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Scientific/Technical/Management Section

Objectives and Significance of Proposed Research

Basic objective - Continue our investigations of tectonic ridges in the northern plains of Mars using MOLA data, theoretical models, and Viking and MOC images.

Expected significance – The proposed research will enhance our understanding of the tectonic history of Mars, the origin of the northern plains, and the possibility of an ancient northern ocean.

Reasons for proposing to this program – This proposed research is very relevant to NASA's planetary program in general and MDAP in particular. Owing to citizenship restrictions, neither NASA nor NSF graduate student fellowships are open to Withers. The requested funding in this proposal is largely to support Withers.

Task 1 – Map ridges in the northern plains, and their properties, using MOLA data. Variations in ridge properties will indicate variations in lithospheric structure or stress regime.

Task 2 – Examine photographic images of these ridges. Viking prints and MOC images may reveal fine-scale structure on these ridges, occurrences of which can be correlated with other ridge properties.

Task 3 – Study the relationship between these ridges and a population of subdued craters, visible in MOLA images of the northern plains and mapped as quasi-circular depressions, or QCDs, by Frey and colleagues, which is not seen in Viking images. This will constrain the pre-Amazonian history of the northern plains, and the degraded topography of the craters will be used to estimate the extent to which the ridges have undergone modification.

Frey's derived data products will be made available to us for this proposed research. Frey will not provide any proprietary data. See "Access to Frey's QCD dataset" section.

Task 4 – Calculate regional strain magnitudes and directions in the northern plains using the results of **Tasks 1, 2,** and **3**. This will provide a constraint on tectonic models of the northern plains.

Task 5 – Model stress and strain in the northern plains. Adjusting the model parameters to best fit the results of **Task 4** will constrain the nature of the lithospheric structure and loading in the vicinity of the northern plains.

With the exception of Frey's derived data products, **publicly available data** will be used to perform this proposed research.

Impact of Proposed Research

Figure 1 shows a Viking photomosaic of the northern part of the Utopia impact basin. Craters are visible on a mottled terrain. Figure 2 shows a digital terrain model generated from gridded MOLA data available from the Planetary Data System (PDS) (Smith *et al.* 1999). Many new features are visible, including a second, subdued, population of craters and a network of ridges. The shallow slopes of the ridges and subdued craters, and consequent lack of shadows, explain why they are not visible on photographic images. Improved global photomosaics, *e.g.* from the MOC and THEMIS instruments, they will suffer from the same handicaps in imaging these shallow features. MOLA has no such limitations.

MOLA data reveal that the northern plains of Mars are the flattest known surface in the solar system and that they are criss-crossed by ridges of likely tectonic origin (Smith *et al.*, 1998; Aharonson *et al.*, 1998; Withers and Neumann, 2000, 2001a, b; Head *et al.*, 2001a, b, c). High-resolution shaded topographic images of the polar basin, available at http://ltpwww.gsfc.nasa.gov/tharsis/mola.html, show the ridges clearly. A global digital terrain model at 1/32° resolution was made publicly available via the PDS in March 2001. This, and any digital terrain models of improved resolution made available during the duration of this proposed research, will be the primary dataset used.

The causes of the youth and smoothness of the northern plains are still debated (Smith *et al.*, 1998, and references therein; Zuber *et al.*, 2000). The network of ridges is the dominant, indeed the only, tectonic feature throughout this enigmatic region, which covers a quarter of the planet. The most complete survey of martian ridges to date, which mapped over 16,000 ridges, commented that “as is well known, the northern plains have few ridges” and was not able to identify the network of ridges revealed by MOLA (Chicarro *et al.*, 1985).

Wrinkle ridges, a subset of ridges, are one of the most commonly observed, yet least understood, classes of planetary structure (*e.g.* Schultz, 2000; Watters, 1992). They occur on all the terrestrial planets, including Mercury (*e.g.* Strom *et al.*, 1975), Venus (*e.g.* Kreslavsky and Basilevsky, 1998; Bilotti and Suppe, 1999), Earth (*e.g.* Plescia and Golombek, 1986; Watters, 1988), the Moon (*e.g.* Lucchitta, 1976, 1977; Sharpton and Head, 1988), and Mars (*e.g.* Plescia, 1991, 1993; Watters and Robinson, 1997). Observations of martian wrinkle ridges have been used to constrain the planetary thermal history (*e.g.* Banerdt *et al.*, 1992), tectonic history (*e.g.* Tanaka et al., 1991; Schultz and Tanaka, 1994), volcanic history (*e.g.* Watters, 1993), impact history (*e.g.* Wilhelms and Squyres, 1984; Chicarro *et al.*, 1985), lithospheric structure (*e.g.* Zuber and Aist, 1990), and changes in orbital and rotational dynamics (*e.g.* Melosh, 1989; Grimm and Solomon, 1986; Schultz and Lutz, 1988).

This research proposal will map and measure this network of ridges, then use that information to constrain martian tectonic models and the history of the northern plains. A preliminary test of the ancient ocean hypothesis has been published and further tests of shoreline candidates are a natural part of **Tasks 1** and **2** (Withers and Neumann, 2001a).

Preliminary Results

In earlier work, we began to investigate the distribution and nature of these ridges and published a test of the ancient northern ocean hypothesis (Withers and Neumann, 2000, 2001a, b).

Task 1 – Ridge locations have been mapped and we have begun to measure ridge properties. Figure 3 shows ridges that we have mapped in the northern plains (black) and also wrinkle ridges mapped globally by Watters (1993) using Viking images (white). The ridges have characteristic wrinkle ridge profiles, characteristic lengths of 100s of kilometers, characteristic heights of 100 metres, and characteristic flank slopes on the order of only 1 degree. Ridge spacings vary throughout the northern plains, but are on the order of 100 km.

Task 2 – Guided by Figure 2, several ridges can be seen in Figure 1. We have verified that high-quality prints of Viking images of the ridges, available at the University of Arizona's Regional Planetary Image Facility, show detail beyond that seen in the more common representations of Viking images, such as the USGS MDIM-2 available online, and have begun to study these.

Task 3 – We have not found any examples of ridges clearly cutting fresh or stealth craters, suggesting that the ridges may predate both populations of craters. However, we have not yet examined other types of ridge-crater interaction, such as those discussed by Sharption and Head (1988). Stealth craters, using the terminology adopted by Head and Kreslavsky, are subdued craters that are easily visible in the MOLA data. They are a subset of Frey's QCDs.

Task 4 – Regional strain *directions* are readily apparent from Figure 3. Regional strain *magnitudes* are harder to estimate. Using the techniques of Golombek *et al.* (1991) we estimate a regional strain on Lunae Planum, in the southern highlands, of a few x 10^{-3}, consistent with Golombek *et al.* (2001), and about half that in nearby Chryse Planitia, in the northern plains. This surprisingly large decrease over a distance short by comparison with the scale of Tharsis, the source of the stress, is discussed in the Technical Approach and Methodology section.

Task 5 – Figure 4 shows a prediction of compressive strain in the martian lithosphere, performed by Banerdt. Also shown are ridges that we have mapped in the northern plains (white) and wrinkle ridges mapped globally by Watters (1993) using Viking images (red). Many of the ridges are orthogonal to the predicted direction of maximum compressive strain, as expected for wrinkle ridges underlain by thrust faulting. An obvious exception is the family of radial ridges within the Utopia impact basin. These do not have the elevation offsets characteristic of wrinkle ridges underlain by thrust faulting and may instead be shallow compressional features related to the infilling of Utopia (Turtle, personal communication, 2001).

Technical Approach and Methodology

Task 1 – Ridges will be mapped and their morphology studied using gridded MOLA topographic data publicly available from the PDS. Maps of absolute surface slope will be generated. Ridges will stand out as linear regions of greater than background slope and be easily identifiable. Then, in the topographic data, these linear regions will be illuminated across-strike and can be confirmed as ridges, rather than troughs or other features. Then, topographic profiles will be constructed across the ridges using gridded MOLA topographic data, and the height, width, flank slopes, elevation offset, and asymmetry of each ridge will be measured. Using gridded data to construct profiles eliminates the directional bias that would occur from using individual north-south MOLA profiles to study these ridges.

These results will be used to see if there are any distinct classes of ridges within the northern plains, or if all are morphologically similar. Wrinkle ridges, a compressional tectonic landform, are a subset of ridges. Ridges are classified as wrinkle ridges on the basis of their morphology (Watters, 1988, 1993; Schultz, 2000). Distinguishing between tectonic and non-tectonic ridges is clearly important (see Preliminary Results for **Task 5**). Ridge properties will be compared to those of previously studied wrinkle ridge provinces on Mars and elsewhere in the Solar System.

The presence, or absence, of elevation offsets across wrinkle ridges will let us infer the presence, or absence, of underlying thrust faults and study the depth penetration of these faults. Ridge spacings are greater than those found on the neighbouring known wrinkle ridge provinces (Montesi and Zuber, 2000, 2001; Zuber and Aist, 1990, and references therein). Montesi and Zuber use this observation to calculate crustal thickness in the northern plains.

Task 2 – Using the high-quality prints of Viking images available at the University of Arizona's Regional Planetary Image Facility and MOC images available via the PDS, we will classify ridge morphologies as seen in photographic images. Schultz (2000) summarizes some of the existing classification schemes.

The detail visible in these Viking prints is significantly greater than the detail visible in more common representations of Viking images, especially photomosaics. Due to their shallow slopes, not all the ridges are visible in even the best Viking prints, but the Viking prints will provide a nominal resolution several times better than that of the gridded MOLA data. We will examine ridges first identified in MOLA data rather than reproducing the mapping work of Chicarro *et al.* (1985) and Watters (1993). We have not identified fine-scale structure, such as the "wrinkle" of wrinkle ridges, in the km-scale resolution gridded MOLA data. Such detail might be visible in the Viking prints or the ridges might lack fine-scale structure. If the latter is true, then we can draw conclusions about the modification that the ridges have undergone since their formation.

MOC images, with typical widths of a km, typical lengths of several tens of km, and metre-scale resolution may show much finer detail than MOLA is capable of resolving.

However, image coverage is sparse and the ridges, many of which appear at least partially buried, may not stand out clearly in MOC images. Nonetheless, a careful survey is warranted.

Task 3 – In their studies of QCDs on Mars, Frey and colleagues have produced a dataset of both fresh and subdued craters (Frey *et al.* 2000, 2001a, b). Figure 5, prepared by Jim Roark, overlays these QCDs on a shaded relief map. QCDs are identified by Frey and colleagues using highly-stretched contoured MOLA data. They are not necessarily easily visible in the shaded relied representation of the data. Frey's QCD dataset will be made available to us for this proposed research. See "Access to Frey's QCD dataset" section.

We shall examine MOLA data and Viking images for evidence for crater deformation by ridges, ridges deformed or obliterated by craters, control of ridge position and orientation by craters, and other ridge-crater interactions. If a crater intersects a pre-existing ridge, then part of the ridge will be obliterated by the crater bowl and ejecta blanket. If a ridge intersects a pre-existing crater, then any component of strike-slip faulting may cause lateral offsets in the crater rim and any component of thrust faulting may distort crater circularity or cause vertical offsets in the rim or introduce lobate mounds of material into the interior of fresh craters (Sharpton and Head, 1988). Ridges which appear to have orientations controlled by craters, *e.g.* a set of ridges that are radial to a crater, indicate that the crater predates the ridges. We will distinguish between fresh craters and craters in various stages of degradation in this work. This will enable us to date the ridges relative to the various types of craters and hence place them in the martian stratigraphy.

We shall also use the morphology of the QCDs, such as the relationship between their depth-diameter ratios and those of fresh craters (Melosh, 1989; Garvin *et al.* 1998, 1999, 2000), to constrain the amount of deposition that has modified the ridges. This will be useful for **Task 4**.

Task 4 – Strain *directions* in the northern plains can be easily obtained from wrinkle ridge orientations. Using the technique of Golombek *et al*. (1991), the topography of an unmodified wrinkle ridge reveals the strain *magnitude*. However, as suggested by the preliminary results for **Task 3**, the apparent burial of the ridges in the northern plains causes this technique to underestimate the actual strain. Despite this limitation, lower limits on strain magnitude will still be a useful constraint on tectonic models. If **Task 3** suggests that deposition has been relatively uniform across the northern plains, then the ranking of measured strains is likely to approximate the ranking of actual strains. This will be a further useful constraint.

The results of this task will be used to determine the orientations of the stress field responsible for wrinkle ridge formation at the time of formation. Study of the geometry of these geological structures hence places constraints on the dynamics of the relevant lithospheric deformation mechanisms.

Forthcoming results of the research groups of J. W. Head (especially concerning the deposition of the Vastitas Borealis Formation) and R. A. Schultz (especially concerning the modification of ridges, *e.g.* Wilkins *et al.*, 2001) may improve our knowledge of the depositional history of the northern plains to the point that reasonable inferences can be made about the pre-modification state of the ridges.

Task 5 – Gravity and topography provide the basic observables from which the loading of the lithosphere can be derived. However, given the non-unique character of potential field interpretation, understanding the partitioning between surface and subsurface components of this load (and thus the structure of the crust and upper mantle) requires additional information. For example, a flexurally-supported surface load and an isostatically maintained edifice could exhibit the same topographic and gravitational signature with the right distribution of density with depth. One clue to this puzzle is the state of stress. A flexural displacement will generate a quite different stress field than an isostatic situation. Estimates of the strain magnitude and direction at the surface (from which the stress can be derived) can be used to provide constraints for computer-generated lithosphere deformation models (Banerdt *et al.*, 1982; Banerdt, 1986; Banerdt *et al.*, 1992)

For this study we will use a thin spherical shell deformation code (Banerdt, 1986; Golombek and Banerdt, 2000) to investigate lithospheric deformation on Mars, particularly around Utopia and northern Tharsis. Various lithospheric structures will be used (e.g., isostatic compensation at different depths, varying amounts of compensation, etc.) and the stresses and strains generated from the present-day topography and gravity will be compared with the strains derived from our analysis of the plains ridges. Note that several lines of evidence support the assumption that present-day topography and gravity are little changed from the early Hesperian (Banerdt and Golombek, 2000; Phillips *et al.*, 2001).

Relevance of Proposed Research

This proposed research will broaden scientific participation in the analysis of the Mars Global Surveyor mission's dataset. It will enhance the scientific return of the Mars Global Surveyor mission in the following ways:

A – Discovery and characterization of an unsuspected class of tectonic features on the northern plains, an enigmatic region of near global scale, of Mars.
B – Uses these features to constrain global scale tectonic models, with special emphasis on Tharsis.
C – Tests the ancient northern ocean hypothesis.
D – Constrains the resurfacing history of the northern plains of Mars.

Enhancement C indirectly addresses the issue of extra-terrestrial biology, an issue that thoroughly permeates NASA's plans and aims.

All these enhancements satisfy the Science Goal of the Space Science Enterprise Strategic Plan of "Understand the nature and history of our Solar System" and the two Science Objectives of "Characterize the history, current environment, and resources of Mars, especially the accessibility of water" and "Investigate the processes that underlie the diversity of solar system objects" (Office of Space Science, 1997).

The National Academy of Sciences' Committee on Lunar and Planetary Exploration (COMPLEX) has advised NASA on NASA's plans (COMPLEX, 1994). It stated a primary objective for understanding planets to be: Specify the nature and sources of stress that are responsible for the global tectonics of Mars. Enhancements A and B address this objective. It stated another primary objective to be "Advance significantly our understanding of stratigraphic relationships for all solid planets." Enhancement D addresses this objective.

COMPLEX also posed several key questions for understanding the surfaces and interiors of solid bodies.

It asked: How do global- versus local-scale processes contribute to the observed tectonics? Enhancements A and B address this question.

It asked: How did the Tharsis and Elysium bulges on Mars form, and what do they imply for the state of stress in the crust and the dynamics of the interiors of the planet? Enhancement B addresses this question.

It asked: What are the erosional and sedimentation histories of Mars? Enhancements C and D address this question.

It asked: To what extent have materials been redistributed across their surfaces? Enhancements C and D address this question.

Outline of Plan of Work

First six months

Continue	Task 1 Map ridges	Withers, Neumann
Continue	Task 2 Examine Viking and MOC images	Withers
Continue	Task 3 Study ridge-crater interactions	Withers

Present results at a scientific meeting

Second six months

End	Task 1 Map ridges	Withers, Neumann
End	Task 2 Examine Viking and MOC images	Withers
Continue	Task 3 Study ridge-crater interactions	Withers

Present results at a scientific meeting
Submit paper covering results of Tasks 1 and 2 and latest results from Task 3

Third six months

Continue	Task 3 Study ridge-crater interactions	Withers
Continue	Task 4 Estimate regional strains	Withers, Neumann
Continue	Task 5 Theoretically model tectonics	Banerdt

Present results at a scientific meeting
Submit paper covering latest results from Tasks 3, 4, and 5

Fourth and final six months

End	Task 3 Study ridge-crater interactions	Withers
End	Task 4 Estimate regional strains	Withers, Neumann
End	Task 5 Theoretically model tectonics	Banerdt

Present results at a scientific meeting
Submit paper on final results from this research proposal

Expected Contributions

Melosh (Principal Investigator)

Professor Melosh has studied planetary tectonics for many years. He is an expert on the modelling of tectonic problems and all aspects of impact cratering (Melosh and Raefsky, 1980, 1981; Melosh and Williams, 1989; Melosh, 1989).

- Responsible for quality and direction of research, and for use of awarded funds
- Supervisory role for Withers

Withers (Co-Investigator and Science PI)

Mr. Withers, a PhD candidate, initiated this project during a summer research placement at NASA's Goddard Space Flight Center. He has presented initial results at several conferences and in the peer-reviewed literature (Withers and Neumann, 2000, 2001a, b).

- Lead role in proposal preparation
- Responsible for day-to-day progress in most Tasks

Banerdt (Collaborator)

Dr. Banerdt, a member of the MOLA Science Team, wrote the standard reference on martian tectonics (Banerdt *et al.*, 1992). He uses theoretical tectonic models to constrain lithospheric structure and loading on the terrestrial planets (Banerdt *et al.*, 1982; Banerdt, 1986; Banerdt *et al.*, 1992).

- Use theoretical models to predict stress and strain for Task 5

Neumann (Collaborator)

Dr. Neumann, a member of the MOLA Science Team, leads the processing of raw MOLA data into a scientifically useful product. He supervised the summer research placement of Withers and is intimately familiar with the MOLA data.

- Continue to guide Withers through the use of large gridded data sets
- Assist in automating the measurement of ridge properties for Tasks 1 and 4

Figure 1 - Viking Photomosaic

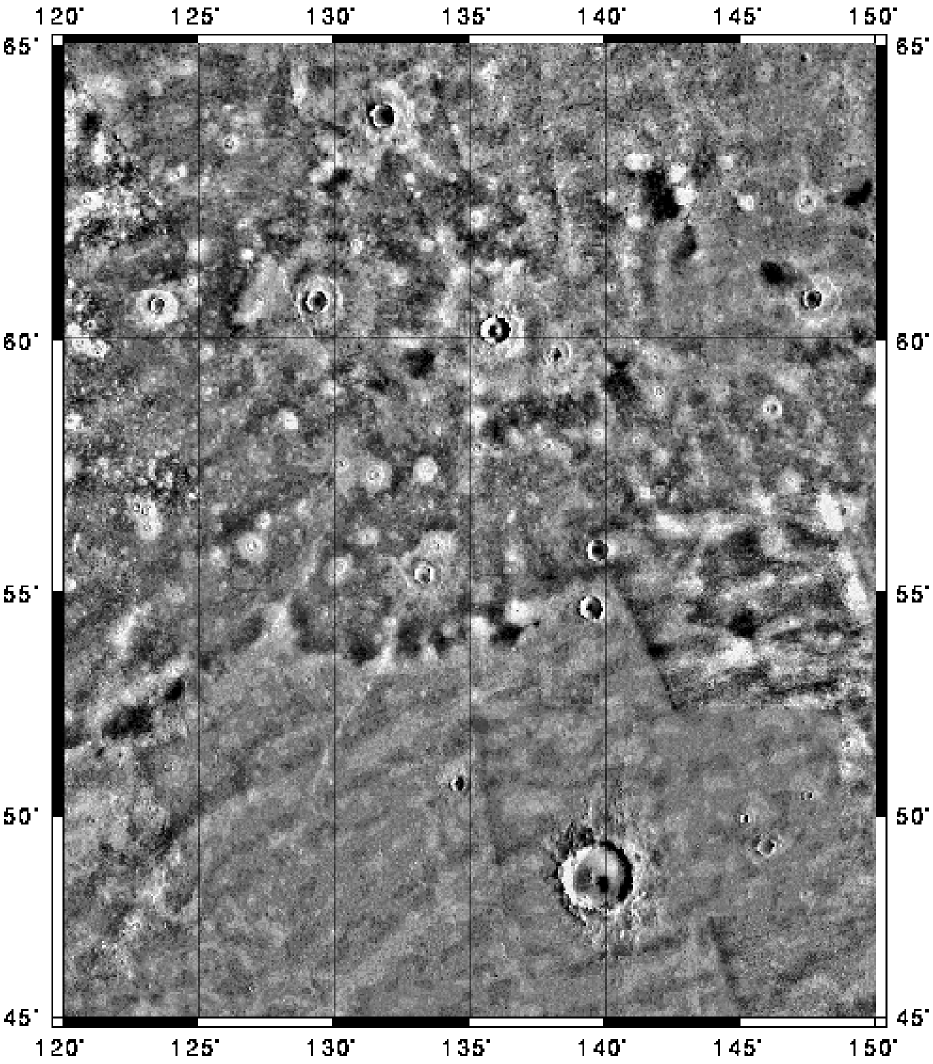


Figure 2 - MOLA Data

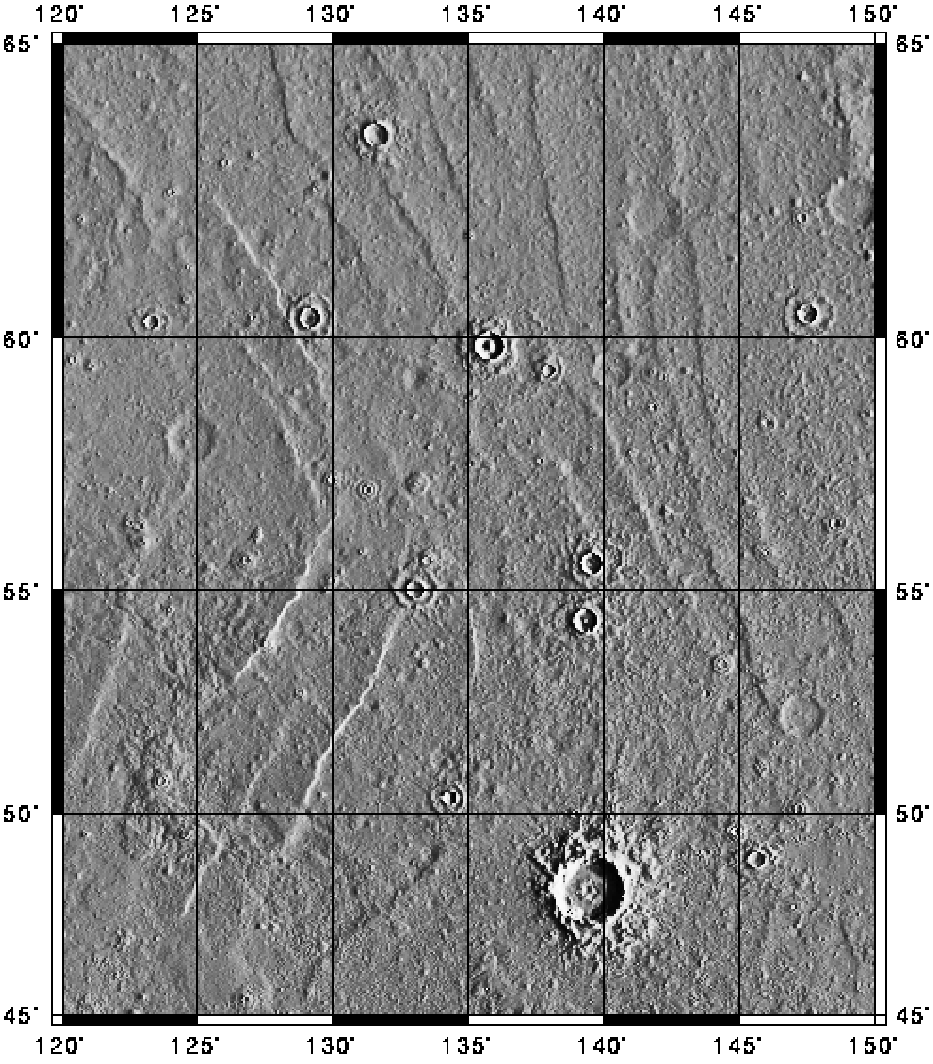


Figure 3 - Ridge Locations

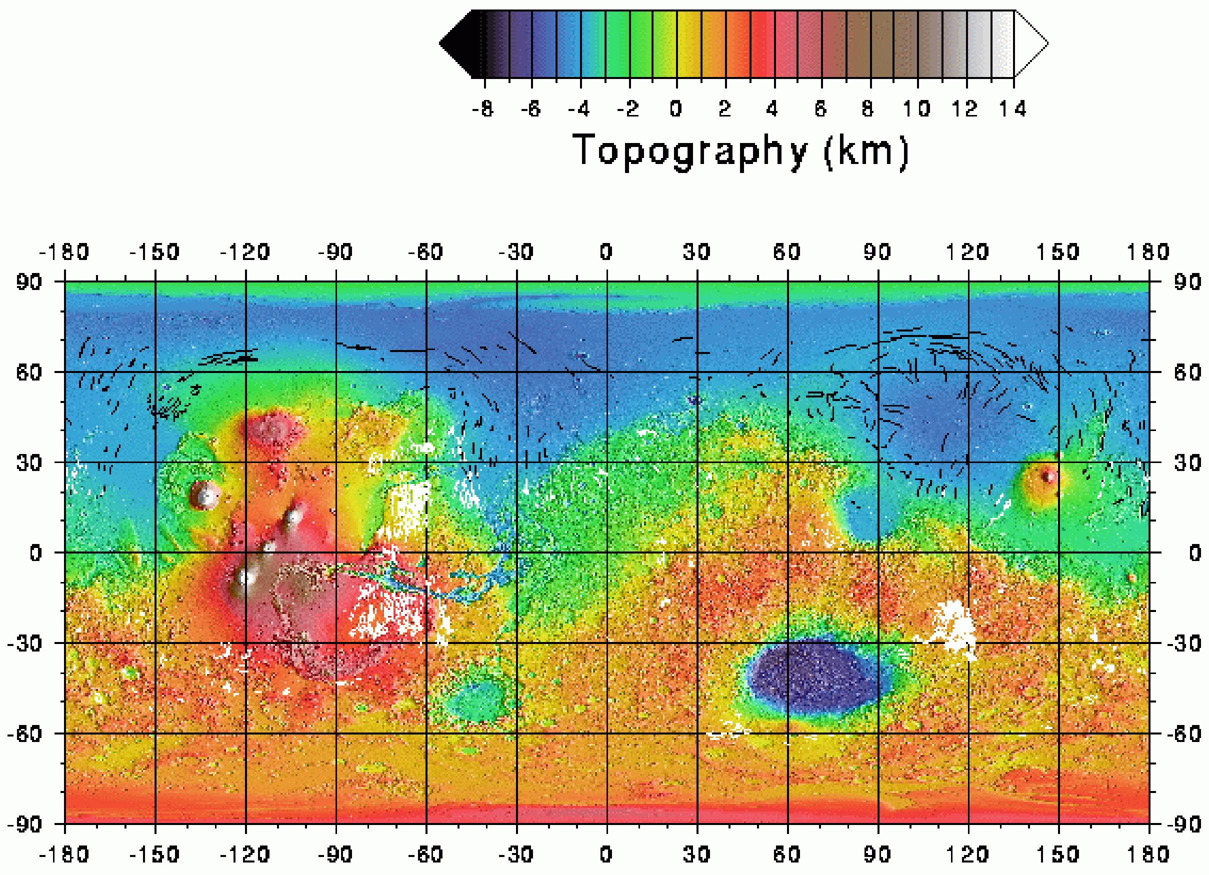
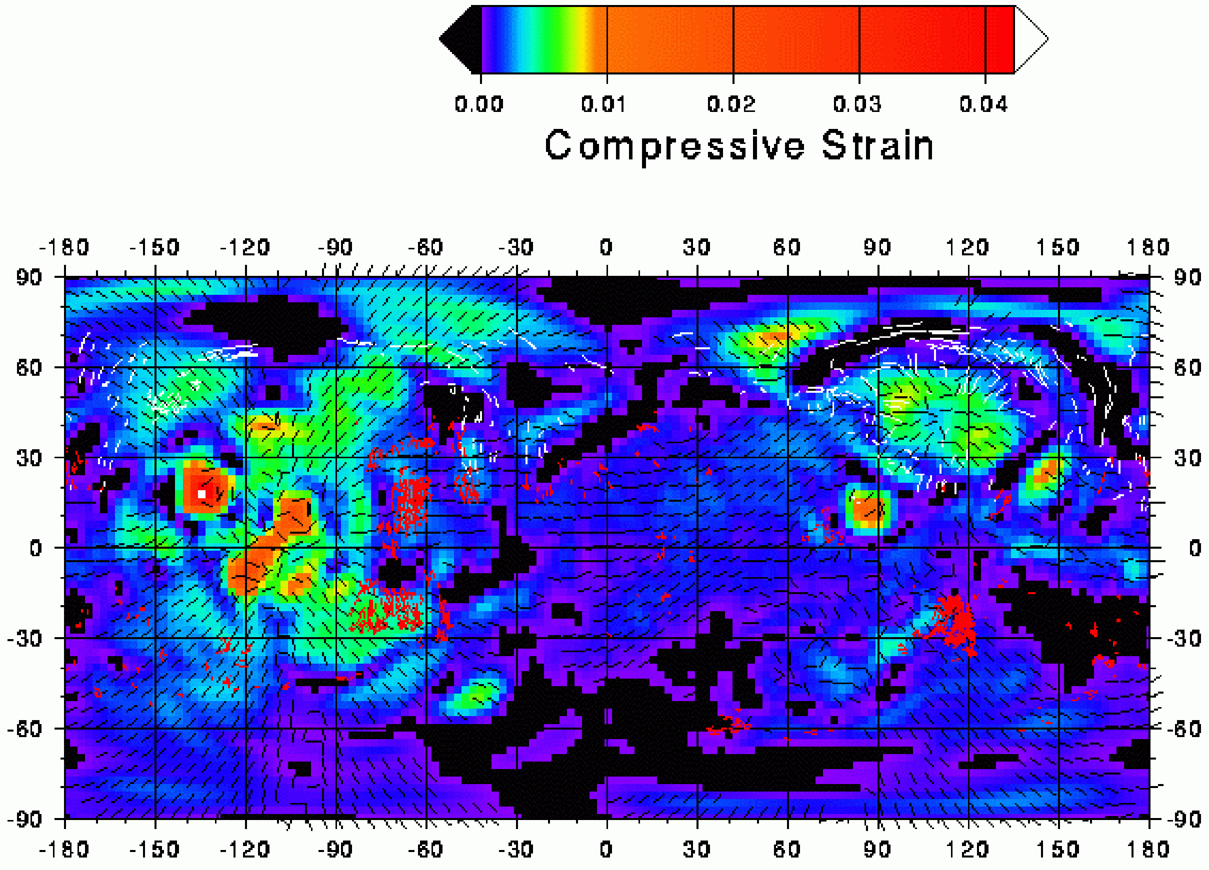


Figure 4 - Tectonic Model



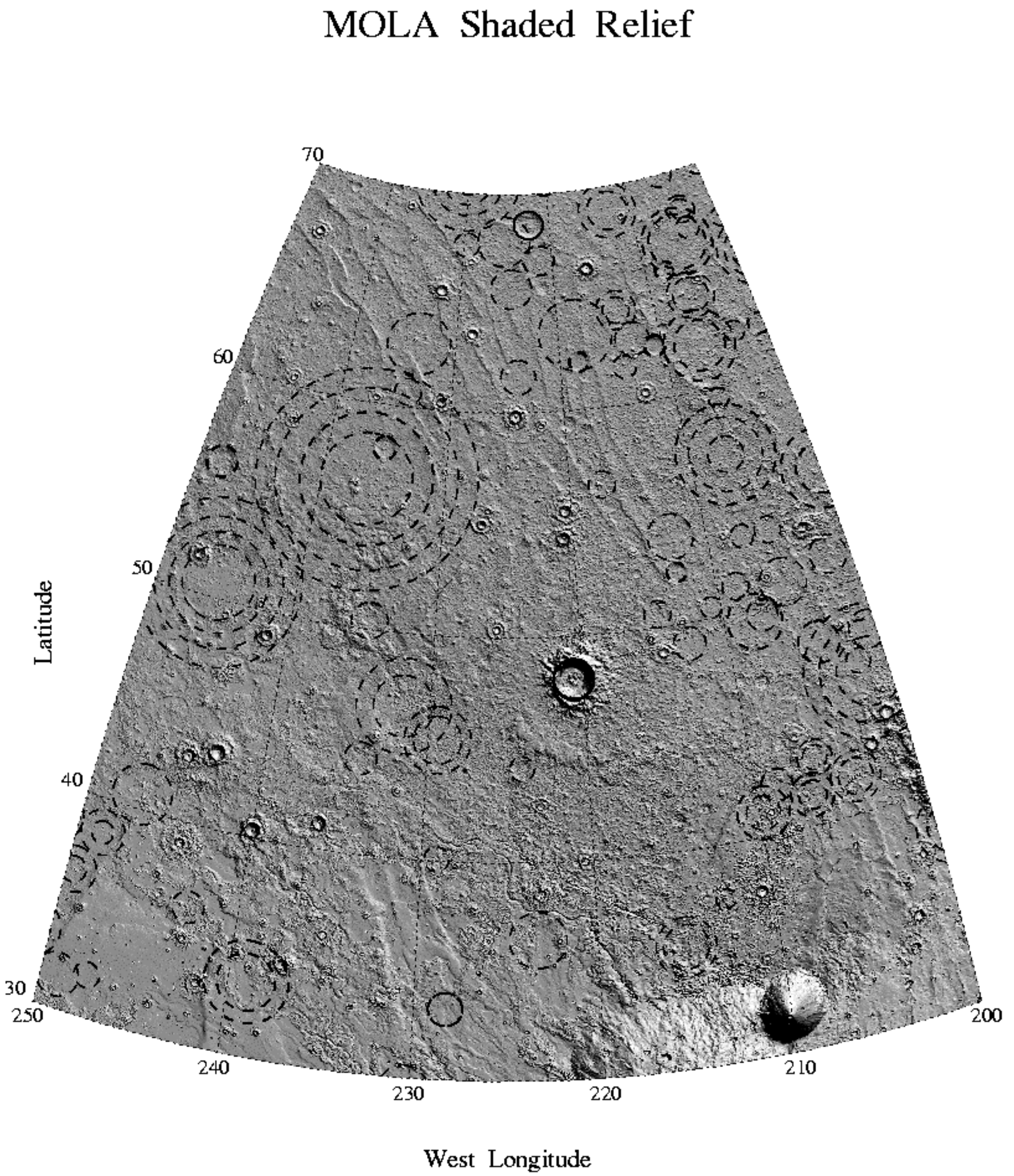


Figure 5 – QCDs overlain on a shaded relief map
Figure prepared by Jim Roark

Access to Frey’s QCD dataset

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Date: Thu, 09 Aug 2001 09:03:24 -0100
To: withers@LPL.Arizona.EDU
From: Herb Frey <frey@core2.gsfc.nasa.gov>
Subject: Fwd: Images for Paul Withers
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   2        300 KB     Image
   3        451 KB     Image
   4 Shown   11 lines  Text
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Paul:

Attached are two GIF versions of the figure you requested, showing QCDs from our preliminary northern lowlands survey superimposed on a shaded relief version of the MOLA topography. Jim roark prepared this figure, and you might acknowledge him as well as reference us. The QCDs can be referenced to our submitted paper:

Frey, H.V., J. H. Roark, K.M. Shockey, E.L. Frey and S.E.H. Sakimoto , Ancient Lowlands on Mars, submitted to GRL, July 2001.

A couple of important points:

(1) [TEXT DELETED]

(2) Ability to find QCDs depends on the current MOLA grid being used. These were from the 64x32 which is not yet officially released. So this is really a "private communication". You are NOT using the 64x32 gridded data (which you are not yet "allowed" to use until it is in the public domain). You are using a product derived from that by a MOLA team member who is a collaborator and who has agreed to provide the derived product (not the data). This is important because MDAP proposals that indicate use of non-released data are in violation of the requirement of the NRA, and such proposals have been rejected in past panel reviews for that reason. YOU MUST EMPHASIZE THAT THE WORK YOU DO WITH MOLA DATA WILL BE DONE WITH RELEASED MOLA DATA ONLY.

(3) [TEXT DELETED]

[TEXT DELETED]

Have a good one today.

--Herb

Abridged email from Herb Frey. The “derived product” that will be provided is the QCD dataset. It was later agreed that it was not necessary for Frey to be a collaborator.

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Facilities and Equipment

Existing facilities and equipment at the University of Arizona, the Jet Propulsion Laboratory, and the Goddard Space Flight Center will be used to perform this proposed research.

Curriculum Vitae – Principal Investigator Melosh

H. Jay Melosh is a Professor of Planetary Science in the Lunar and Planetary Laboratory of the University of Arizona. He is a specialist in the physics of impact cratering on both the Earth, other planets and on small bodies such as comets and asteroids. He and his students have developed computer codes to accurately simulate cratering events both in the laboratory and on small bodies where fracture plays an important role in the cratering process. He developed ideas on how the Martian and lunar meteorites survived ejection at high speed while suffering little shock damage and speculated on the possibility of interplanetary panspermia as a result of the ejection of living organisms. Other work involved study of the orbital evolution of impact ejecta and its ultimate fate. Melosh has also been active in the study of the effects of large impacts on the Earth's biosphere. Author of a well-received monograph on impact cratering, Melosh has considerable experience with theoretical study of the impact process.

BORN:	June 23, 1947, Paterson, New Jersey
ATTENDED:	Princeton University, 1965-1969, A.B. (physics) magna cum laude Caltech 1969-1972, Ph.D. (physics and geology)

Academic Experience

Graduate Teaching Assistant, Caltech, 1969-1971
Visiting Scientist, CERN (Geneva, Switzerland), 1971-1972
Research Associate, University of Chicago, Enrico Fermi Institute, 1972-1973
Instructor in Geophysics and Planetary Science, Caltech, 1973-1975
Assistant Professor of Planetary Science, Caltech, 1976-1978
Associate Professor of Planetary Science, Caltech, 1978-1979
Associate Professor of Geophysics, SUNY, Stony Brook, 1979-1982
Associate Professor of Planetary Science, Univ. of Arizona, 1982-1985
Professor of Planetary Science, Univ. of Arizona, 1985-present

Fellowships and Honors:

Phi Beta Kappa
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NSF Fellowship, 1969-1972
Best Scientific Secretary Prize, Int' l Summer School of Theoretical Physics, Erice,Sicily, 1972
Fellow of the Meteoritical Society (July, 1988)
Fellow of the Geological Society of America (November, 1988)
Fellow of the American Geophysical Union (January 1993)
Paul Simon Guggenheim Fellow, 1996-1997.

Recent National and International Committees and Panels

Member, Origin of Sedimentary Basin Task Force, International Lithosphere Program, French Petroleum Institute, Malmaison, France

Scientific Observer, European Science Foundation, Network on "The role of impact processes in the geological and biological evolution of planet Earth". 1993-1996.

Editorial Committee, Annual Reviews of Earth and Planetary Science, 1997-2002.

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Curriculum Vitae – Co-Investigator Withers

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Summer research placements at:

Beagle 2 group at the Open University, Great Britain, summer 2001
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Academic Status:

Completed required courses at University of Arizona, all grades A.
GRE Physics, 92nd percentile, and GRE General, 97th percentile or better in all subjects.
BA and MS in Physics, University of Cambridge, all grades equivalent of A.

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Work on MGS accelerometer measurements of upper atmospheric density during aerobraking has so far led to lead authorship of several conference presentations and coauthorship of a paper submitted to *Geophys. Res. Lett.*

Highly Commended –Young Science Writer of the Year contest, 2000, offered by *The Daily Telegraph*, a British national newspaper
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