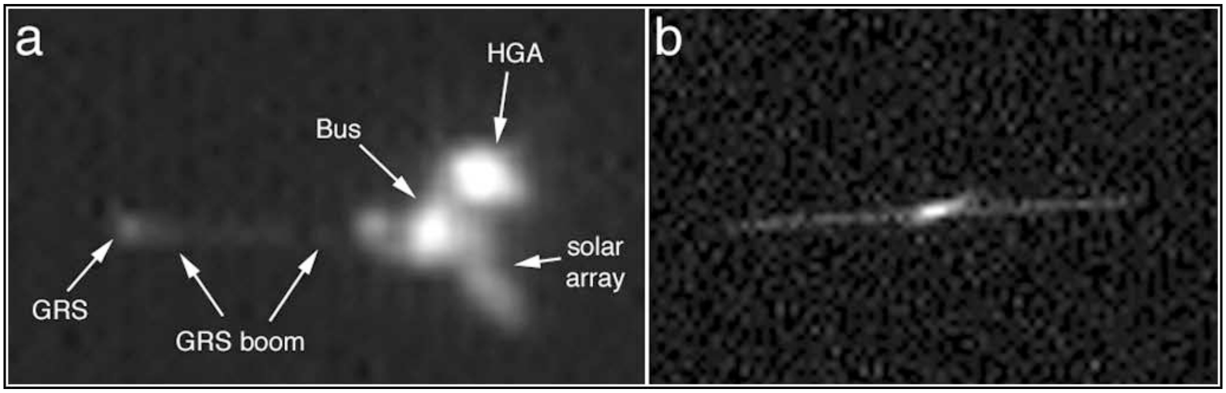

Figure 12. (a) MOC view of Mars Odyssey on 22 April 2005 in a sub-frame of image S05-01239 from a distance of about 80 km. Major features, including the Gamma Ray Spectrometer (GRS) and High Gain Antenna (HGA) are labeled. **(b)** Mars Express spacecraft bus and solar arrays as seen by MOC on 10 February 2006 in MOC image S15-00998 from a distance of about 122 km (figure12.png).

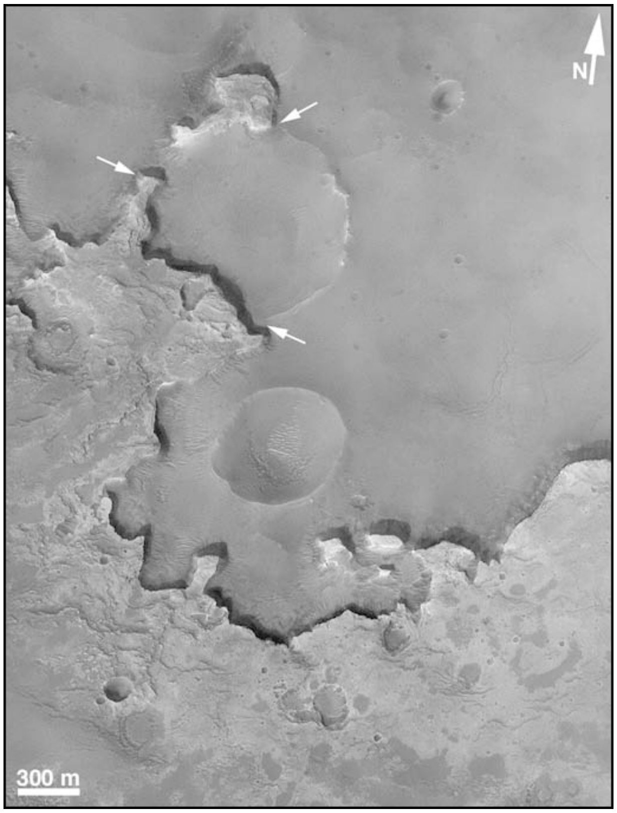

Figure 13. Example of partial exhumation of buried crater (arrows) emergent from beneath a cratered, light-toned rock unit in a larger crater in western Arabia Terra near 36.6°N, 1.4°W. This is a sub-frame of MOC image R10-03225 (figure13.png).

which the sediment was composed of the same material and was deposited in each episode in the same amount, perhaps in a subaqueous setting.

Evidence for persistent fluvial flow and aqueous clastic sedimentation

The best evidence from MOC concerning the depositional setting of an occurrence of sedimentary rock was found in Eberswalde Crater (Figure 17). In this case, the images show the lithified remains of a fluvial delta (Malin and Edgett 2003, Wood 2006). Former channels were inverted as the interchannel rock was less resistant to erosion than the material that filled the channels or comprised their floors. Inverted channels occur at different stratigraphic levels, and at least one exhibits a cut-off meander (Figure 18). These features indicate clastic sedimentation occurred in a setting where a liquid was both the agent of clast transport and the environment of deposition. Building of the delta and the cut-off meander required persistent fluvial flow into Eberswalde Crater for some period of time; published speculations range from decades to millions of years (Moore et al. 2003, Jerolmack et al. 2004, Bhattacharya et al. 2005). The deltaic form and other features suggest that the crater was once the site of a lake. Inverted channel segments elsewhere (not related to the deltaic feature) on the Eberswalde floor suggest that there might have been periods of subaerial exposure and channel formation at times when no lake was present.

Bedforms preserved in sedimentary rock

Examples of sedimentary rock outcrops exhibiting bedforms preserved in the rock that are of a scale sufficiently large to be observable from orbit in MOC narrow angle camera images are rare. But they do occur. No examples of eolian crossbeds were unambiguously identified in MOC images, but at least one example of a lithified eolian dune field was found (Edgett and Malin 2000, Malin and Edgett 2001), a second site in Melas Chasma near 11.2°S, 75.2°W, might also consist of lithified dunes, and a very large (relative to terrestrial counterparts) exposure of crossed beds occurs in southern Galle Crater (Figure 19). In addition to these, layered rock outcrops in the craters Gale and Terby exhibit lithified bedforms with wavelengths in excess of several meters that are preserved in distinct layers (Figure 20). Whether the bedforms in Terby and Gale were created in subaqueous or subaerial settings is not known but if they formed in water, then they would provide an intriguing hint that Gale might, at the time, have hosted a lake, and Terby might have been a bay, or completely submerged, in a Hellas-filling sea. These results were previously noted in a conference abstract by Edgett and Malin (2005).

Ancient streams and evidence for rainfall

Since their initial discovery in Mariner 9 images, many investigators have discussed and debated whether some of the fluvial valleys and their channels on Mars might have formed from precipitation-fed runoff (rainfall or snowmelt). To have "smoking gun" evidence that it once rained on Mars, one would need to find a mudstone or siltstone (or, more rarely, a sandstone) in which the crater-like impressions of raindrops have been preserved (Twenhofel 1926). From orbit, the best that can be hoped for—*i.e.*, a "gun," although not a "smoking gun"—is to locate high spatial density hillslope rills that merged to form larger streams, which in turn were tributaries to still larger streams, and so forth. This was a major objective of the MOC investigation when it was proposed in 1985, but initial results suggested that no such rills and low-order streams had been preserved at the planet's surface (Malin and Carr 1999, Carr and Malin 2000).

Owing to the multiple extensions of the MGS mission, however, in 2003 we found and made a narrow angle image mosaic of an unambiguous example on the plains immediately west of Juventae Chasma. The existence of these landforms was first mentioned in note #13 of Malin and Edgett (2003) and further discussed by Williams et al. (2005). The hillslope rills and low-order streams near Juventae Chasma have, like the channels of the Eberswalde delta, been inverted by erosion. Figure 21 shows the networks formed by these ridges, and Figure 22 shows examples of some of the hillslope rills that fed these streams. Analysis and comparison to terrestrial streams of the same scale indicate that the volumes of liquid needed to form and maintain runoff streams on these hillslopes would have been too great for them to have formed by the slow trickle of melting snow (Williams et al. 2005). Rainfall or springs (which require precipitation for recharge) are more likely.

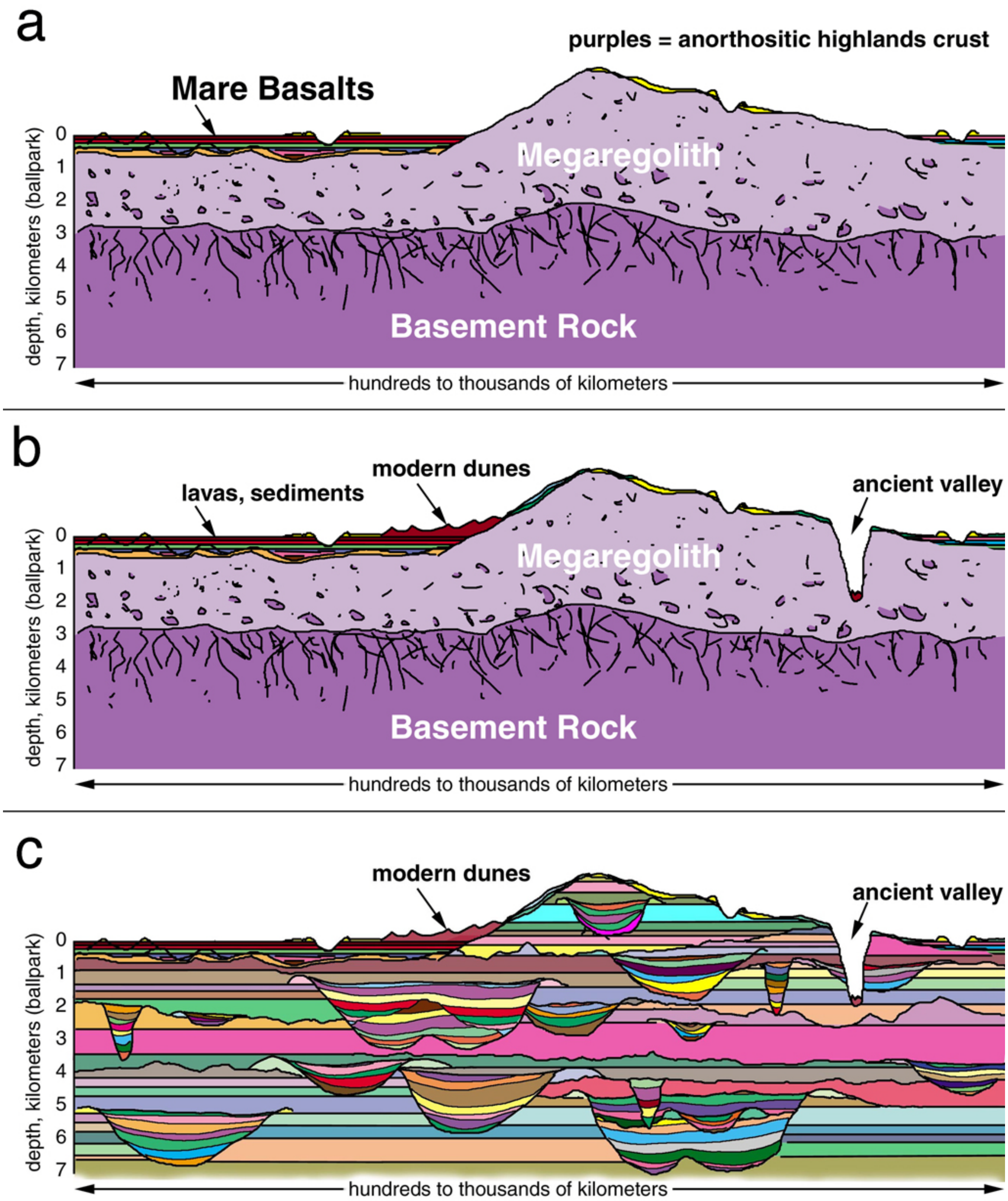

Figure 14. Extremely hyper-simplified cartoons depicting nature of the upper Martian crust. **(a)** Lunar example. **(b)** Pre-MGS view of Mars as being similar to the Moon with an atmosphere on which agents of geologic and geomorphic change acted upon a previously heavily-cratered surface. Examples of this prevalent view come from the scientific literature, for example see Figure 1 of Clifford (1993), Figure 1 of MacKinnon and Tanaka (1989), and, particularly, Figure 10 of Davis and Golombek (1990). **(c)** The authors' MGS MOC view of abundant subsurface layering with filled, buried, and interbedded impact craters and valleys. Wavy jagged lines represent erosional unconformities (figure14.jpg).

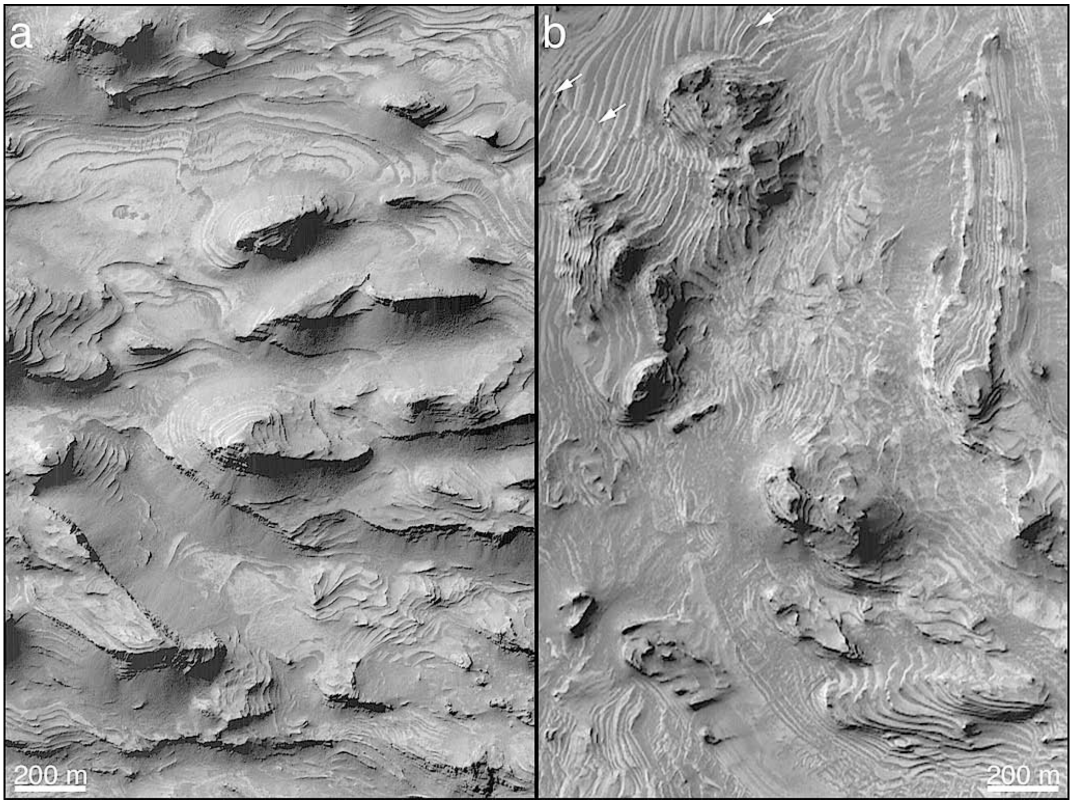

Figure 15. March 1999—early views of layered sedimentary rocks exposed in western Candor Chasma. These are sub-frames of two narrow angle camera images acquired on the same orbit. **(a)** Sub-frame of image FHA-01278. The rocks exposed here consist of hundreds of layers of repeated thickness, physical properties and erosional expression. This image is located near 6.5°S, 77.3°W. **(b)** Sub-frame of FHA-01279, showing similar layered rocks exhibiting a dip toward the east (right). The arrows indicate two of several faults that cut through the rocks. This image is located near 5.3°S, 72.4°W (figure15.png).

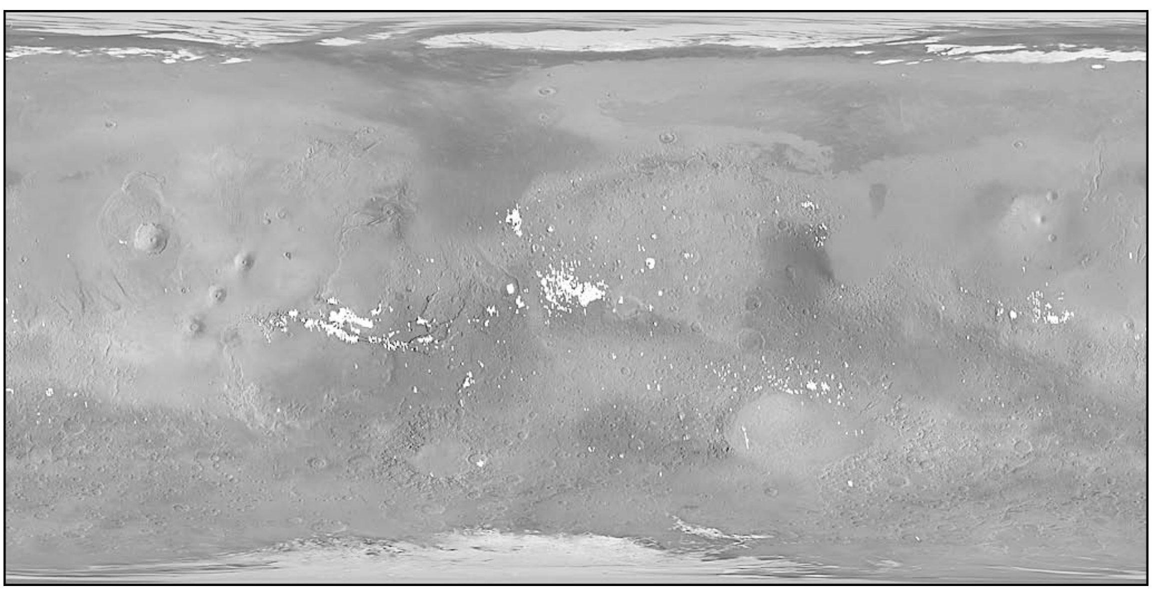

Figure 16. Global map of Mars showing (in white) the locations of all MOC narrow angle camera images in which layered rock outcrops of possible or likely sedimentary origin were identified. This simple cylindrical map is centered on the equator and prime meridian and is derived from MOC red wide angle Geodesy Campaign data and topography (depicted as shaded relief) derived from MGS MOLA data (figure16.png) (figure16.txt).

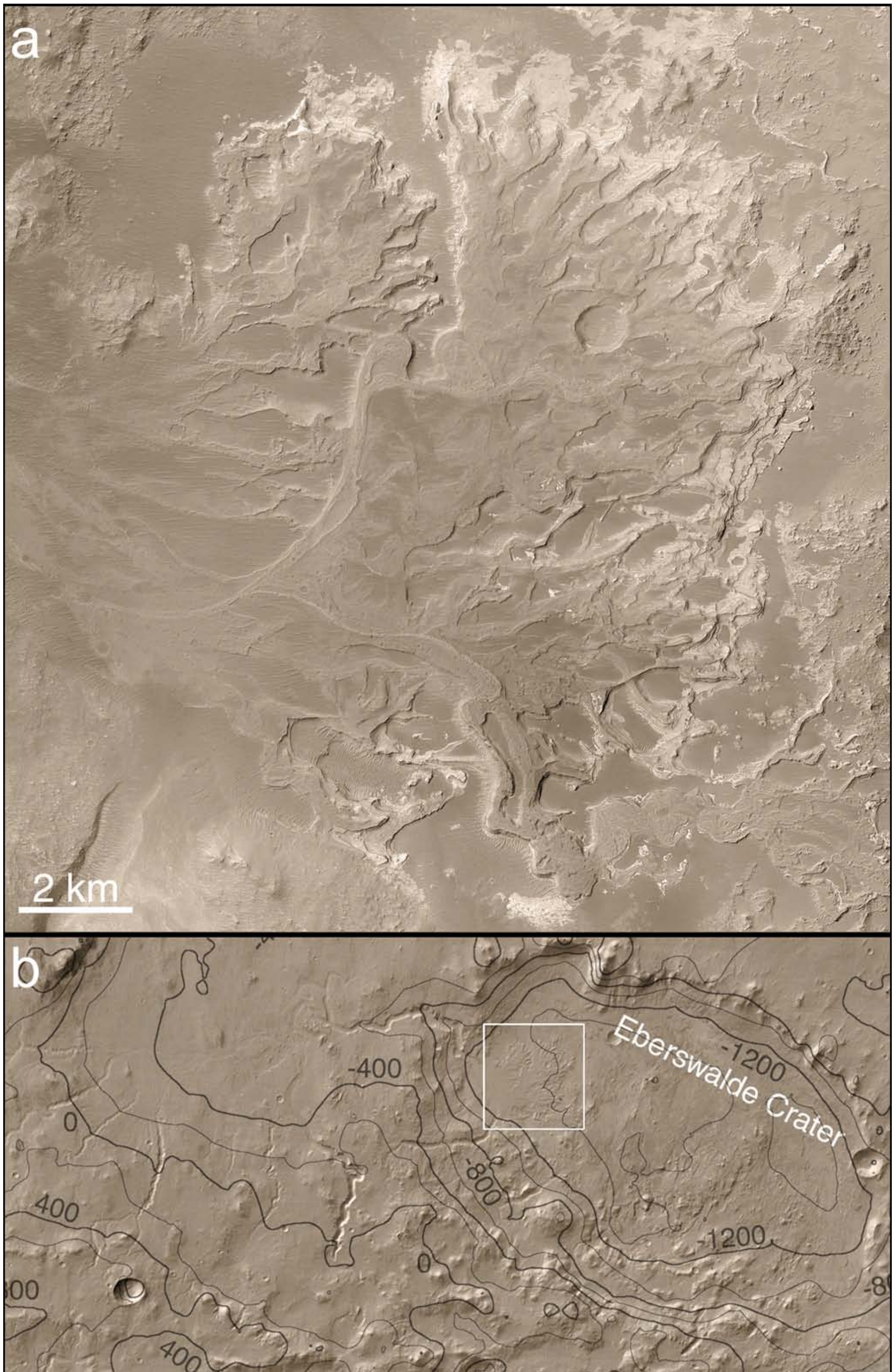

Figure 17. (a) Lithified, exhumed delta in Eberswalde Crater. This is a mosaic of MOC images M18-00020, E14-01039, E17-01341, E18-00401, E21-01153, E21-00454, E22-01159, E23-00003, R06-00726, R08-01104, and R09-01067. **(b)** Context. The delta is located within the area outlined by the white box in this mosaic of Mars Odyssey THEMIS thermal infrared images. Contours indicate topography, in meters, relative to the Martian datum, as measured by the MGS MOLA instrument. The color in both figures was derived from the color information in THEMIS Visible Imaging Subsystem data. North is up in these simple cylindrical projection maps (figure17.png).

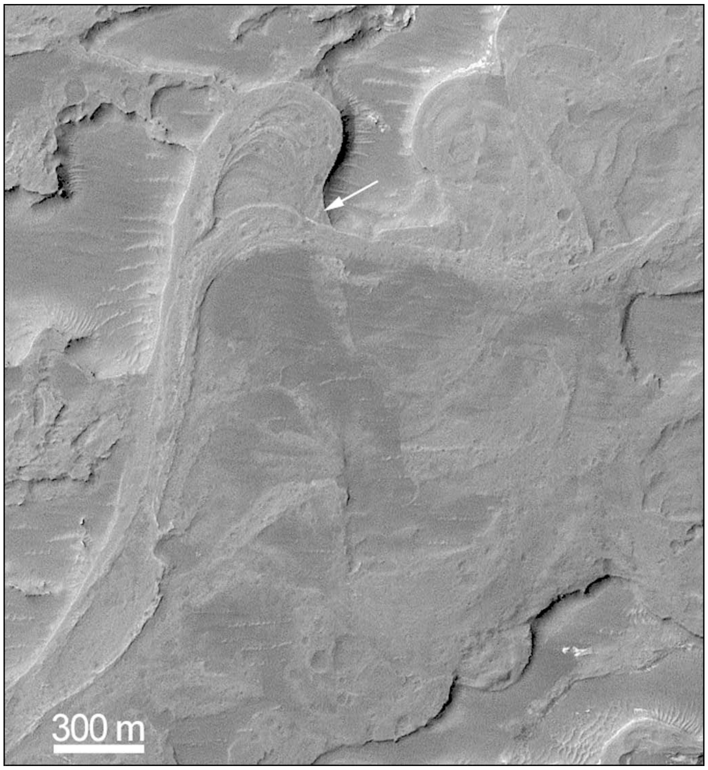

Figure 18. Inverted form of a cut-off meander (arrow) in the lithified Eberswalde delta. This is a sub-frame of MOC image E18-00401; north is up (figure18.png).

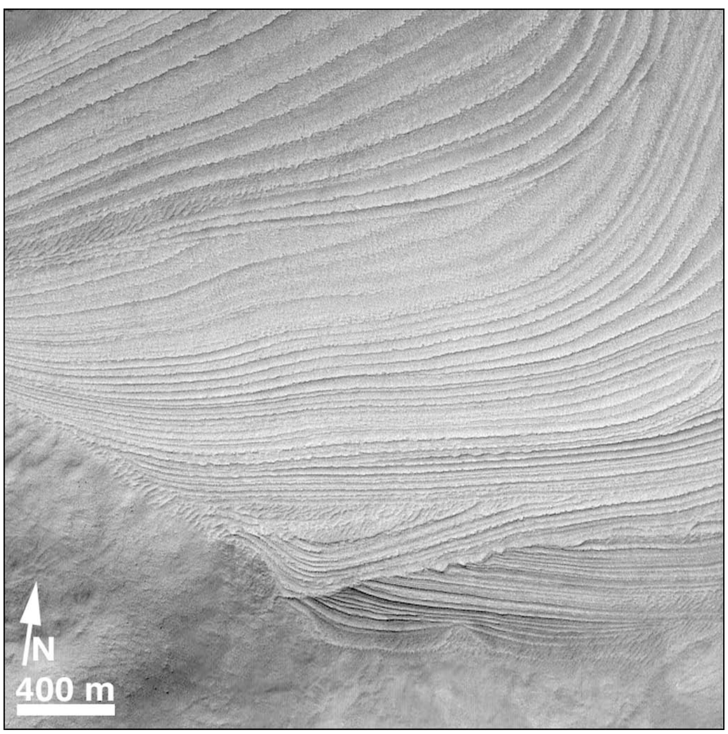

Figure 19. Multiple unconformities or cross-bedded sedimentary rock in an exposure seen in planform (from above) in southern Galle Crater near 52.3°S, 30.0°W. This is a sub-frame of MOC image M14-02055 (figure19.png).

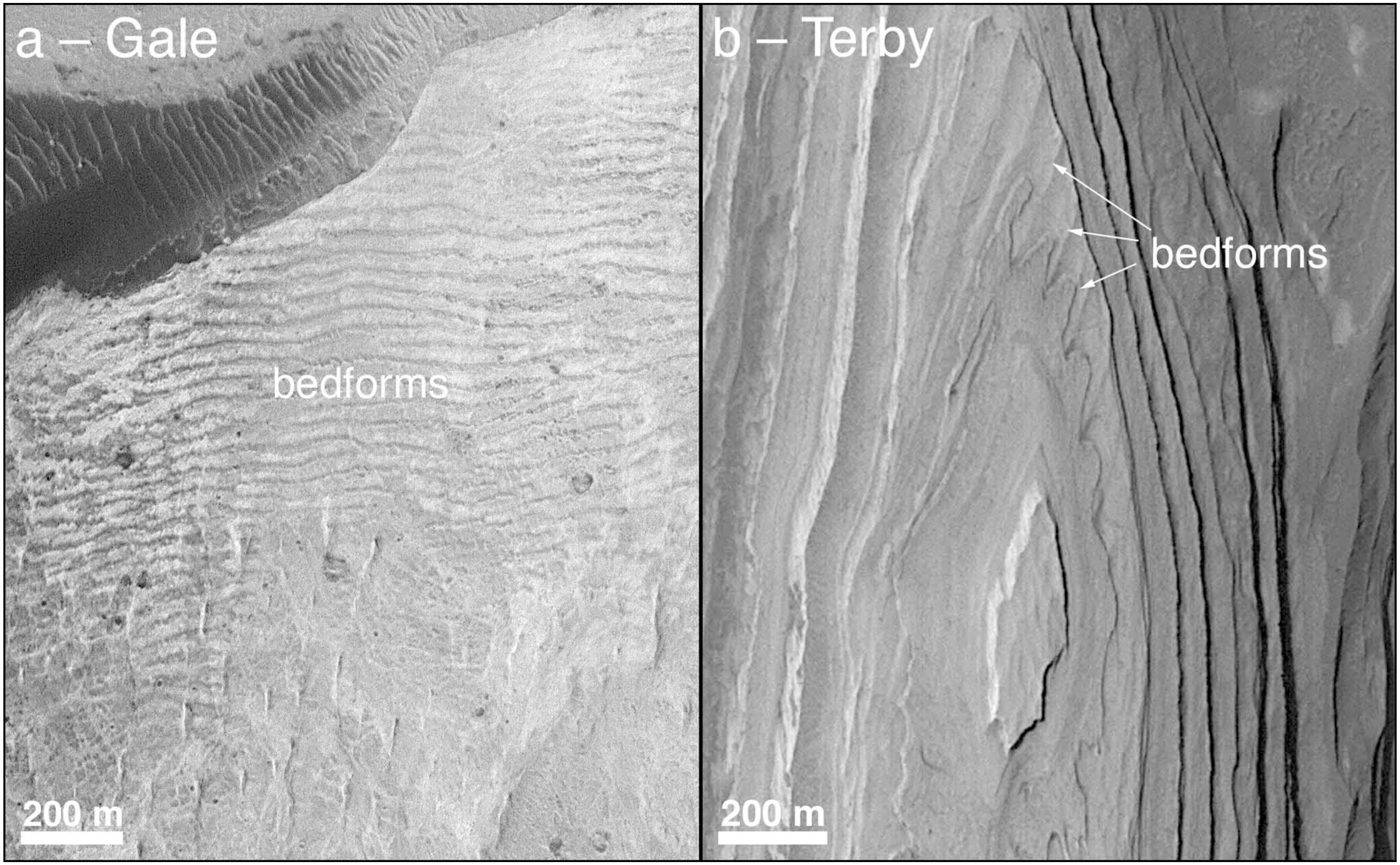

Figure 20. Large, lithified sediment bedforms preserved in light-toned layered rocks in **(a)** Gale Crater and **(b)** Terby Crater. The Gale picture is from MOC image R12-00762, near 5.2°S, 2222.7°W; the Terby image is from MOC image R06-00372, located near 27.6°S, 285.8°W (figure20.png).

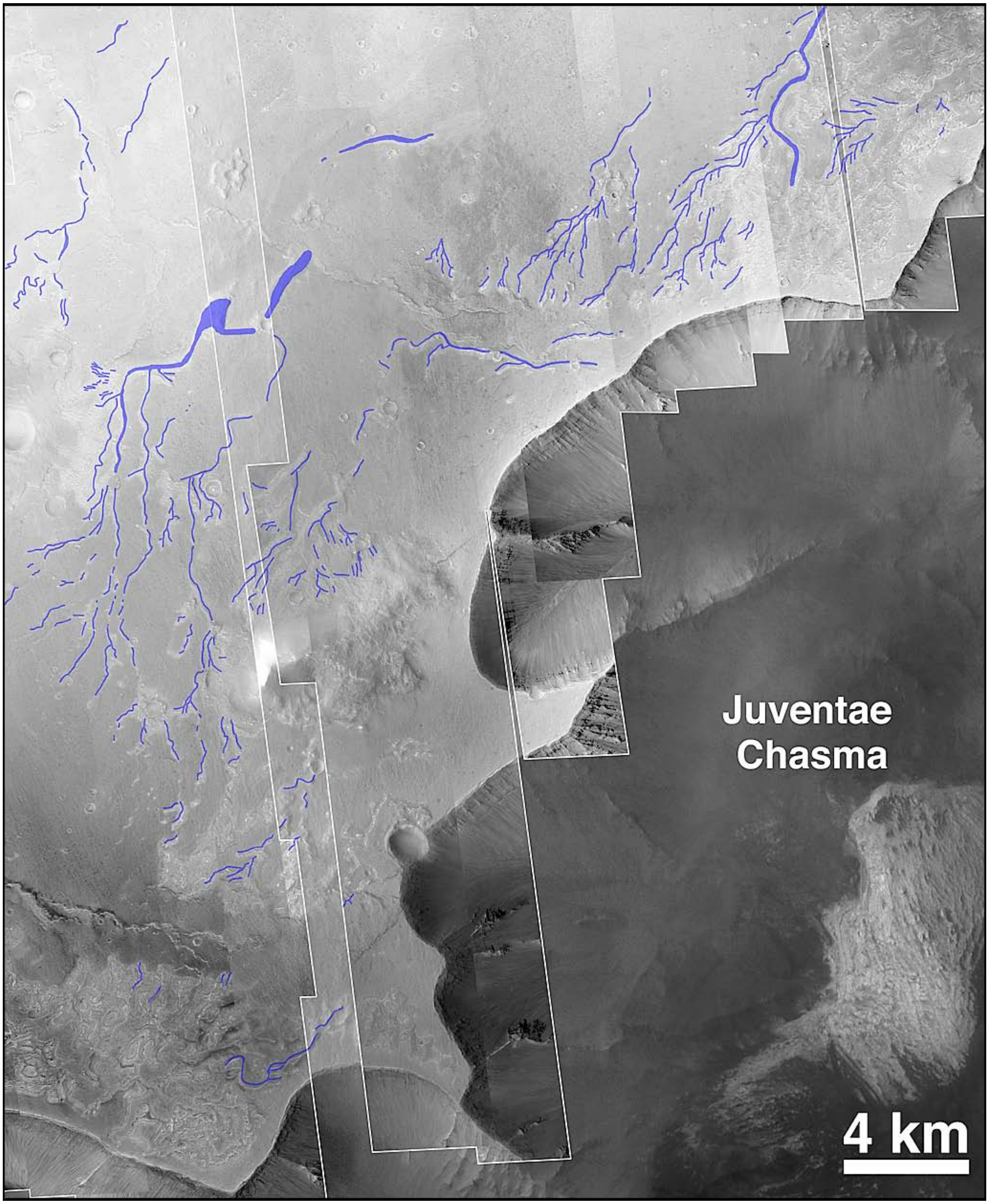

Figure 21. Mosaic of MOC images (outlined in white) overlain on mosaic of THEMIS VIS images covering a portion of the region near the southwest rim of Juventae Chasma that exhibits many segments of inverted streams and rills (blue). North is up. When the streams were active, they generally flowed toward the north-northeast. Note that one stream north of the center of the image was diverted eastward by the presence of a mare-type ridge (sometimes known as a "wrinkle ridge"). These landforms constitute the best evidence yet found on Mars to indicate that rainfall and surface runoff occurred. The map is centered near 4.4°S, 63.4°W (figure21.png) (figure21noannotation.png) (figure21.txt).

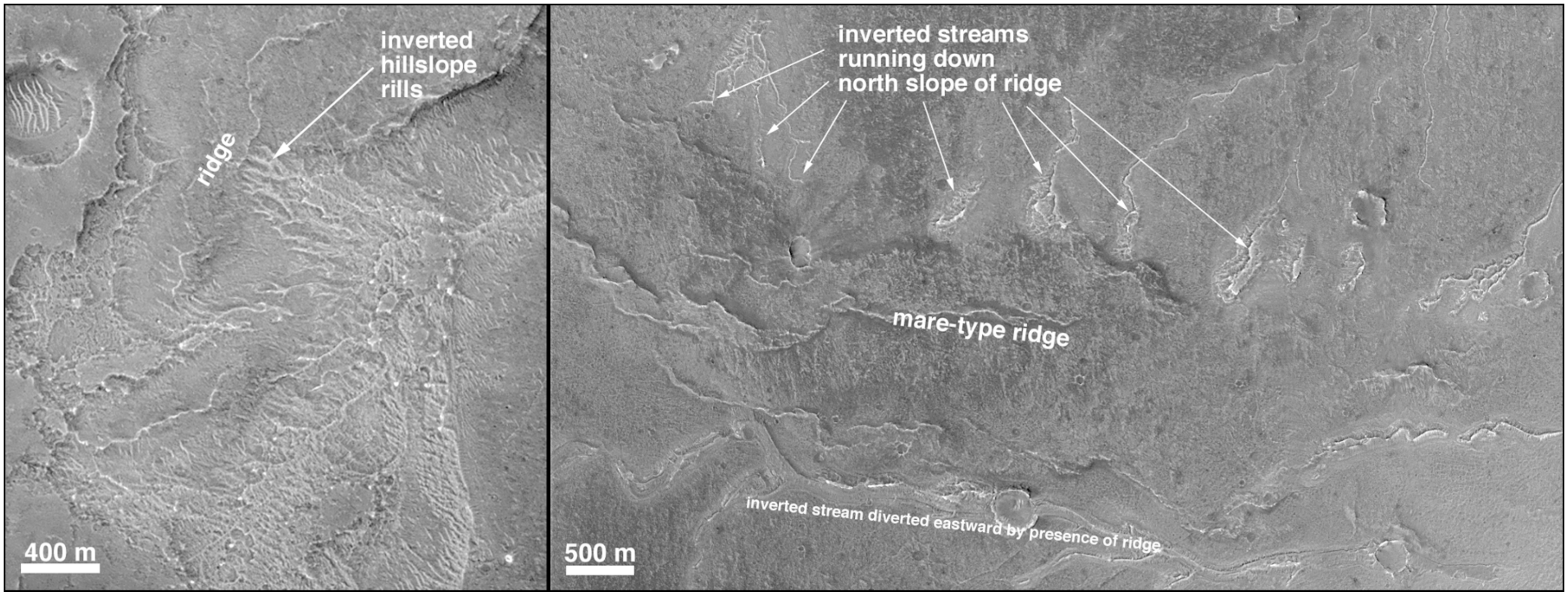

Figure 22. Inverted hillslope rills and low-order streams near Juventae Chasma. North is up in both figures. **(a)** Cluster of inverted rills on east side of ridge in MOC image R12-00450, located near 4.4°S, 63.6°W. **(b)** Inverted runoff streams on north slope of mare-type ridge near 4.3°S, 63.4°W. This is a mosaic of sub-frames of MOC images R09-02851, R10-01114, R12-00618, and S08-03068 (figure22.png).

Gullies and present-day liquid water

MOC narrow angle images of some slopes at middle and high latitudes revealed geologically youthful gullies. As first reported by Malin and Edgett (2000), the hallmark of these landforms is a channel through which debris was transported (Figure 23). The debris forms a fan or apron at the downslope break in slope (*e.g.*, crater wall/floor interface). Some of the channels are banked and some are sinuous. Aprons commonly exhibit multiple lobate flows (Figure 24). Figure 25 shows the locations at which gullies were observed in MOC images. The majority occur poleward of 30° latitude in each hemisphere. They do not all occur on pole-facing slopes. Alcoves found above many of the gully channels appear to have formed by undermining, collapse, and mass-movement of debris. Malin and Edgett (2000) proposed that the most likely source for the fluids that cut the gully channels and formed the lobate flows that comprise the aprons was groundwater that percolated through porous fractured and layered rock at depths of less than 1 km below the Martian surface. This hypothesis is supported by observation of channels originating beneath overhanging rock layers and channels associated with faults (Figure 26).

When first reported in 2000, the gullies appeared to be so young that it was possible that water might flow through some of them today. To test this hypothesis, gullies were frequently re-imaged throughout the MGS Extended Mission. Malin et al. (2006) reported that two gully sites, one in Penticton Crater (38.7°S, 263.3°W), the other in Naruko Crater (36.6°S, 161.8°W), did indeed exhibit changes over the course of the MGS mission. An example of one of these is shown in Figure 27. In both cases, a light-toned flow feature appeared, indicating the combined products of fine-scale erosion and deposition along the course (and further downslope of) a gully channel. Malin et al. (2006) proposed that these deposits are not likely to be the product of dry mass movement, but are instead indicators that liquid water—which came from beneath the ground—ran out onto the surface of Mars during the MGS mission, because:

1) of their association (morphology and setting) with gully channels,
2) the gullies occur outside of regions where dry dust avalanches were observed by MOC to create new slope streaks, and
3) no similar flows—either formed new during the MGS mission or older ones—were observed on non-gullied slopes elsewhere at the latitudes at which gullies occur.

South polar CO_2 and climate change

A critical observation that resulted from the first MGS Extended Mission came from repeating narrow angle coverage of the south polar residual cap. MOC images of the south polar cap in 1999 showed that it is composed of light-toned, layered material that has eroded to form mesas, circular pits, arcuate scarps, and troughs arranged in fingerprint-like patterns (Thomas et al. 2000). We repeated the imaging of the landforms in 2001 and discovered that they changed considerably during the previous southern summer (Malin et al. 2001). In general, the polar cap scarps retreated about 3 m during the previous Martian year, particularly in the summer season (Figure 28). This scarp retreat rate continued and was documented during the subsequent MGS mission extensions through 2006 (Thomas et al. 2005, Thomas and James 2006).

The rate of retreat requires the bulk of the layered material to be frozen carbon dioxide (Malin et al. 2001). Because the CO_2 ice was eroding or subliming during southern summer, and none was apparently re-deposited on the residual cap, it seems likely that the present climate is warmer than it was when the layered carbon dioxide was deposited. Working backward from a ~3 m per year scarp retreat rate, the climate must have been cool enough to deposit the CO_2 a few centuries to millennia ago (Malin et al. 2001). Thomas et al. (2005) speculated, on the basis of comparison to Mariner 9 images of the residual cap, that there might actually have been a depositional event between the Mariner 9 and MGS missions. In any case, the deposits seen today will not last more than a hundred Mars years unless they are replenished.

Present-day impact rate

A serendipitous observation in January 2006 led Malin et al. (2006) to realize that the MOC cameras could be used to detect the sites of meteoritic impacts that had occurred during the course of the MGS mission. Full-resolution red wide angle camera images of dust-mantled terrain in Amazonis, Tharsis, and Arabia Terra acquired January–March 2006, when compared with similar data obtained during the Geodesy Campaign in May 1999 (Caplinger and Malin 2001), showed 19 new dark spots of about 1–4 km diameter that indicated the locations of fresh impact sites. The impacts all occurred during the MGS mission, between May 1999 and March 2006, and all within an area of about 21.5×10^6 km^2. The dark spots were "blast zones" where the impact event disrupted a mantle of dust; typically, the impact craters (some of which were clusters) were much smaller, of the order of two to a few tens of meters in diameter. Figures 29 and 30 show a couple of examples. From these observations, Malin et al. (2006) noted that the modeled cratering rate described by Hartmann (2005) compares favorably with the observed, present-day cratering rate. These results constituted the first time that the present-day cratering rate on any natural Solar System object had been estimated from actual observations of new impact craters.

Dust storms occur year-round

Images from all three MOC cameras demonstrated that, over a period spanning 4.8 Martian years (September 1997–October 2006), dust is raised by wind, somewhere on Mars, every day. Various forms and scales of dust-raising events are illustrated in Figure 31. MOC wide angle camera daily global images cover 4.04 Mars years between March 1999 and October 2006. These data show that dust storms occur year-round (Figure 32). Cantor (2007) noted that most storms were observed to develop in close proximity to the seasonal and residual polar cap margins (*e.g.*, Figure 33).

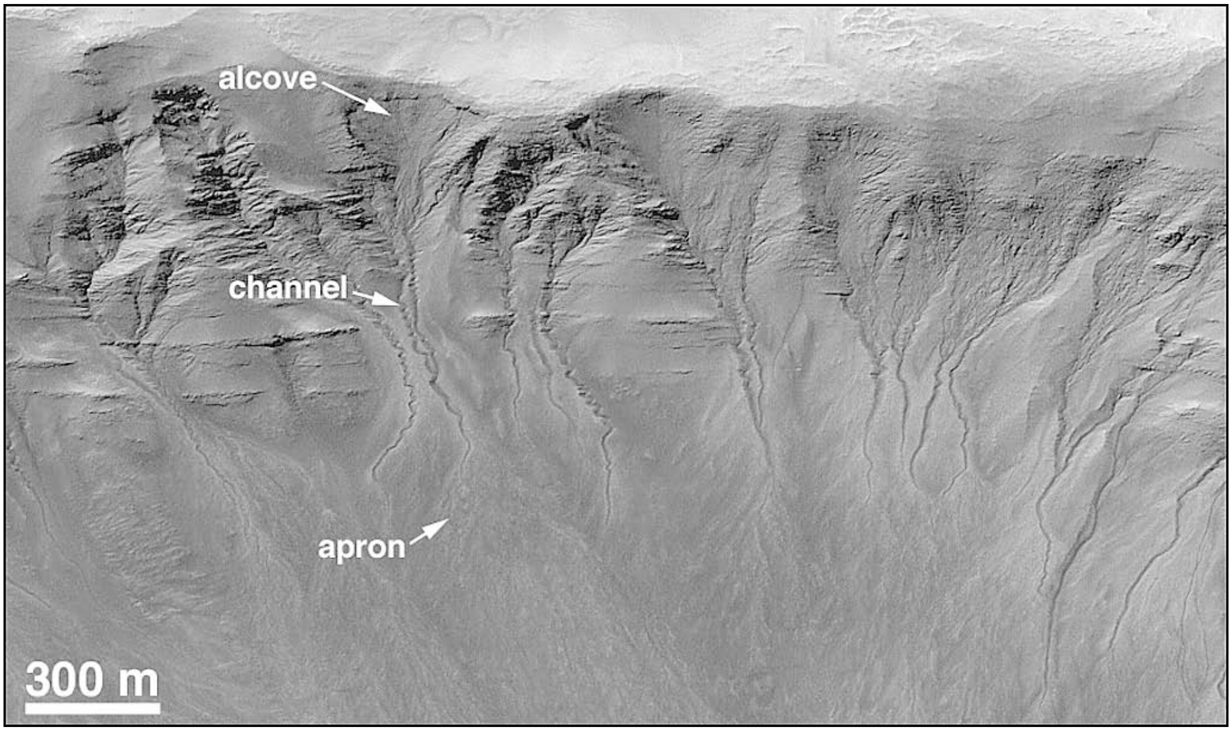

Figure 23. Examples of banked and sinuous mid-latitude gully channels in an unnamed crater in Newton basin near 41.8°S, 158.0°W. The crater wall exhibits layered rock. Aprons formed from material transported through the gullies. Alcoves formed by undermining, collapse, and mass movement above some of the channels. This is a sub-frame of MOC image E16-00043. The aspect ratio is 1.5, thus the north–south dimension is shown here at only 50% of its true aspect. North is toward the top/upper right (figure23.png).

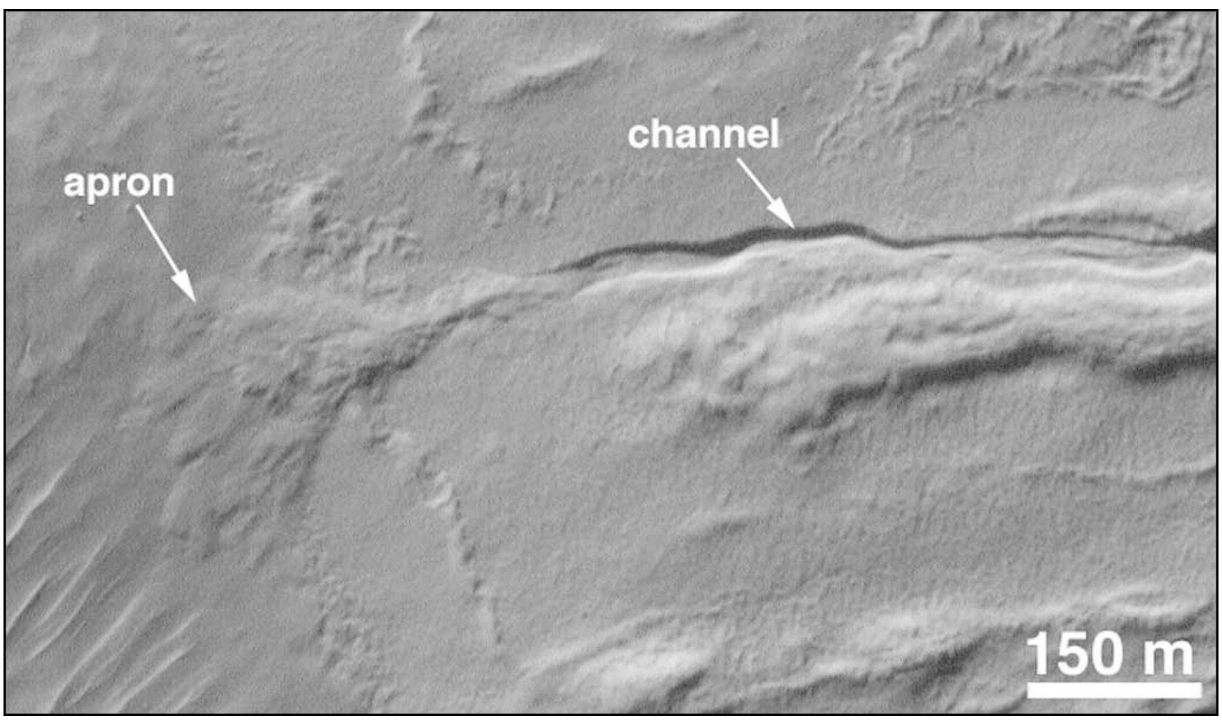

Figure 24. Example of gully apron composed of multiple lobate flows. The flows indicate that the debris transported through the channel contained a fluid, such as water. This is a sub-frame of image S20-01767. North is toward the top/upper right. The gully, in this case, was facing almost due west. This occurs on the lower wall and eastern floor of an unnamed impact crater located near 46.6°S, 120.1°W (figure24.png).

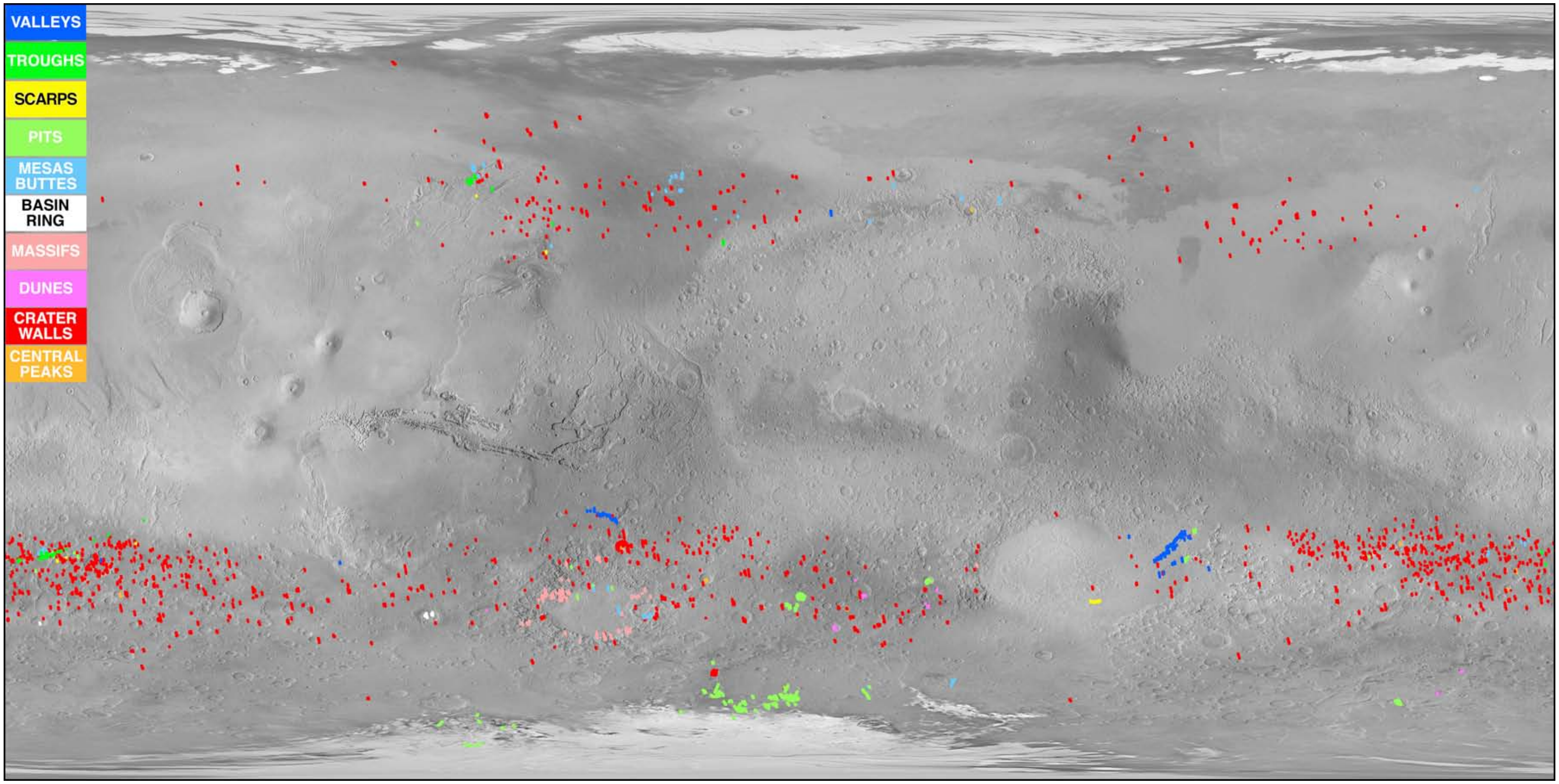

Figure 25. Global map of Mars showing the locations of all MOC narrow angle camera images in which gullies were identified. The locations are color-coded according to geomorphic setting. This simple cylindrical map is centered on the equator and prime meridian and is derived from MOC red wide angle Geodesy Campaign data and topography (shown here as shaded relief) derived from MGS MOLA data (figure25.png) (figure25.txt).

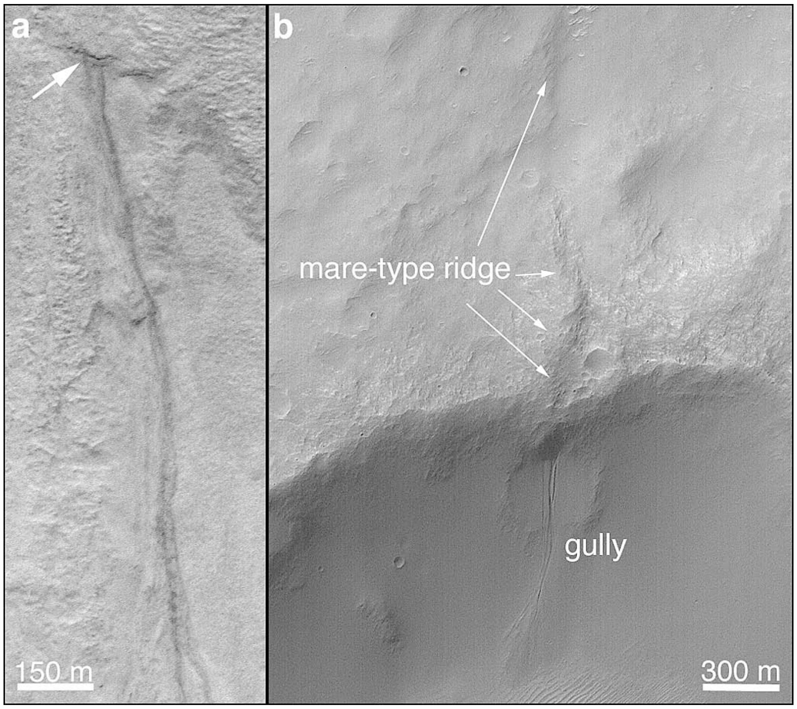

Figure 26. Gully occurrences suggesting a groundwater source for the fluid. **(a)** A gully channel heads just below an overhanging rock layer in the wall of Dao Vallis. This is a sub-frame of MOC image S14-01017, located near 34.2°S, 268.0°W. **(b)** A gully channel head associated with a fault (expressed at the surface as a mare-type ridge, also sometimes known as a "wrinkle" ridge). The gully provides key evidence for the involvement of groundwater because water would have flowed along the fault and emerged where the fault intersects the surface. The picture is a sub-frame of S02-00674, located near 29.1°S, 207.5°W. North is toward the top/upper right in both images (figure26.png).

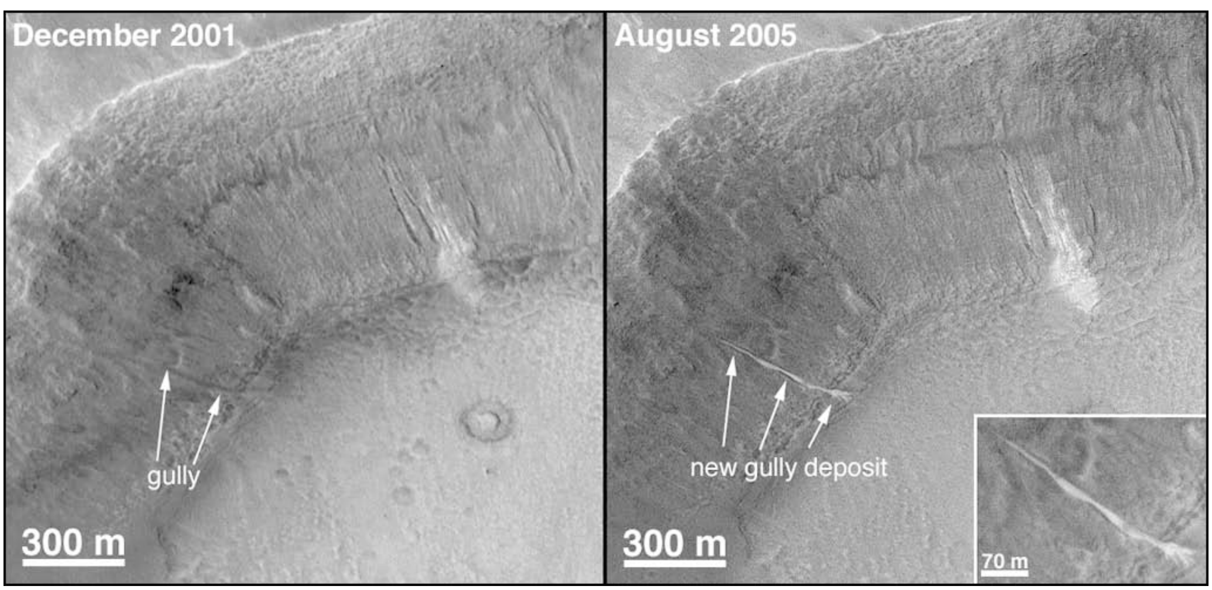

Figure 27. New, light-toned feature that formed in a Martian south mid-latitude gully in Naruko Crater (36.5°S, 161.8°W) sometime between December 2001 and August 2005. The images were acquired at about the same time of year (E11-03412 at L_s 295.2°; S09-02603 at L_s 276.0°; S10-01184 at L_s 295.0°). This new feature and a similar one in Penticton Crater suggest that water may have recently flowed on the surface of Mars. Note the digitate apron at the end of the gully in the inset at lower right (figure27.png).

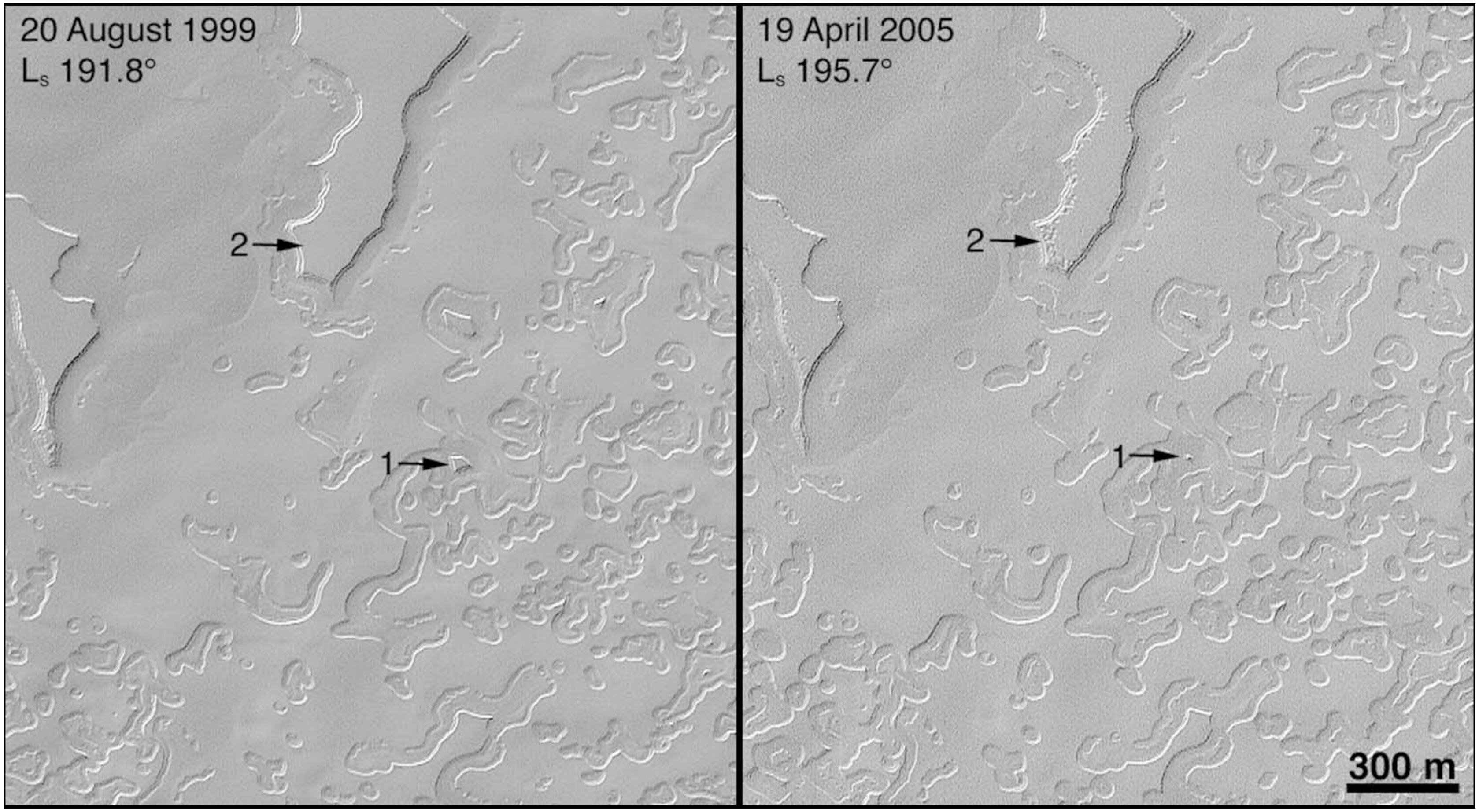

Figure 28. A comparison of south polar residual cap mesas and pits, composed largely of frozen CO_2, as seen by MOC in August 1999 (image M04-02205), and 3 Mars years later in April 2005 (image S05-01045). The scarps retreated at a rate of about 3 m per Martian year. Sunlight illuminates the features from the upper left (figure28.png).

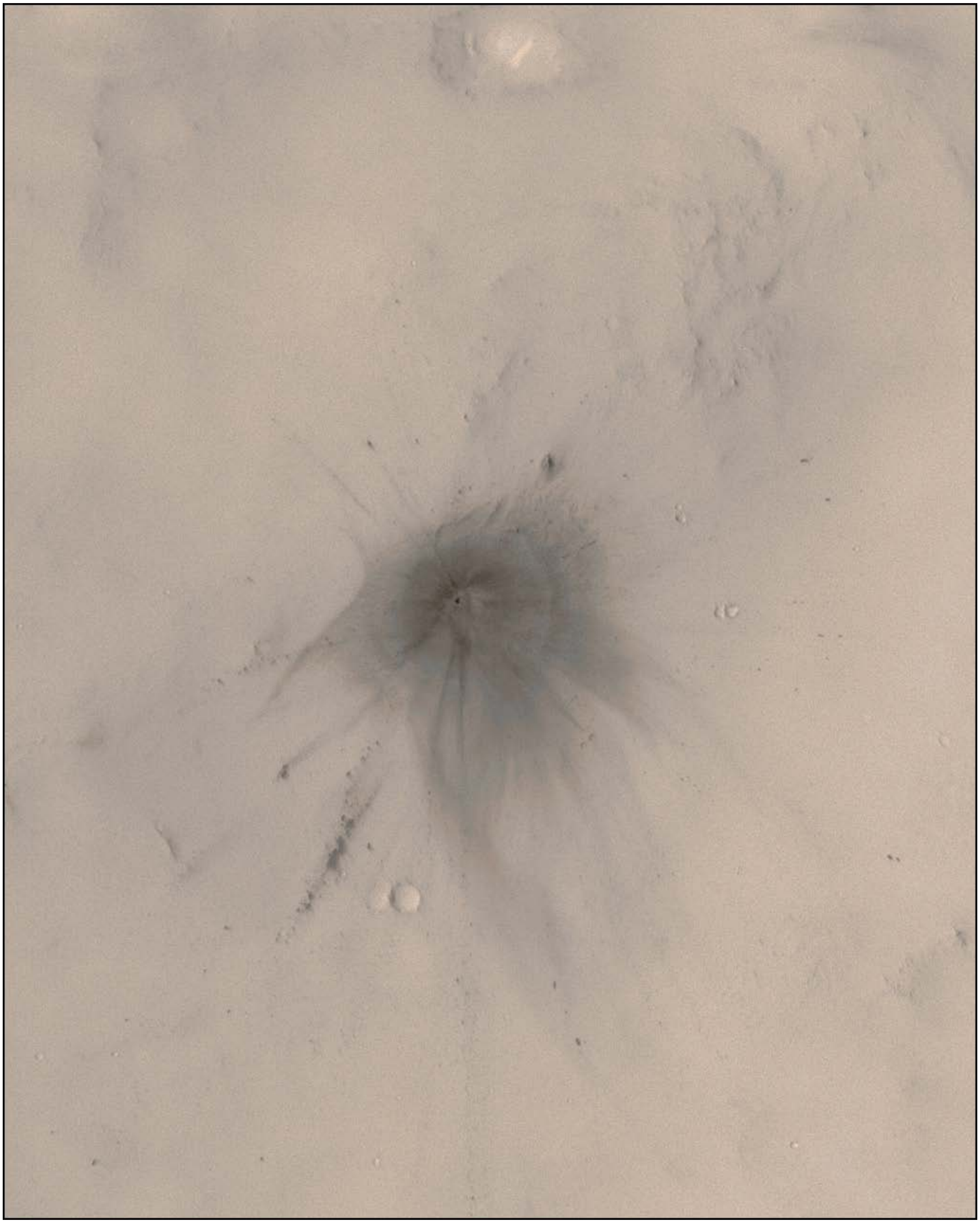

Figure 29. Fresh impact crater in Arabia Terra near 26.4°N, 336.5°W. The crater (small dark spot near center of the larger feature) has a diameter of 22.6 ± 1.7 meters. MOC and THEMIS imaging of the area constrain the date when the impact occurred to have been between the acquisition of MOC image R12-00786 on 8 December 2003 and THEMIS image I17523014 on 26 November 2005. This is a colorized composite of sub-frames of images S16-01674, S17-00795, S17-02191, and S18-01407. North is up (figure29.png).

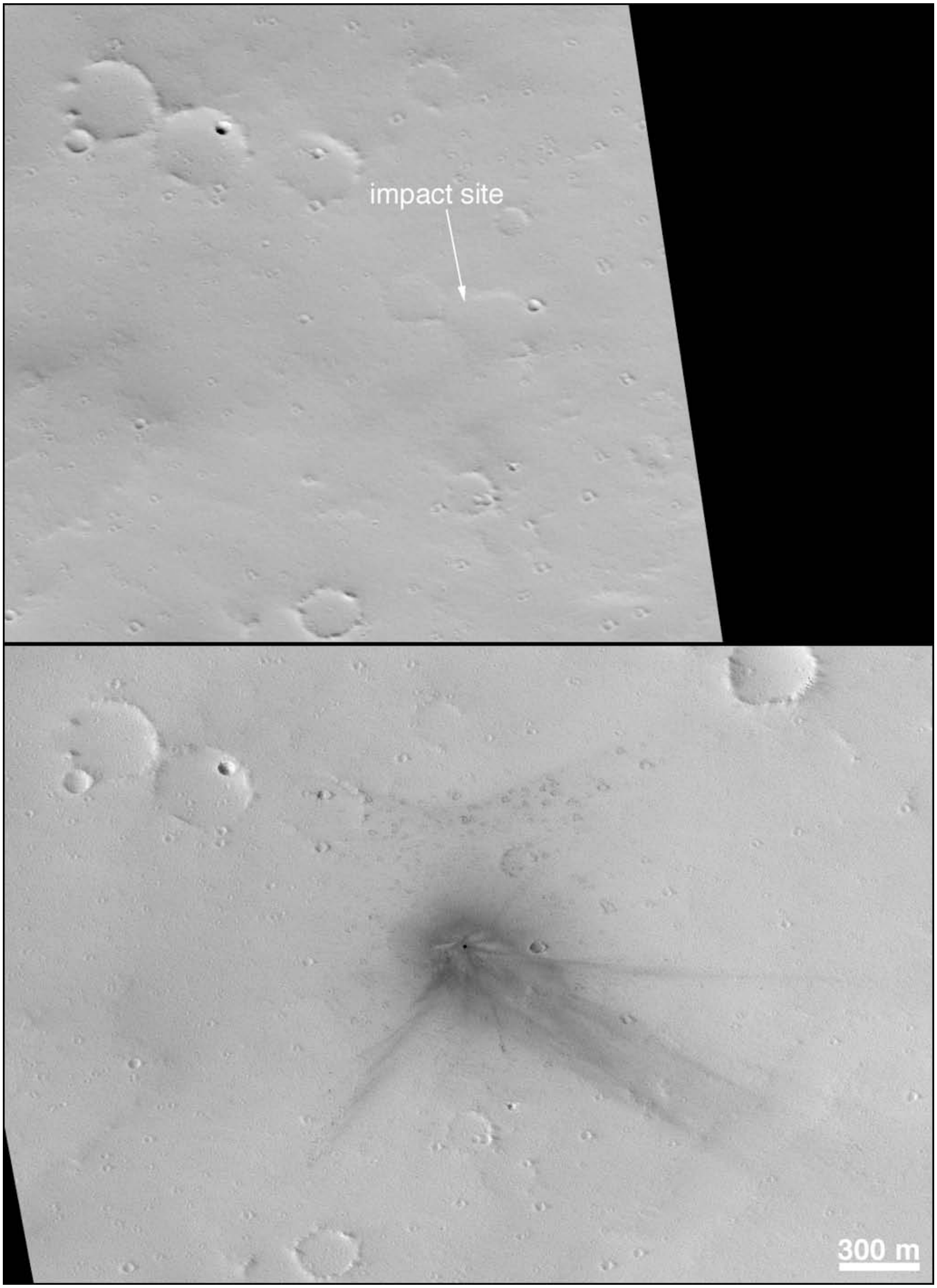

Figure 30. Fresh impact crater on Ulysses Patera near 27.3°N, 91.8°W. The top image is a sub-frame of MOC image E13-02112; it was acquired on 24 February 2002, before the impact occurred. The bottom image, MOC S16-01140, was obtained on 13 March 2006. MOC wide angle image R04-01354 and THEMIS image I09540014 constrain the timing of the impact between 18 April 2003 and 7 February 2004. The crater has a diameter of 19.8 ± 3.0 m (figure30.png).

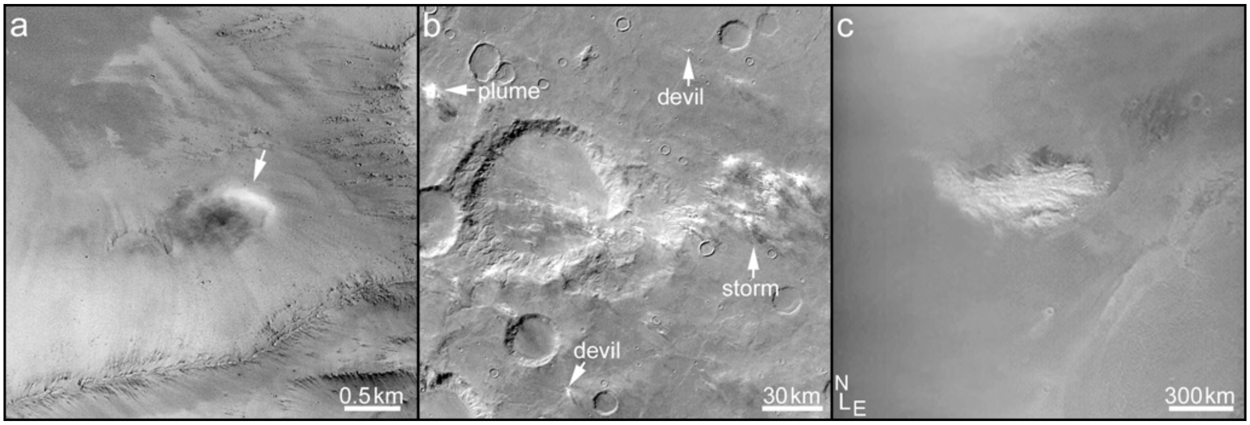

Figure 31. The scale of different Martian dust-raising events as observed in MOC images. **(a)** A "dust gust" (797 by 773 m) generated by a local, non-rotational wind gust in a crater in southwest Arabia in narrow angle image E01-01215. **(b)** Large dust devils (0.5 by 1.5 km), a dust plume (6.7 by 7.7 km), and a local dust storm (long axis of 165 km) all within a few hundred km of each other in Noachis in wide angle image M01-00432. **(c)** An even larger, more mature local dust storm observed in northern Amazonis in MOC image M14-00403. Still other dust-raising events can be even larger (*i.e.*, regional in scale) (figure31.png).

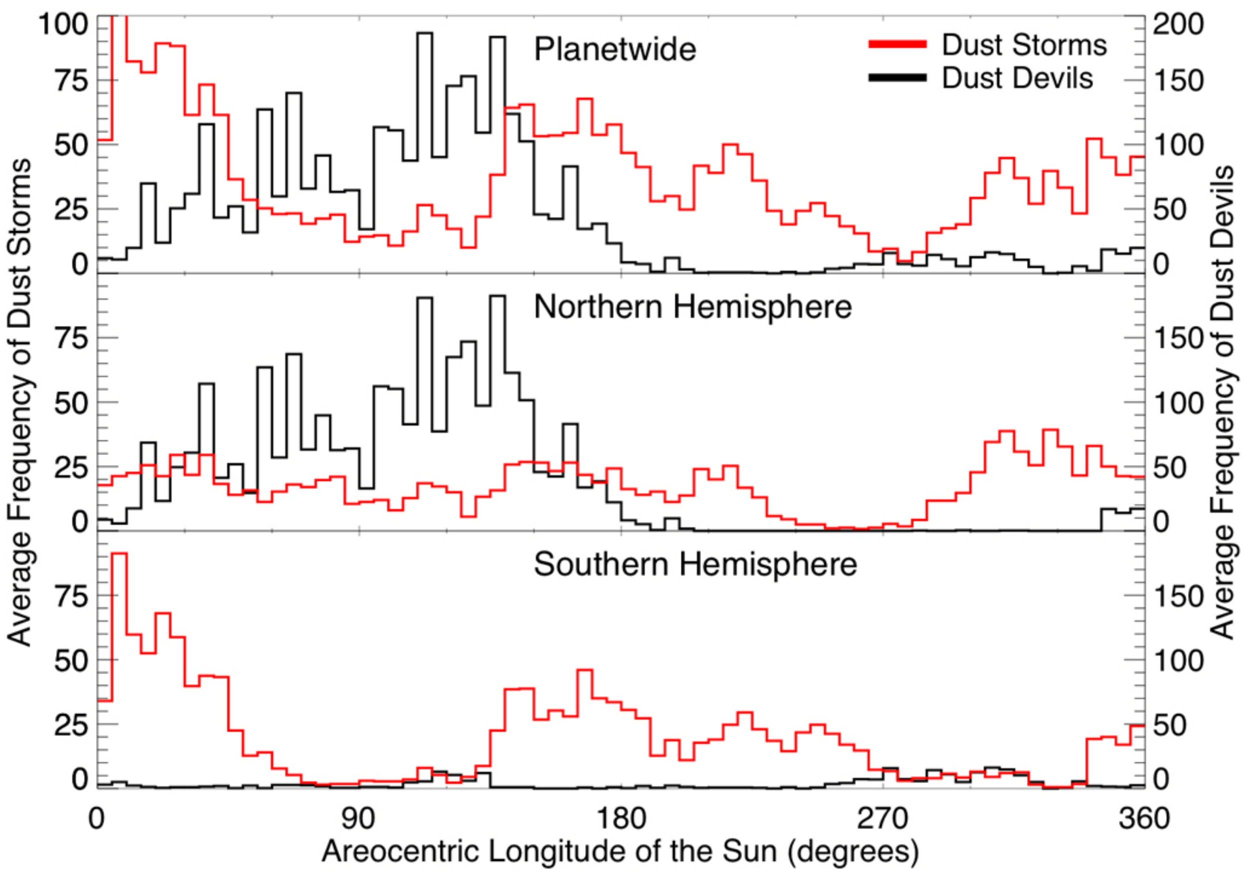

Figure 32. Histograms of the annual average frequency of dust storms (red) and dust devils (black) observed in MOC images as a function of L_s over the entire planet as well as in the northern and southern hemispheres. Note the different labeling of the y-axis on the left and right sides of the figure. Also note that dust devil occurrence in the northern hemisphere is heavily biased by frequent monitoring of large dust devils in northern Amazonis that occur each northern spring and summer (figure32.jpg).

The MOC results indicate that there is no particular "dust storm season" on Mars. There is, however, a period of time during which large regional storms most commonly occur. Martin and Zurek (1993) considered this period, which they called the "great dust storm season," to occur between Mars solar longitude (L_s) 160° and 330°. MOC observations show that this period actually spans nearly two-thirds of a Martian year, from late southern winter past the middle of southern summer, L_s 130° to 340° (Cantor 2007).

Dust devils do not lead to dust storms

A notion that dust devils trigger or generate Martian dust storms has been a part of the Mars scientific literature and popular lore for several decades, as noted by the following examples (italics added for emphasis):

- "It has long been suspected that dust devils occur on Mars and that *they may be important in the initiation of large dust storms* or in increasing the general atmospheric dust content." (Thomas and Gierasch 1985)
- "It is likely that dust devils play a major role in the rapid delivery of fine particulates into the Martian planetary boundary layer and *are a possible trigger for the planet-encircling dust storms* to which Mars is subject." (Metzger et al. 1999)

While the notion appears from time to time in scientific discourse, there is no single, specific publication that describes the concept that is often portrayed (typically, Gierasch and Goody (1973) is cited, even though this is not the model those authors presented). We believe the idea is traceable to confusion over the distinction between "dust storm" and "dust cloud." Before spacecraft acquired images of large dust-raising events on Mars, astronomers described observations of Martian "yellow clouds". These were commonly—especially by the 1960s—interpreted to be clouds of dust. Neubauer (1966) and Sagan et al. (1971) presented models in which dust devils might raise dust to create a cloud of sufficient size and opacity so as to be visible from Earth as a "yellow cloud". These authors did not intend to imply that the dust devils created dust storms, but sometime thereafter, "yellow clouds" or "dust clouds" became synonymous with "dust storms" in the Martian scientific conversation.

More than 12,000 active dust devils were observed by the MOC narrow angle and wide angle cameras (Cantor et al. 2006). Some dust devils were imaged in the process of creating a streak on the Martian surface (Figure 34). In addition to the > 12,000 dust devils, more than 10,500 dust storms of local to regional scale were imaged by the MOC cameras. Taken together, the observations show that dust devils do not precede dust storms (Cantor et al. 2006). The two forms of dust-raising event are usually anticorrelated, with dust devils most common during quiescent periods when dust storm activity in that hemisphere is at a minimum (Figure 32). In a few observed cases, dust devils were triggered by the passing of a storm front, near the margin of a dust storm; and in one observed case, the advancement of a dust cloud over a region changed its atmospheric conditions such that dust devil activity was triggered for a single sol (Cantor et al. 2006).

Interannual repetition of weather events

One of the advantages of the multiple MGS extended missions was that, instead of the planned 1 Mars year of daily global observations, we obtained a record of meteorological events that cover slightly over 4 consecutive Mars years. As first reported by Cantor et al. (2002), these data showed that Martian weather during the MGS mission was largely repeatable from year to year. Specific cloud and dust-raising events typically repeated to within ± 7.5° of L_s each year. Three examples are shown in Figures 35–37. The slight interannual variation exhibits a direct relationship with documented changes in solar irradiance. Events that do not seem to be repeatable are the large, regional dust storms, a few of which led to the planet-encircling event of 2001. While it may seem like the MGS instruments only observed one global dust event (the 2001 event), the global spread of suspended dust was repeated each Mars year, and the person targeting MOC images could expect, for example, that the period around L_s 210°—240° would be dusty nearly everywhere. As dust storms are the visible manifestation of atmospheric circulation where the atmosphere interacts with the planet's surface, some (if not all) of the variability regarding when and where the regional dust storms occurred was a function of where loose dust was available for transport in a given year, particularly after new dust deposits formed as a result of the 2001 planet-encircling dust event. The repeatability of dust-raising events made it possible to target the MOC cameras to observe specific, anticipated dust storms and dust devil events and to predict weather conditions at future landing sites; for example, prior MOC observations suggested that a dust storm would occur in Isidis Planitia within two weeks of the December 2003 Beagle 2 landing attempt and this storm did indeed occur—exactly two weeks before the scheduled landing.

Planet-encircling dust events

Dust clouds encircled Mars every year that MGS observed the planet. However, only in one year, during 2001, was the planet-encircling dust cloud particularly opaque such that it earned the popular name of "global dust storm" (Figure 38). Cantor (2007) described the MOC observations of the 2001 event in great detail. The images showed that there really is no such thing as a global dust storm, as dust is not raised from the surface everywhere and a person standing on the ground, at most locations on the planet, would not experience high winds and the impact of dust, silt, and sand grains on their spacesuit. Instead, during the 2001 event, dust was lifted from the surface in specific regional storms; the rest of the obscuration was caused by dust suspended in the atmosphere, not by dust-raising conditions everywhere on the ground. Dust-raising occurred in one particular region, Syria–Claritas, for 86 sols in a row. As the planet-encircling dust haze obscured the planet, opacities reached $\tau_{vis} \sim 5.0$ and dust was lofted as high as 60 km altitude. During this same period, the MOC instrument temperature sensors registered

Figure 33. Local dust storm observed along the edge of the seasonal south polar cap. Dust streamers on the southern side of the storm are an indication that the storm was moving northward, consistent with the strong surface wind blowing off the cap at the time the image was acquired on 21 June 2001 (L_s 181.8°). Centered near 55°S, 310°W, this is a composite of MOC red wide angle image E05-01975 and blue wide angle daily global swath E05-01972 (figure33.jpg).

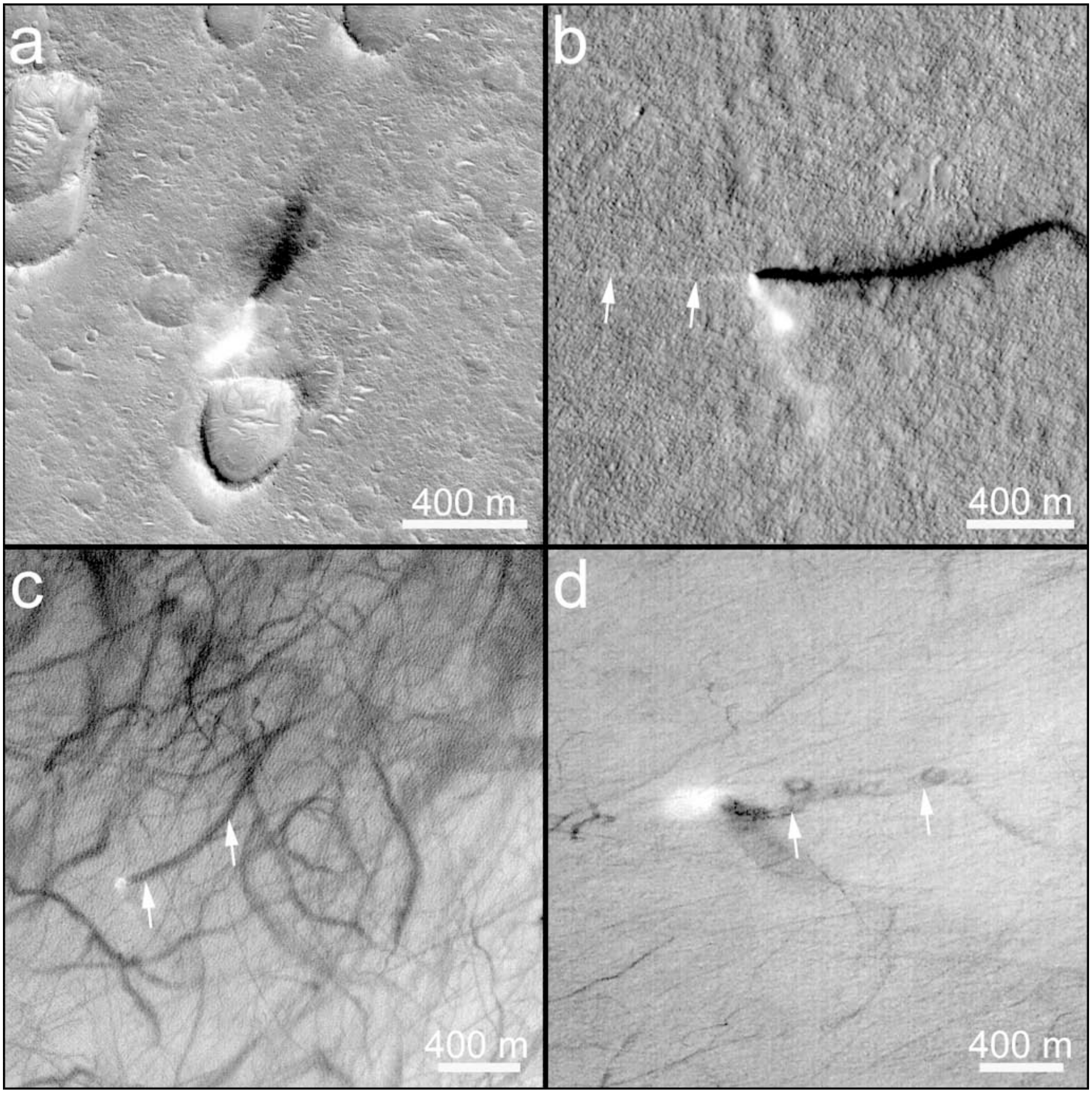

Figure 34. Active dust devils commonly (but not always) create dark or light streaks on the Martian surface. **(a)** An active dust devil for which no streak contrasting with surrounding terrain was being created. The dark feature is the dust devil's shadow. This event occurred in Elysium near 18.7°N, 239.5°W, in image R11-02181. **(b)** A light streak (arrows) caught in the act of forming in Amazonis near 35.2°N, 160.6°W, in image E03-00938. The dark feature is the dust devil's shadow. **(c)** A dark streak (arrows) forming in Noachis Terra near 59.2°N, 337.8°W, in image M11-03289. **(d)** A cycloidal dark streak (arrows)—similar to patterns created by some tornados (see Fujita et al. 1970)—forming in Promethei at 54.1°S, 242.8°W, in image M10-01267 (figure34.png).

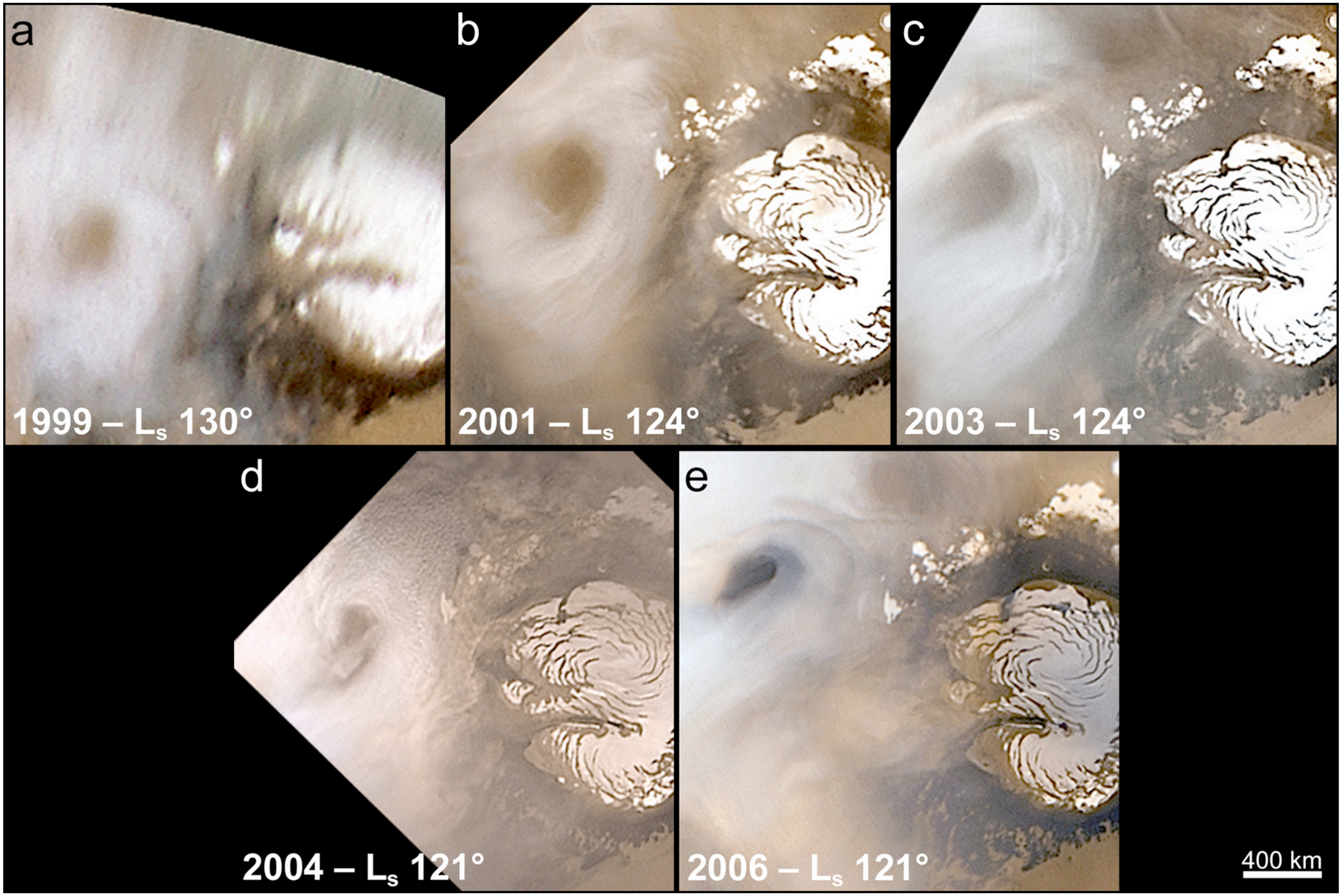

Figure 35. Repeated weather event. These pictures show a northern extratropical water ice cloud that was seen during five successive northern summers at about the same time of year and at the same location in each year. **(a)** View from the WFPC-2 camera on the Hubble Space Telescope on 27 April 1999 (MOC was turned off at this time because of a MGS spacecraft upset). Views from MOC daily global images acquired on **(b)** 2 March 2001, **(c)** 19 January 2003, **(d)** 27 November 2004, and **(e)** 15 October 2006. No significant rotation was seen in the cloud during the daylight hours, but the cloud shape is consistent with that of a counter-clockwise flow in a low-pressure system (figure35.jpg) (figure35.txt).

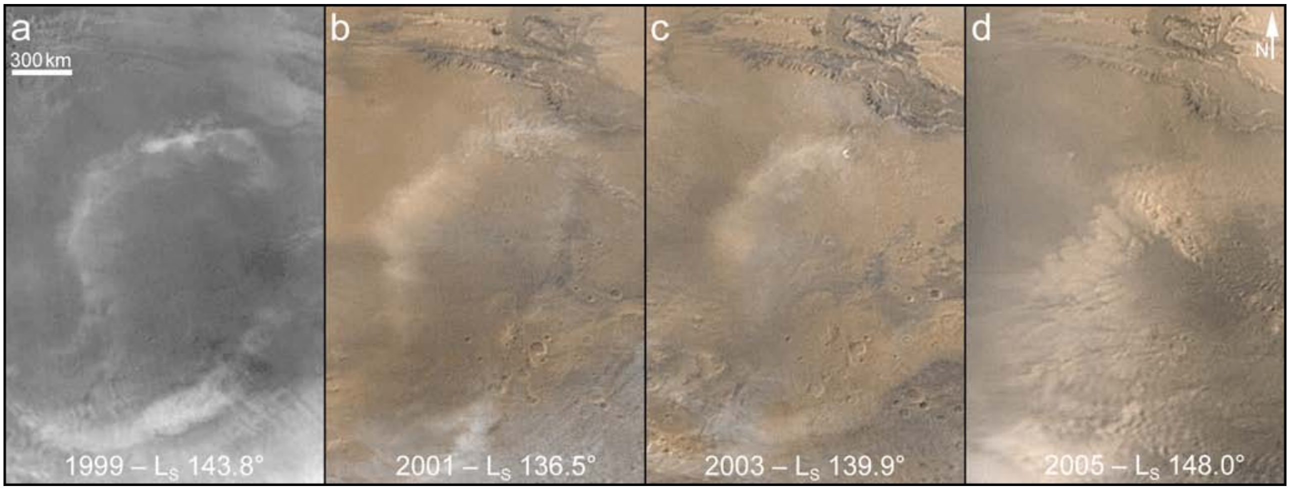

Figure 36. Repeated weather event. These images from the MOC wide angle cameras show dust storm activity in the Solis-Sinai region during southern winter over four successive Mars years as observed on **(a)** 24 May 1999 (image M01-03747), **(b)** 27 March 2001 (E02-02454 and E02-02455), **(c)** 19 February 2003 (R02-01007 and R02-01008), and **(d)** 22 January 2005 (S02-00854 and S02-00855) (figure36.jpg).

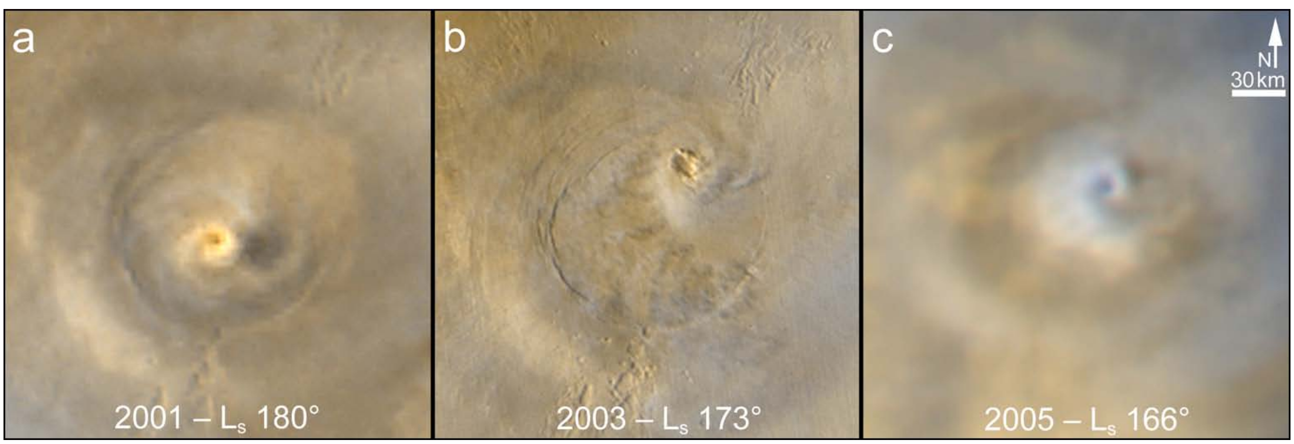

Figure 37. Repeated weather event. These images from the MOC wide angle cameras show spiral dust storms observed in late southern winter in the caldera of Arsia Mons over three successive Mars years on **(a)** 19 June 2001 (images E05-01721 and E05-01722), **(b)** 24 April 2003 (images R04-01809 and R04-01810), and **(c)** 25 February 2005 (images S03-01234 and S03-01235). The storm rotated in a clockwise direction, indicating that it was associated with a low-pressure system. The images have been simple cylindrically projected. Rafkin et al. (2002) presented a discussion on how these spiral clouds form (figure37.jpg).

an average cooling on the order of 1–2 K, with the daytime average dropping by about 3 K and the nighttime average actually increasing by about 0.7 K compared to the same time in the previous Mars year (Figure 39). Monitoring of conditions using the MOC wide angle cameras also showed that after the dust-raising period ended, and almost as soon as the dust settled out of the atmosphere, the Martian climate returned to its normal, repeatable pattern, as if the planet-encircling event had never occurred. The only difference was that new dust deposits were formed on the surface, which led to the observation of additional dust storms in subsequent years that were not repeated from previous years. These dust storms were likely the product of annually repeated wind events, but it was only after new dust became available for transport that these winds were rendered visible to MOC.

Other results

Other results of the MOC investigation included observation of eolian features, impact craters, volcanic landforms, fluvial landforms, water ice clouds, and more. The narrow angle camera was used to repeatedly image eolian bedforms (dunes and large ripples) to search for evidence of movement; in one case, several small patches of dark sand eroded away, but larger, neighboring dunes did not move (Bourke et al. 2008), and many dunes seemed to be crusted or indurated such that movement is inhibited (Schatz et al. 2006). Narrow angle images of the north polar region showed a stratigraphy of two or three major units, with the uppermost, ice-rich layers undermined by eolian erosion to form arcuate scarps as sand from the middle (and lower?) unit is removed by wind (Edgett et al. 2003, Edgett and Malin 2003). MOC cPROTO images showed that the upper unit is composed of material of sufficient strength that it produces boulders along cliff faces (Malin and Edgett 2005). MOC images also revealed some of the youngest flood features in the Kasei Valles, including a cataract and morphologic observation of likely mudflow deposits (Williams and Malin 2004). MOC narrow angle images of a crater in Xanthe Terra showed forms that so closely resemble terrestrial desert alluvial fans (Williams et al. 2004) that we urged and the International Astronomical Union accepted the name, Mojave, for this crater. MOC images showed seasonal frost occurring in the afternoon during southern winter at latitudes as low as 24°S, north of Hellas, and on slopes, elsewhere, to latitudes as low as 33°S (Schorghofer and Edgett 2006). Other results of the MOC investigation were summarized by Malin and Edgett (2001) and will be discussed in more detail in the forthcoming (and much longer) Mars Orbiter Camera final report document.

Mars Reconnaissance Orbiter follow-up

The MGS spacecraft was lost during the same week that the Mars Reconnaissance Orbiter (MRO) primary science phase began. The MRO carried three instruments that provided a direct follow-up to the MOC investigation and allowed our interannual observations to be carried seamlessly forward in time. Like MGS, MRO was placed in a nearly circular, nearly polar orbit with its ascending node on the day side of Mars. MRO was placed in a ~3 p.m. orbit, whereas MGS was in a ~2 p.m. orbit. The MOC narrow angle camera is followed by the MRO High Resolution Imaging Science Experiment (HiRISE), which acquires images of up to 6 km cross-track and > 10 km down-track with a spatial resolution as high as ~30 cm/pixel (McEwen et al. 2007), and the Context Camera (CTX), which acquires images with an up to 30 km wide cross-track and up to ~314 km down-track at about 6 m/pixel (Malin et al. 2007). Daily global imaging is continued using the Mars Color Imager (MARCI), a capability re-flown on MRO following the loss of Mars Climate Orbiter (MCO) in 1999 (Malin et al. 2008, Bell et al. 2009).

The same personnel who operated the MGS MOC began in 2006 to operate the MRO MARCI and CTX instruments. In December 2006 and January 2007, the MOC science operations team examined the remaining MOC targets (regions of interest) in the MOC database and determined that many of them had science objectives that could be addressed by acquiring images using the MRO CTX or HiRISE. Thus, these MOC targets were converted to suggestions that were added to the CTX database and/or suggested to the HiRISE team. The CTX target database was also populated with targets that would provide context for various MOC observations, particularly in cases where a mosaic of MOC narrow angle images was desirable but not completed before the end of the mission. The MRO instruments are thus continuing some of the studies that MOC began, such as monitoring Martian weather, observing changes in south polar carbon dioxide landform scarp retreat, observing interannual variations in seasonal polar cap retreat, and monitoring changes in eolian features and albedo patterns.

Conclusions

It has been said that a picture speaks a thousand words. The results of NASA's Mariner, Viking, Voyager, Magellan, Galileo, Deep Impact, MER, and Cassini projects, to name a few, demonstrate that imaging is an extremely powerful tool in Solar System exploration. Much of what is known about bodies in our Solar System comes from images. With its high resolution narrow angle and wide-angle daily global mapping capabilities, the MGS MOC experiment—an effort that spanned the greater part of three decades from conception to completion—provided data that revolutionized our view of Martian climate, geology, and the role that liquid water might have played on that planet in the past as well as the present.

The major discoveries of the MOC investigation came about because of the following factors:

1) *Spatial resolution*. The narrow angle camera was specifically proposed in anticipation that acquiring images to bridge the spatial resolution gap between what was observed by the Viking orbiters and the Viking landers would lead to new discoveries. The discovery of the Martian gullies and the recognition of a layered upper Martian crust and vast outcrops of sedimentary

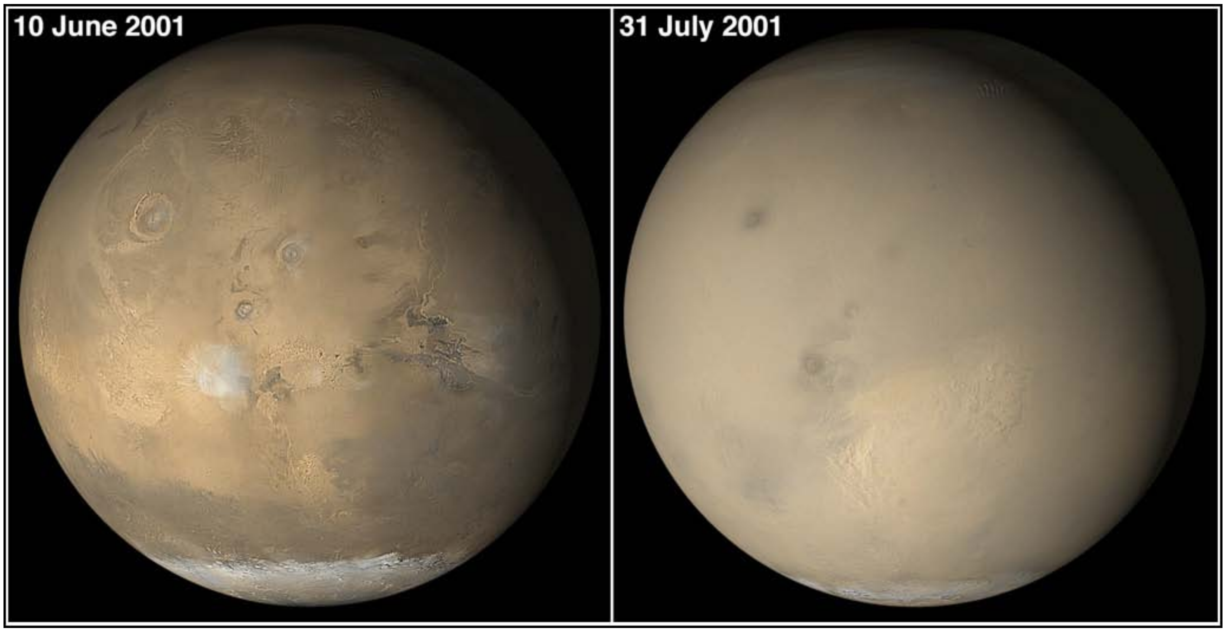

Figure 38. Planet-encircling dust cloud event of 2001. These composites of MOC daily global image swaths acquired on 10 June 2001 (L_s 176.1°) and 31 July 2001 (L_s 205.3°) show how the planet looked before the dust storm activity began and how it looked during the dust event in July. Shown here is the Tharsis face of Mars; note that during the dust storm event the south polar region and the summits of the Tharsis volcanoes remained relatively dust-free; these were the areas where we concentrated our MOC narrow angle imaging activities during the 2001 dust event (figure38.jpg) (figure38.txt).

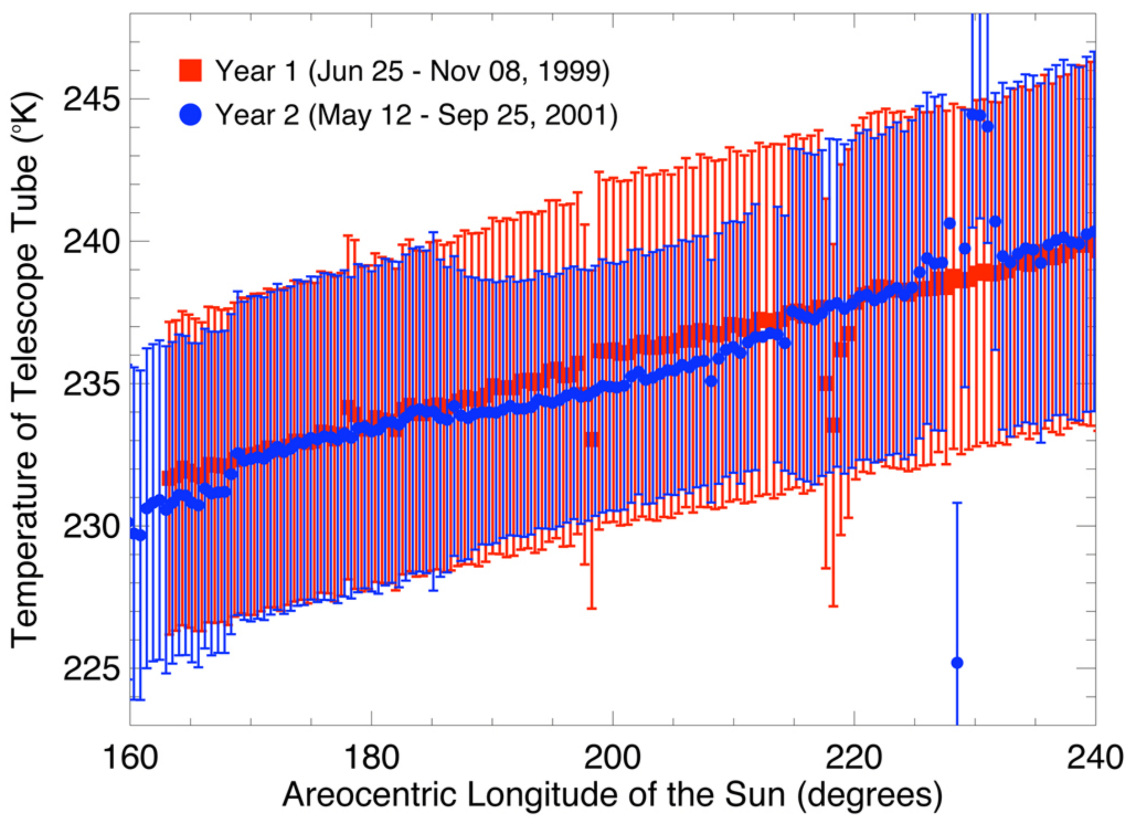

Figure 39. Normalized MOC telescope tube temperatures during the 2001 planet-encircling dust event (blue) compared to temperatures from same time of year the previous Mars year (red). The vertical bars show the minimum and maximum values observed each sol (figure39.jpg) (figure39.txt).

rock are key results that came from having the improved spatial resolution.

2) *Areal coverage.* After the initial flood of discoveries that accompanied the first receipt of unprecedented data, the pace of discovery with the MOC became nearly constant, even as the mission continued into its second, third, and fourth Martian year. This was in part because of the increased areal coverage by the MOC narrow angle camera, which was originally expected to image much less than 1% of the planet's surface, but instead viewed > 5%. Increased areal coverage, coupled with careful target selection, led to discoveries such as the inverted hillslope rills and streams near Juventae Chasma and the lithified delta in Eberswalde Crater.

3) *Temporal resolution and spatial coverage.* The meteorological results of the MOC investigation benefited greatly from the multiple extensions of the MGS mission, providing more than 4 Mars years of observations which led to the recognition of the repeatability of Martian weather patterns and placed dust storms and planet-encircling dust events into context. Prior to the MGS mission, there were no consistent, daily observations of Mars and much of what was known about the dust and water cycles of Mars came from telescopic observations which were limited by Earth–Mars geometry and available observing time. Temporal resolution not only included daily observations; at high latitudes, it allowed dust storms and cloud formations to be tracked at ~2 hour intervals as the polar orbits converged over these regions.

4) *Repeated observations.* Repeated observation was critical not only for the meteorological investigation, but also for narrow angle camera studies. Efforts were made to monitor changing albedo features, gullies, mass movements, and eolian bedforms. The narrow angle camera results that came from repeated observations included those of the south polar residual cap that showed ~3 m of scarp retreat each Martian summer (which further suggested that the climate today is different than in the recent past when the now-eroding layers of CO_2 were deposited over the south polar region). Repeated observation of gullies also revealed two places where new material had moved through a gully channel system, suggesting that perhaps liquid water is present beneath the ground, today, and flowed across the surface at these two locations during the course of the MGS mission.

5) *Off-nadir targeted observations.* Developed in 1998 to image the Viking and Mars Pathfinder landing sites and popular landforms in Cydonia, off-nadir targeted imaging was further refined and employed in 1999–2000 to search for the missing Mars Polar Lander, and then became a routine aspect of MGS Extended Mission operations from February 2001 through the end of the mission. In 2003, another technique was developed which provided sub-meter-per-pixel scale imaging (in the down-track image dimension). The ability to point and target the MOC allowed relatively rapid acquisition of mosaics of key geologic features, including the Eberswalde delta and the inverted streams near Juventae Chasma. Sub-meter imaging made it possible to identify the Mars Exploration Rover hardware and rover tracks on the planet's surface. Perhaps the most important result that came from the ability to point and target the MOC came about in 2006, when the team identified and then, using off-nadir targeting, quickly imaged and examined a suite of fresh impact craters that helped, for the first time on any Solar System body, determine the present-day impact cratering rate.

6) *Philosophy and practice of the targeting effort.* Using the MOC to make new discoveries and identify new phenomena was greatly assisted by the approach taken to the image targeting effort. The majority of the image targets were selected, almost daily, by scientists who carefully examined each predicted ground track to see what landforms the camera would pass over a few days hence. The group that did the targeting was very small and two of these persons, in particular, were involved in this effort from start to finish. These two met nearly every day to discuss the latest images, propose hypotheses and tests that could be conducted by acquiring new MOC images, and then implemented those ideas as rapidly as possible. The MOC Ground Data System, with its built-in ability to specify targets and place them in a database for future reference (Caplinger 1993), was vital to allowing these two persons to work together and advise other personnel (whom they oversaw) on what MOC targets should be selected. Each day that MOC was operational was treated like the last, thus the highest priority targets were usually acquired as rapidly as possible (especially when off-nadir targeting became routine), and each day's new results were quickly integrated into plans for further imaging.

7) *Motivation.* The personnel who worked on the MOC effort during all of the various phases of the endeavor—from proposal to design and development through operations and science activities—were highly motivated to do this work and they contributed their hearts-and-souls to make this investigation a success.

Following the loss of MGS in November 2006, the daily global imaging and meteorology objectives of the MOC investigation were continued using the MRO MARCI. Likewise, narrow angle camera targets that had not been acquired and new targets emergent from further analysis of the MOC data were passed along to the MRO CTX and HiRISE teams for imaging in 2007–2009. Overall, the MOC investigation was highly successful and exceeded all anticipated measures of its potential for scientific return.

Directory of supporting data

root directory
    malin_mars_2010_0001.pdf this file
    Fig. 1 figure1.jpg full-resolution image

Fig. 2 figure2.jpg full-resolution figure
Fig. 3 figure3.jpg full-resolution figure
Fig. 4 figure4.png full-resolution figure
Fig. 5 figure5.jpg full-resolution figure
Fig. 6 figure6.jpg full-resolution figure
Fig. 7 figure7.png full-resolution plot; figure7.txt source data in tabular format
Fig. 8 figure8.png full-resolution plot; figure8.txt source data in tabular format
Fig. 9 figure9.png full-resolution plot; figure9.txt source data in tabular format
Fig. 10 figure10.png full-resolution figure
Fig. 11 figure11.png full-resolution figure
Fig. 12 figure12.png full-resolution figure
Fig. 13 figure13.png full-resolution figure
Fig. 14 figure14.jpg full-resolution "cartoon"
Fig. 15 figure15.png full-resolution figure
Fig. 16 figure16.png full-resolution map/plot; figure16.txt source data in tabular format
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Fig. 18 figure18.png full-resolution figure
Fig. 19 figure19.png full-resolution figure
Fig. 20 figure20.png full-resolution figure
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Fig. 22 figure22.png full-resolution figure
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Fig. 25 figure25.png full-resolution map/plot; figure25.txt source data in tabular format
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Fig. 36 figure36.jpg full-resolution figure
Fig. 37 figure37.jpg full-resolution figure
Fig. 38 figure38.jpg full-resolution figure; figure38.txt source data in tabular format
Fig. 39 figure39.jpg full-resolution plot; figure39.txt source data in tabular format

data/ — This directory contains MOC images used in this report that are not otherwise available in public archives. In this case, these are images of Mars acquired by the Mars Observer MOC in July 1993. After the Mars Observer spacecraft was lost, the public archive of NASA planetary mission data, the NASA Planetary Data System (PDS), elected not to receive data acquired by Mars Observer during the cruise phase of its mission.

C12-3_6.txt ancillary information about the images
C12-3.gif unprocessed image
C12-4.gif unprocessed image
C12-5.gif unprocessed image
C12-6.gif unprocessed image

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