# THE MARS 2000 PROJECT: USING MARS ORBITER LASER ALTIMETER DATA TO ASSESS GEOLOGICAL PROCESSES AND REGIONAL STRATIGRAPHY NEAR ORCUS PATERA AND MARTE VALLIS ON MARS.

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## INTRODUCTION

Data returned by NASA missions flown during the past several decades have significantly improved our ability to decipher the intriguing and complicated geological history preserved on Mars. The rich Mariner and Viking Orbiter datasets collected during the mid-1960's to mid-1970's revealed a great deal about the basic characteristics of the planet's geology, and in 1997 this satellite exploration process continued when the Mars Global Surveyor spacecraft successfully entered Mars orbit. The Mars Orbiter Camera (MOC) carried by the spacecraft is returning photographic images at spatial resolutions as high as a few meters per pixel [*Malin et al.*, 1992, 1998]. Although this resolution is roughly one to two orders of magnitude better than the photographs captured during earlier missions, to date MOC has only taken photographs of a small percentage of the Martian surface. Mars Global Surveyor also carries the Mars Orbiter Laser Altimeter (MOLA) instrument, which is being used to study the topography of the surface at local, regional and global scales [*Zuber et al.*, 1992; *Smith et al.*, 1998]. The vertical precision of the altimetry data collected by MOLA is a meter or less across all but the roughest areas on Mars, and with many millions of data points collected thus far the topography of the entire planet is now resolved at a spatial resolution of several hundred meters, allowing direct examination of many new geological features. The spectacular data collected by MOC and MOLA provide exciting new opportunities for geologists to study the operation and by-products of the diverse range of geological processes which shaped (are shaping!) the Martian surface.

During the summer of 2000 a Keck Geology Consortium sophomore project based at NASA's Goddard Space Flight Center in Greenbelt, Maryland, introduced students to planetary geology in general and Mars in particular by involving them directly in analysis of the new data being returned by the active Mars Global Surveyor mission. To place the study in a broader context our goal was to identify and then characterize a potential future landing site. After selecting an area to study (2-21°N, 170-184°E; roughly 1100 km by 800 km; see **Figure 1**), five student teams explored different aspects of the geology in the region, which has been shaped by a variety of fluvial, eolian, volcanic, tectonic, and impact cratering processes and contains such prominent features as Orcus Patera (a large, elliptical depression of unknown origin), the Marte Vallis fluvial channel system and the linear volcanic vents within the Cerberus Plains.

## PARTICIPANTS

The Mars 2000 project was guided by three faculty: Eric Grosfils from Pomona College, Susan Sakimoto from the Goddard Space Flight Center, and Carl Mendelson from Beloit College. Valuable assistance and voluminous good cheer were provided by Jake Bleacher, the project's Research Assistant. Visiting faculty sponsors were Phil Armstrong from California State University Fullerton, Laurie Leshin from Arizona State University, Brian McAdoo from Vassar College, and Don Wise from Franklin and Marshall College.

There were ten student participants in the Mars 2000 project: Andrew Gendaszek, Carleton College; Sven Moller, Pomona College; Kate Poulter, Colorado College; Sara Santiago, Arizona State University; Matthew

Silver, Whitman College; Jes Therkelsen, Amherst College; Krystal Tribbett, Vassar College; Dolores van der Kolk, California State University Fullerton; Roderick Yazzie, Crownpoint Institute of Technology; and Jesse Yoburn, Franklin and Marshall College.

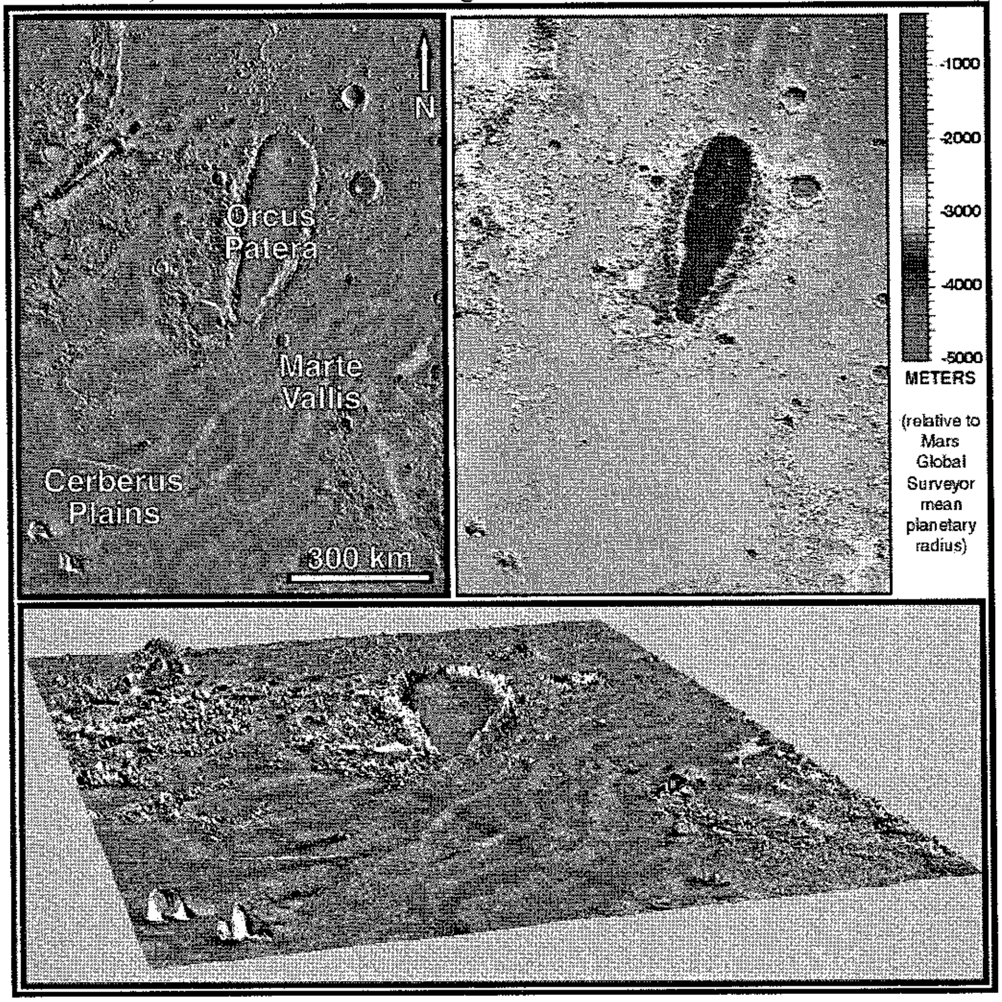


**FIGURE 1**. **Upper Left**: Viking Mars Digital Image Mosaic (MDIM) showing the study area for the Mars 2000 project, which extends from 2-21°N and from 170-184°E. Orcus Patera is the large, ellipsoidal depression near the center of the image, and the Marte Vallis channel system can be seen running from the lower center portion of the image towards the northeast past Orcus Patera. **Upper Right**: Mars Orbiter Laser Altimeter grid illustrating the topography within the study area. The dominance of the Orcus Patera topography is evident, as is the general slope down towards the northeast where the Marte Vallis channel system has formed. **Lower**: Perspective view of the study area looking NE with the Viking MDIM overlaid upon the MOLA grid. The image is shown at roughly 2x vertical exaggeration.

## PROJECT ORGANIZATION AND ACTIVITIES

The Mars 2000 project was organized into three primary phases. In the first, several days of intensive lecture introduced students to basic image analysis techniques, the geology of Mars, existing (Mars Surveyor 2001) landing site selection criteria, and the origin of ancient microbial life on Earth. Using principally *Gridview* [*Roark et al.*, 2000], Adobe's *Photoshop* and *Illustrator*, and Synergy's *Kaleidagraph*, students also learned the basic skills required to load and manipulate MOLA data and both MOC and Viking images. Then, using online landing site selection resources and USGS 1:2,000,000 controlled photomosaic maps, the students collectively examined the entire near-equatorial region of Mars from 15°N to 15°S in order to select a single region for detailed study. Finally, once the target area was chosen, faculty and students worked together over a two-day period to define five student teams and formulate each team's research project. The first phase of the project ended with each team submitting a formal 1-2 page proposal to the faculty defining a research question, the steps necessary to resolve it within the limited time available, and the potential significance of the outcome.

During the second phase of activity, which lasted approximately three weeks, each student team focused upon (1) exploring the literature to learn about and absorb lessons from previous research efforts, (2) collecting the data required to address their research question, and (3) analyzing the data, a process which in all cases involved a quantitative component. Throughout this phase of the project, each team also wrote the bulk of an iterative research paper—i.e. after meeting an initial deadline by submitting its Introduction, each team met a second deadline by handing in a revised version of the Introduction and a new section describing Methods, and so on. This process was of necessity very fluid as ideas changed and evolved during the course of the research activity, but it helped faculty identify potential difficulties on an ongoing basis and kept each project focused and moving forward by periodically encouraging team members to submit their ideas in writing for discussion and evaluation.

Throughout the second phase, the regular schedule of project activity at Goddard was punctuated by a variety of events. Most significantly, students interacted with a diverse and extensive array of talented scholars and scientists who took the time to visit, tell us about their careers/research, and in some cases work with the teams on their projects. These visitors included (in alphabetical order): *Phil Armstrong* (California State University Fullerton), *Marcelino Bedolla* (Maryland Science Center), *Harvey Cohen* (S.S. Papadopulos), *Orlando Figueroa* (NASA Headquarters), *Herb Frey* (Goddard Space Flight Center), *Jim Garvin* (NASA Headquarters), *Steve Korpon* (Severn High), *Laurie Leshin* (Arizona State University), *Mellie Lewis* (Baltimore Public Schools), *Brian McAdoo* (Vassar College), *Jerry Soffen* (Goddard Space Flight Center), *Don Wise* (Franklin & Marshall College), *Martin Wong* (Universities Space Research Association) and *Jim Zimbelman* (National Air and Space Museum). Additionally, the project members were given a tour of the Goddard Space Flight Center and visited the Center for Earth and Planetary Studies at the National Air and Space Museum (Host: *Jim Zimbelman*), NASA Headquarters (Hosts: *Phillip Sakimoto, Joe Boyce, Julius Dasch*), the National Museum of Natural History (Host: *Ed Venzke*), and the mission control center for the then-active Near Earth Asteroid Rendezvous mission at the Applied Physics Laboratory (Host: *Noam Izenberg*). On each trip we learned about the site's activities/facilities and interacted with several of the resident scientists and engineers.

In the third phase of the project the teams completed their research efforts and finalized their research papers. In addition, the project members invited the community of scientists at Goddard's Geodynamics Branch to a series of talks in which the students presented their results. Finally, each team designed and constructed a poster detailing the results of its research. These posters have subsequently been displayed at the students' home institutions, and all five teams are presenting their research results at this year's 32nd Lunar and Planetary Science Conference in Houston, Texas [*Moller et al.*, 2001; *Silver et al.*, 2001; *Therkelsen et al.*, 2001; *van der Kolk et al.*, 2001; *Yoburn et al.*, 2001]. I am especially proud to report that the final phase of activity was representative of the Mars 2000 project spirit as a whole—all members of the group worked together during this intensive period to ensure that each project was concluded on time in a polished, professional manner.

## STUDENT PROJECTS

In order to learn as much as possible about the geology and history of the targeted area (2-21°N, 170-184°E) within the time available, the project members worked together to identify the key geological features and processes in need of detailed study. Prioritized on the basis of geological significance and student interest, each of the most important five processes was then examined by one of the student teams.

### I. Orcus Patera: Origin of an Enigmatic Depression

***Krystal Tribbett*** (Vassar College) and ***Dolores van der Kolk*** (California State University Fullerton) spent their summer studying Orcus Patera, a large (~350 km by 100 km), elliptical depression of uncertain origin and age located several hundred kilometers north of the global dichotomy boundary, a topographic feature which separates the northern lowland plains from the heavily cratered southern highlands on Mars. Based upon examination of Viking images, proposed explanations for the formation of Orcus Patera include (1) volcanism [*Greeley et al.*, 1978], (2) compressional strain of a single large, circular impact crater [*Jons*, 1984] and (3) erosion of a suite of smaller, closely spaced and co-aligned impact craters [*Trego*, 1985]. Krystal and Dolores explored whether the new MOLA data could be used to discriminate between these competing hypotheses. After mapping the topography of Orcus Patera in detail they used several key geometric parameters (e.g. flank slopes, plan view ellipticity) to compare Orcus Patera with a number of large, elliptical impact craters and volcanic calderas on Earth, Mars and the Moon. The principal result of their study is that careful analysis using the MOLA data provides significant new insight into the detailed morphology of Orcus Patera, but still does not permit confident discrimination between the impact and volcanic origin hypotheses as Orcus Patera exhibits key characteristics of both. A second and equally exciting result is that, regardless of how Orcus Patera first formed, it is clear that younger volcanic deposits have buried the original cavity floor, and as part of their study Krystal and Dolores identified a 150-m-high, S-shaped ridge system—similar in appearance to spatter ridges seen in Hawaii—which runs more than 300 km along the length of the depression.

## II & III. MARTE VALLIS: FLUVIAL ORIGIN AND CHANNELIZED LAVA FLOW

Two teams examined different aspects of the intriguing Marte Vallis channel system. Unlike the large, prominent channel systems which cut the southern highlands, the topography of Marte Vallis is quite subtle and thus this intriguing feature within the northern lowland plains has been difficult to study in the past. While intriguing from a fluvial perspective alone, Marte Vallis has also attracted a great deal of attention recently because lava flows which occupy portions of the channel system have been identified as some of the youngest (~10 Ma) volcanic materials on the planet [*Hartmann and Berman*, 2000]. These lava flows are interwoven with episodes of sediment deposition, demonstrating that fluvial and volcanic processes alternated repeatedly during the active life of the channels.

***Kate Poulter*** (Colorado College) and ***Sven Moller*** (Pomona College) investigated the origin and evolution of the Marte Vallis fluvial channel system. Similar channel systems elsewhere on Mars are thought to have formed during catastrophic floods [*Baker and Milton*, 1974] or as the result of multiple, lower energy fluvial events [*Williams et al.*, 2000]. Employing along- and cross-channel MOLA profiles, MOC images and regional geological mapping, Kate and Sven identified massive streamlined bedforms, anastomosing channels, fine-scale terracing along the edges of many channels, evidence of ponding, and an increase in the channel system's cross-sectional area downstream. The principal finding of their study is that the Marte Vallis channel system, though carved initially by catastrophic flooding, also served to channel water during lower energy fluvial events later in its history.

***Sara Santiago*** (Arizona State University) and ***Jes Therkelsen*** (Amherst College) explored the physical conditions which characterized emplacement of a single spectacular lava flow occupying one of the fluvial channels in Marte Vallis. Using MOLA profiles, a MOC image showing the flow's terminus, and a numerical channelized flow model [e.g. *Gregg and Sakimoto*, 1998] Sara and Jes deciphered the morphology and topography of the flow in order to assess lava flow rate and volume as well as the duration of the final phase of the eruption. The principal finding of their analysis is that the lava flow shares many characteristics of long basaltic flows on Earth, traveling at velocities of less than 1 m/s along minimal slopes with flow rates of roughly $10^5$ $m^3/s$.

## IV. TECTONIC DEFORMATION: MECHANICS OF WRINKLE RIDGE FORMATION

***Andrew Gendaszek*** (Carleton College) and ***Matthew Silver*** (Whitman College) characterized the geometry of prominent tectonic wrinkle ridges within the plains north of Orcus Patera in order to assess the validity of several different mechanical models for wrinkle ridge formation [e.g. *Golombeck et al.*, 1991; *Watters*, 1991; *Schultz*, 2000]. Using Viking images and multiple cross-sectional MOLA profiles Andy and Matt measured wrinkle ridge height, width and orientation and assessed the difference in the elevation of the background plains units on either side of each ridge. These data provide a quantitative basis for exploring whether the wrinkle ridges originated due to folding or faulting and whether the deformation is thin- or thick-skinned. The principal findings of their analysis are that (1) wrinkle ridges in the study area are most likely produced during thick-skinned (deeply rooted) faulting, and (2) the width of wrinkle ridges measured using MOLA profiles is much greater than what can be inferred from images alone, suggesting that the deformation affects a broader area than was realized previously and that future attempts to investigate wrinkle ridge formation in other areas should make detailed use of MOLA-derived topographic constraints.

## V. Stratigraphy: Relative and Absolute Dating

***Jesse Yoburn*** (Franklin & Marshall College) and ***Roderick Yazzie*** (Crownpoint Institute of Technology) assessed the timing of the major geological events which shaped the study area, providing a solid temporal framework within which to place and integrate the project's research results. Using Viking and MOC images Jesse and Rod defined (and refined) regional-scale map units, then used standard crosscutting and superposition relationships to assess the relative stratigraphic history for the area. In addition, following techniques developed by other authors [e.g. *Neukum and Wise*, 1976; *Hartmann*, 1999], they used the size-frequency distribution of impact craters within each unit to constrain its absolute age. Their principal findings are that (1) stratigraphic and absolute dating sequences for the region are self-consistent, and (2) the regional-scale units in the study area range from approximately 0.8-3.9 Ga, with the plains-forming and channel units younger than both Orcus Patera and a suite of knobby material interpreted as remnants of the nearby southern highlands.

# LANDING SITE SELECTION

NASA is currently in the process of selecting landing sites for the two rovers it intends to send to the equatorial region of Mars, a mission currently scheduled for launch in 2003. During this process a complex combination of requirements is used iteratively to narrow down which portions of the planet meet the mission's engineering and scientific constraints. At the time of the Mars 2000 project, as the criteria for the 2003 mission had not been announced, the project employed the landing site selection criteria used for the cancelled Mars 2001 lander mission – and we *almost* guessed right. Shortly before the first official landing site selection meeting, which was held at NASA's Ames Research Center in the early Spring of 2001, NASA announced that the northernmost latitude consistent with the mission's engineering parameters would be 5°N, which unfortunately eliminated our ability to propose Marte Vallis—a site with very young, stratigraphically intermixed fluvial and volcanic events—as a candidate landing site. NASA is exploring plans for additional rover missions, however, and it is my hope that the work performed by the project members, and the geological significance of the Marte Vallis region, will combine with the engineering constraints for future missions more favorably!

# ACKNOWLEDGMENTS

The faculty and students on the Mars 2000 project would like to begin by thanking the Keck Foundation, the National Science Foundation and the MOLA Science Team for providing the financial support which made this research possible; it is our hope that the results from this project justify the faith these institutions have in the Keck Geology Consortium's ability to involve undergraduate students in significant, exciting, cutting-edge geological research. We would next like to offer our sincere appreciation to our gracious hosts in the Geodynamics Branch at the Goddard Space Flight Center, and we extend special thanks to Herb Frey, Jim Garvin, Jim Roark, Greg Neumann and Martin Wong for their generosity, their patience, and for sharing their expertise; it was tremendous fun having you all as colleagues during the five weeks we were in Greenbelt, and it is in no small part thanks to your efforts that this project was so successful. Finally, in addition to again thanking all of our visiting speakers, we wish to thank those individuals who arranged and hosted our project visits to NASA Headquarters, the Smithsonian Institution's National Air and Space Museum, the Smithsonian Institution's National Museum of Natural History, and the NEAR mission operations center at the Johns Hopkins Applied Physics Laboratory.

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