AEOLIAN PROCESSES ON MARS: ATMOSPHERIC MODELING AND GIS ANALYSIS

Thesis by

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"…Combining this evidence with that we already possess of the presence of water in its liquid, vaporous, and solid states, upon the surface, and with the certainty that the red tint of parts of the planet is due to a real ruddiness of substance (corresponding to the tint of certain soils upon our own earth), we cannot but recognise the extreme probability that in all essential habitudes the planet Mars resembles our own earth."

— Richard A. Proctor, *The Orbs Around Us,* 1872.

"But it does not seem too much to hope that some day (haply not so far distant) that the lesson taught us by Professor Smyth's Teneriffe experiment will be appreciated as it deserves. Then a telescope surpassing in power any yet constructed shall be placed where alone the power of such an instrument can be efficiently exerted – where Newton long since told men that such an instrument should be placed – far above the denser atmospheric strata whose disturbances never cease, and are magnified and aggravated by every increase of telescopic power. When this is done, we may look in Mars for that which has long been sought for fruitlessly upon the lunar surface – the signs of life, of change, of progress, of decay."

— Richard A. Proctor, *Essays on Astronomy,* 1872

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ABSTRACT

Wind is currently the dominant geological agent acting on the surface of Mars. A study of Martian aeolian activity leads to an understanding of the forces that have sculpted the planet's face over the past billion years or more and to the potential discovery of climate shifts recorded in surface wind features that reflect ancient wind patterns. This work takes advantage of newly available tools and data to reconstruct the sedimentary history reflected in aeolian features on Mars. The thesis is divided into two main projects. In the first section, a widely accepted hypothesis, that oscillations in Martian orbital parameters influence atmospheric circulation patterns, is challenged. A Mars global circulation model is run at different obliquity, eccentricity, and perihelion states and the predicted surface wind orientations are correlated with observed aeolian features on the Martian surface. The model indicates that orbital parameters have little effect on wind patterns, suggesting that aeolian features not aligned with the current wind regime must have formed under atmospheric conditions unrelated to orbital parameters. In the second project, new spacecraft data and a mesoscale model are used to determine the sedimentary history of Proctor Crater, a 150 km diameter crater in the southern highlands of Mars. Using high-resolution imagery, topography, composition, and thermal information, a GIS was constructed to study the aeolian history of the crater, which was found to have a complex interaction of deposition and erosion. Surficial features include 450 m of sediments filling the crater basin, small bright bedforms, dust devil tracks, and a dark dunefield consisting of coarse, basaltic sand and containing slipfaces indicative of a multidirectional, convergent wind regime. All wind features, both ancient and contemporary, are coaligned, indicating that formative wind directions have changed little since the first aeolian features formed in this area. Mesoscale model runs over Proctor Crater indicate that two dune slipfaces are created by winter afternoon geostrophic westerlies and summer evening katabatic easterlies, and

that dust devil tracks are created by summer noontime rotational westerlies. Using all available tools, this thesis begins the work of understanding how aeolian processes have influenced the Martian surface.

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NOMENCLATURE

GCM – General Circulation Model

GFDL – Geophysical Fluid Dynamics Laboratory

GIS – Geographical Information System

L_s – Solar Longitude of Mars' orbit around the sun, a measure of season (0º – 360º, where 0º = northern spring equinox/southern fall equinox, 90º = northern summer solstice/southern winter solstice, 180º = northern fall equinox/southern spring equinox, and 270º = northern winter solstice/southern summer solstice)

MGS – Mars Global Surveyor

MM5 – Mesoscale Model 5

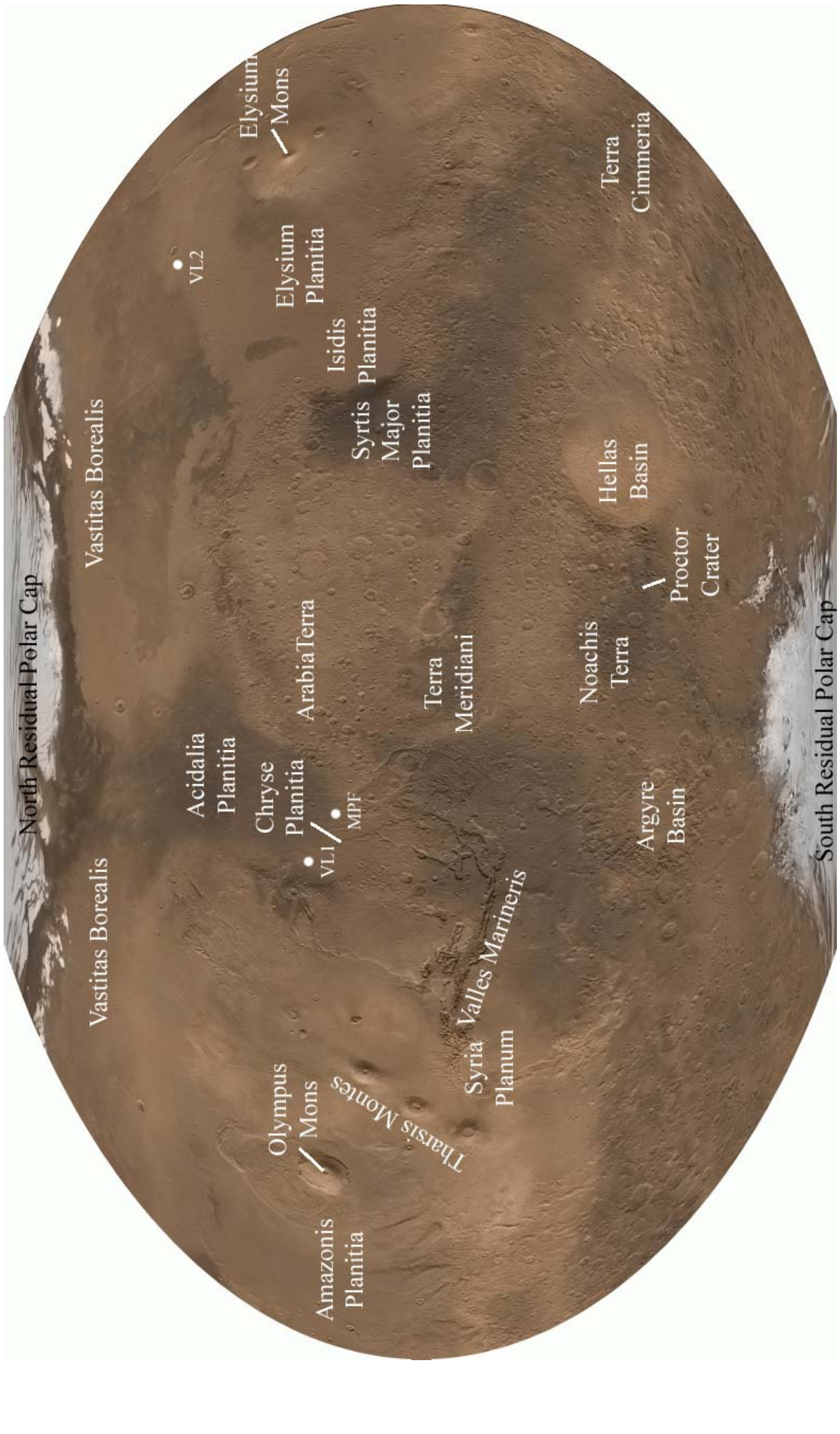
MOC – Mars Orbiter Camera

MOLA – Mars Orbiter Laser Altimeter

MPF – Mars Pathfinder

TES – Thermal Emission Spectrometer

VL 2 – Viking Lander 2


North Residual Polar Cap
Vastitas Borealis
Vastitas Borealis
VL2
Elysium Mons
Elysium Planitia
Isidis Planitia
Syrtis Major Planitia
Terra Cimmeria
Hellas Basin
Proctor Crater
Arabia Terra
Terra Meridiani
Noachis Terra
Acidalia Planitia
Chryse Planitia
VL1
MPF
Argyre Basin
South Residual Polar Cap
Valles Marineris
Syria Planum
Tharsis Montes
Olympus Mons
Amazonis Planitia

Chapter 1

INTRODUCTION AND OVERVIEW

Wind is currently the dominant geological agent acting on the surface of Mars. The general lack of contemporary aqueous, volcanic, and tectonic features suggests that aeolian (*i.e.,* wind) processes have prevailed on the Martian surface for a geologically significant period of time. Thus a study of aeolian activity leads to a better understanding of the forces that have sculpted the face of Mars over the past billion years or more. Furthermore, such a study has the potential for the discovery of climate shifts recorded in aeolian features that reflect ancient wind patterns. The instruments on the Mars Global Surveyor (MGS) spacecraft have provided data on the Martian surface with unprecedented detail, revealing wind-related features such as tracks eroded by dust devils as they travel downwind, small bright bedforms indicative of persistent strong winds, and sand dunes where previous spacecraft imagery indicated only dark "splotches." MGS images have also shown layered sediments with complex stratigraphic relationships, indicative of several episodes of successive erosion, deposition, and inactivity, all of which may well have been produced by aeolian activity [*e.g., Malin and Edgett,* 2000a]. In addition, mesoscale models of the Martian atmosphere with horizontal resolutions down to tens of meters are now available and can be used to study small-scale interactions between the surface and atmosphere. Given the acquisition of new data and the advent of these new tools, there has been no better time to investigate Mars' ubiquitous aeolian features to develop an understanding of how and when they formed, and how they are influenced by and subsequently reflect changes in climate.

I chose this work for its obvious potential implications on recent climate change on Mars, as well as for the excitement of studying a currently active process on a body that has so often been termed "dead." There are a number of advantages in taking on such a thesis topic at this time. One such benefit is that with the new high-resolution spacecraft data and mesoscale models, the study of Mars has shifted from an astronomical to a geological perspective. That is, in the past, typical studies encompassed a large part or all of the Martian surface, with conclusions indicating regional or global trends in cratering, dust mantling, ice cover, and the like. The new data and models allow for detailed studies of small areas which produce an understanding of local histories and conditions. These small-scale studies must ultimately be tied in with the regional and global-scale studies, but they add a refinement and precision that the larger-scale studies cannot provide. Both scales of studies are necessary for a complete understanding of the Martian history, and for the first time both types of study are possible.

Another advantage may be gained from using the new data and models. The availability of high-resolution imagery, topography, thermal, and compositional data as well as high spatial- and temporal-resolution atmospheric model output may be used in concert, each data set adding its own unique "piece of the puzzle" to the geological and climatic interpretation. The careful combination of geologic data with atmospheric data is particularly important for aeolian studies because they depend on one another. In the past, most work utilized only atmospheric or geological data to study aeolian features on Mars, occasionally leading to errors such as mislabeling aeolian features (which then propagates through the scientific community) or inaccurate estimation of sand and dust transport parameters. However, such interdisciplinary research on aeolian processes from both a geological and an atmospheric perspective is necessary for understanding how the surface and atmosphere interact with one another. It is vital from a geological perspective in that it is the only way to thoroughly study the most active surface process on Mars today, and it is vital from an atmospheric perspective in that surface features provide the only "ground truth" for verification of modeled wind circulation patterns and stresses. For the first time, data and models are available to allow such investigations to proceed, and this thesis work takes full advantage of this technique.

This thesis consists of three chapters, each of which discusses a self-contained research project. The thesis topic was chosen after an extensive research of existing literature on terrestrial and Martian aeolian geomorphology and sedimentology, as well as remote sensing techniques. Originally I had begun work on a sand transport model, which used modeled wind stresses and velocities to determine where the global sand sinks and sources are currently located, but too little is known about the distribution of mobile sand and surface roughness on the Martian surface, and so I decided that it was unlikely that the transport model would produce realistic results. The completed work and motivation for each chapter is described briefly below. Chapter 2 was supported in part by a PG&G grant (NRA 98–OSS–03); Chapter 2 was supported in part and Chapter 3 was supported in full by an MDAP grant (NRA 00–OSS–01 MDAP).

Chapter 2. The obliquity, orbital eccentricity, and argument of perihelion of Mars oscillate significantly over long time periods, with unknown consequences on the planet's climate. Some surface features, such as dunes and bright streaks, match well with the currently predicted wind patterns, and other types of aeolian features, such as yardangs, dark streaks, and ventifacts, do not. As a result, it has long been hypothesized that the astronomical variations change wind circulation patterns, and thus creating aeolian features that do not match present-day wind patterns. To test this hypothesis, my coauthor and I ran the GFDL Mars general circulation model (GCM) at different obliquity, eccentricity, and argument of perihelion states. Using a higher time resolution than has been applied before, we established that dark streaks are contemporary features produced by a wind that in previous studies had been washed out due to poor time resolution. More importantly, we also showed that orbital parameters have little effect on wind circulation patterns, concluding that the aeolian features that do not align with current winds must have been produced under very different conditions unrelated to varying orbital parameters.

Chapter 3. Before the Mars Global Surveyor mission, Martian sand dunes were considered mysterious features. They were known to exist in a sand sea ringing the north polar cap, and as small accumulations in the floors of several craters in the southern highlands. It was not known whether or not they were active. Furthermore, only dunes with a morphology indicative of unidirectional winds appeared to be present in abundance, and it was not clear why this would be the case when on the Earth dunes indicating bimodal and multimodal wind regimes also occur. The introduction of MGS data changed this view drastically, showing that these dark dunes are much more prevalent than previously thought, and that much smaller bright bedforms are visible in high-resolution images where before such features were only hinted at. Noting both a lack of a detailed study of aeolian features in any particular region of Mars, as well as the abundance of new data, I decided to conduct such a study. I built a geographical information system (GIS) for Proctor Crater, a 150 km diameter crater in the southern highlands containing a large dark dunefield. Proctor Crater was the first place where dunes were discovered on Mars during the Mariner 9 mission in 1971–72, and as such it has become the type location for studies on dune morphology, thermal inertia, and composition. Using GIS analysis, I found that the sedimentary history of Proctor Crater has involved a complex interaction of deposition and erosion, much of which is likely to be aeolian in origin. The crater has accumulated as much as 450 m of sediments, the top layer of which now comprises the present-day crater floor. Small bright bedforms, dust devil tracks, and sand drifts abound, indicating that aeolian processes dominate as expected. Close inspection of dunes indicates that the dunefield is located in a multidirectional wind regime, consisting of reversing transverse and star dunes, contrary to what was expected in pre-MGS days. The dark dunes are composed of coarse, basaltic sand that is probably volcaniclastic in origin, and which was blown into the crater from the southwest (locating the provenance of the sand requires a broader regional study). The dunes are undoubtedly active, but because they are located in a convergent wind regime they have little (if any) net transport (thus the lack of dune movement does not necessarily indicate that they are inactive). All observed aeolian features, from the potentially ancient bright duneforms, to the nearly erased remnant of a sand transport pathway into the crater, to the long-lived dunes themselves, and to the annually created and erased dust devil tracks, indicate an unchanging wind pattern, consistent with the model predictions from Chapter 2. A detailed study such as this greatly changes the way dunes and other aeolian features on Mars are regarded, answering many of the old pre-MGS questions but creating new ones as more and more is discovered. Further inquiries of this sort will continue to answer these questions and create a general understanding of how aeolian processes influence the Martian surface.

Chapter 4. The newly developed mesoscale atmospheric models are necessary, although largely unexplored, tools for investigating interactions between the surface and atmosphere. In the past, GCM's predicted only large-scale winds with horizontal scales on the order of hundreds of kilometers. They could not predict small-scale flow dictated by local topography, and often were run with too large a timestep to predict shifts in daily winds (as shown in Chapter 2). Thus the newly developed mesoscale atmospheric models are necessary, although still largely unexplored, tools for investigating interactions between the surface and atmosphere. My coauthors and I applied the Mars Mesoscale Model 5 (MM5) to the atmosphere over Proctor Crater, the same area studied in Chapter 3. In some sense the model output may be regarded as yet another data set to be included in the GIS described in Chapter 3. A Martian atmospheric model has never before been run in conjunction with a thorough geological study of a particular area. In addition, a Martian atmospheric model has never been applied with the intent of understanding the morphology of a dunefield and other nearby aeolian features. The MM5 predicted two of the three observed dune slipface orientations as well as the winds that produce dust devil tracks in the summer. The wind producing the more prevalent of the dune slipfaces (the primary winds) was the strongest of the year, blowing in the fall and winter during the early afternoon as geostrophic-enhanced westerly winds. The wind producing the least prevalent of dune slipfaces (the tertiary winds) blows in the spring and summer evening as easterly katabatic flows down the rim of Proctor Crater, influencing only the eastern portion of the dunefield. Winds producing the remaining dune slipfaces are not predicted by the model, and it may be that these winds are produced by rare storms that the model does not capture. Wind stresses are still not high enough to predict sand saltation, and the reason for this is due to a low model resolution, even though this study used a higher spatial resolution than has been applied in the past. Although there are issues with the model output, the MM5 does a superb job of explaining the forces driving dune morphology and other nearby aeolian features.

The chapters are similar in their approach and their research goals. Each chapter describes research that changes what is known about aeolian processes on Mars by varying different parameters and using higher resolution data and models than before. Chapter 2 challenges an old hypothesis that astronomical oscillations are responsible for ancient wind circulation patterns by running a GCM under those conditions and comparing the results to observed surface features. Chapter 3 uses new high-resolution imagery, topography, thermal, and compositional data to perform the first detailed and comprehensive study of the aeolian history of a region. Finally, Chapter 4 applies a mesoscale model to the study area of Chapter 3 to explain the regional wind patterns behind the observed aeolian features, supporting the aeolian history described in Chapter 3. This thesis takes the first steps towards applying modern methods and viewpoints to the study of Martian surface processes.