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DEPARTMENT OF EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

1 - Grant Title: **Planetary Tectonics and Volcanism**

2 - Type of Report: **Summary of Research**

3 - Principal Investigator: **Maria T. Zuber**

4 - Period of Performance: **4/1/96 - 9/30/97**

5 - Recipient's Institution: **Massachusetts Institute of Technology**
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6 - Grant Number: **NAGW-5021**

Summary of Research

Grant Title: Planetary Tectonics and Volcanism (NAGW-5021)
Principal Investigator: Maria T. Zuber

Objective

The broad objective of the proposed work in this grant is to study tectonic and volcanological processes on the terrestrial planets, with particular emphasis on Venus, in order to better understand the internal structures and thermal and stress histories of these bodies.

Accomplishments:

- Analyzed the tectonic evolution of Bell Regio, Venus, via analytical and finite element models of regional stress, lithospheric flexure and edifice stresses. Submitted paper.

- Developed an analytical model that relates lava flow rheology to measured levee widths that incorporates the effect of cross-flow slopes, and applied the results to well-developed terrestrial and venusian lava flows. Submitted paper.

- Developed a formalism to understand the effect of small-scale topographic perturbations on the mechanics of flowing lava. Manuscript is in preparation.

- Applied analytical models for forced convection to understand flow and heat transport in lava tubes. Submitted paper is in press.

- Derived a formalism to remove the attraction of the Tharsis bulge from the Martian gravity field, and examined implications for the planet's internal structure. Published paper.

- Developed quasi-analytical and numerical models to understand the development of boudinage structures in an extending, cooling lithosphere. Submitted paper.

- Determined new topography and gravity fields, as well as crustal thickness model for the Moon. Published papers on each.

- Studied lunar topography in the vicinity of the south polar region and addressed the implications for the proposed presence of permanently shaded regions. Published paper.

- Determined depth/Diameter relationsip for lunar basins and discussed implications for nature of impact process. Submitted paper is in press.

- Derived a method to measure directly planetary librations from an orbiting spacecraft. Manuscript is in preparation.

- Performing global quantitative characterization of tectonic wavelengths on

Venus using two-dimensional spectral analysis technique. Presentations at Gordon Conference on Venus Geodynamics and Lunar and Planetary Science Conference.

• Relating tectonic wavelengths to lithospheric structure on Venus using numerical and analytical models of compressiona deformation that include lithospheric strength envelope rheologies, effects of macroscale strain localization, and lithospheric cooling. Presentation at Gordon Conference on Venus Geodynamics.

• Effort underway to perform experiments of rock friction at high temperatures to understand the mechanism of faulting on Venus.

• Analyzing crustal compensation dynamics on the Moon via an analytical model that incorporates internal density variations and the finite strength of the lithosphere. Abstract presented at Lunar and Planetary Science Conference.

<u>Refereed Publications</u>

Neumann, G.A., M.T. Zuber, D.E. Smith, and F.G. Lemoine, The lunar crust: Global signature and structure of major basins, *J. Geophys. Res., 101,* 16,841-16,863, 1996.

Smith, D.E., M.T. Zuber, G.A. Neumann, and F.G. Lemoine, Topography of the Moon from the Clementine LIDAR, *J. Geophys. Res.*, *102,* 1591-1611, 1997.

Lemoine, F.G., D.E. Smith, M.T. Zuber, G.A. Neumann and D.D. Rowlands, A 70th degree lunar gravity model from Clementine and other tracking data, *J. Geophys. Res., 102,*16,339-16,359, 1997.

Zuber, M.T., and D.E. Smith, Topography of the lunar south polar region: Implications for the size and distribution of permanently shaded areas, *Geophys. Res. Lett., 24,* 2183-2186, 1997.

Phillips, R.J., C.L. Johnson, S.J. Mackwell, P. Morgan, D.T. Sandwell, and M.T. Zuber, Lithospheric Mechanics and Dynamics on Venus,*Venus II,* ed. D. Hunten, R. Phillips and S. Bougher, 1163-1204, Univ. Ariz. Press, Tucson, 1163-1204, 1997.

Banerdt, W.B., G.E. McGill and M.T. Zuber, Plains Tectonism on Venus, *Venus II,* ed. D. Hunten, R. Phillips and S. Bougher, Univ. Ariz. Press, Tucson, 901-930, 1997.

Zuber, M.T., and D.E. Smith, Mars without Tharsis, *J. Geophys. Res.*, *102*, 28,673-28,685,1997.

Williams, K.K., and M.T. Zuber, Measurement and analysis of lunar basin depths from Clementine altimetry, *Icarus,* in press, 1997.

Sakimoto, S.E.H., and M.T. Zuber, Flow and convective cooling in lava tubes, *J. Geophys. Res.,* in press, 1997.

Rogers, P.G., M.T. Zuber and B.A. Campbell, Crossflow topographic effects on the emplacement of leveed lava flows, submitted to *Bull. Volcanol.,* 1997.

Rogers, P.G., and M.T. Zuber, Tectonic evolution of Bell Regio, Venus: Regional stress, lithospheric flexure, and edifice stresses, submitted to *J. Geophys. Res.,* 1997.

Neumann, G.A., and M.T. Zuber, Diffuse extension and lithospheric boudinage, submitted to *J. Geophys. Res.,* 1997.

Budget Summary

To be provided by MIT Office of Sponsored Programs.

The Shape of Mars and the Topographic Signature of the Hemispheric Dichotomy

David E. Smith and Maria T. Zuber

Reanalysis of occultation data from the Mariner 9 and Viking Orbiter spacecraft to determine the shape of Mars indicated that the hemispheric dichotomy is not a fundamental feature of the shape of the planet. It is a consequence of an approximately 3-kilometer offset between Mars's center of mass and center of figure, and the boundary, along most of its length, consists of broad, gradual surface slopes over distances of thousands of kilometers. This result was supported by analysis of high spatial resolution Earth-based radar topographic profiles. Any successful model for the origin of the dichotomy must explain a planet with an ellipsoidal shape and a long wavelength gradual topographic transition between the northern and southern hemispheres.

The surface of Mars is distinctly different in the northern and southern hemispheres. The south is old and heavily cratered, whereas the north is younger and lightly cratered and was probably volcanically resurfaced early in Mars's history (*1*, *2*). This hemispheric dichotomy is characterized by a geologic boundary between the hemispheres that is expressed as knobby and fretted terrains and detached plateaus (*2–4*) distributed over a relatively limited width of ~700 km (*5*). Along the boundary, elevations have been interpreted to decrease from south to north by ~1 to 3 km (*1*, *6*, *7*), and the change in topography has been correlated with geologic features (*8*).

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The formation of the dichotomy has been attributed to internal processes, such as postaccretional core formation (*9*), and to crustal delamination (in the northern hemisphere) and underplating (in the southern hemisphere) by vigorous mantle convection (*10*). It has also been proposed that the low northern hemisphere was the result of a massive impact (*5*, *11*) or impacts (*12*), and this region may have been the site of an early martian ocean (*13*). The lack of gravity anomalies along the boundary (*14*) may indicate thick crust beneath the southern highlands and thinner crust beneath the northern lowlands (*1*, *15*). In addition, the boundary region has been proposed as the site of relic plate boundaries (*16*). Consequently, understanding the origin of the hemispheric difference has implications for the evolution and internal structure of Mars.

Most analyses of the origin of the dichotomy have been based on global topographic models (*8*) with poor long-wavelength accuracy (*17*). The topography has also been studied by means of higher spatial resolution measurements derived from photoclinometry, stereo imaging, and ultraviolet spectra (*7*, *18*). Although these methods yield information on relative heights within an individual image frame or mosaic, the heights cannot be placed in a global reference frame and are of limited utility in relating local structure to global structure.

Radio occultation measurements (*19–22*) provide estimates of the radius of the planet at the time (and location) when the radio signal from a spacecraft is lost (occulted) behind the planet or emerges from behind the planet in its orbit (*23*). Occultation data formed the basis of several early determinations of Mars's topography (*21*, *22*, *24*) and were included in more recent U.S. Geological Survey (USGS) digital elevation models (DEMs) (*8*), but the data have not been analyzed since the 1970s. Here, we reanalyzed these data by using improved spacecraft orbital information (*25*), the latest planetary ephemerides and dynamical information (*26*), and revised atmospheric refraction correc-

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. E7, PAGES 16,841-16,843, JULY 25, 1996

The lunar crust: Global structure and signature of major basins

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Abstract. New lunar gravity and topography data from the Clementine Mission provide a global Bouguer anomaly map corrected for the gravitational attraction of mare fill in mascon basins. Most of the gravity signal remaining after corrections for the attraction of topography and mare fill can be attributed to variations in depth to the lunar Moho and therefore crustal thickness. The large range of global crustal thickness (~20-120 km) is indicative of major spatial variations in melting of the lunar exterior and/or significant impact-related redistribution. The 61-km average crustal thickness, constrained by a depth-to-Moho measured during the Apollo 12 and 14 missions, is preferentially distributed toward the farside, accounting for much of the offset in center-of-figure from the center-of-mass. While the average farside thickness is 12 km greater than the nearside, the distribution is nonuniform, with dramatic thinning beneath the farside, South Pole-Aitken basin. With the global crustal thickness map as a constraint, regional inversions of gravity and topography resolve the crustal structure of major mascon basins to half wavelengths of 150 km. In order to yield crustal thickness maps with the maximum horizontal resolution permitted by the data, the downward continuation of the Bouguer gravity is stabilized by a three-dimensional, minimum-slope and curvature algorithm. Both mare and non-mare basins are characterized by a central upwarped moho that is surrounded by rings of thickened crust lying mainly within the basin rims. The inferred relief at this density interface suggests a deep structural component to the surficial features of multiring lunar impact basins. For large (>300 km diameter) basins, moho relief appears uncorrelated with diameter, but is negatively correlated with basin age. In several cases, it appears that the multiring structures were out of isostatic equilibrium prior to mare emplacement, suggesting that the lithosphere was strong enough to maintain their state of stress to the present.

Introduction

Large, uncompensated density anomalies ("mascons") coincide with most nearside lunar mare basins [*Muller and Sjogren*, 1968]. These anomalies arise in part from the effects of impact processes on crustal structure [e.g., *Wise and Yates*, 1970; *Bowin et al.*, 1975; *Phillips and Dvorak*, 1981; *Bratt et al.*, 1985a,b] and in part from subsequent volcanic flooding by denser mare basalt [*Conel et al.*, 1968; *Phillips et al.*, 1972; *Solomon and Head*, 1980]. Previous analyses [*Sjogren and Smith*, 1976; *Bills and Ferrari*, 1977b; *Thurber and Solomon*, 1978; *Bratt et al.*, 1985a] have attempted to constrain the crustal structure in association with the major basins in spite of limited topographic coverage and uncertainties in the gravity field. Such deficiencies have so far prevented a uniform and comprehensive analysis of lunar basin structure. *Phillips and Dvorak* [1981] used topography from Earth-based radar, characterized by vertical errors of up to 500 m, to model gravity derived from line-of-sight tracking over the Grimaldi basin. *Bratt et al.* [1985a] used topographic data from a variety of sources, and gravity calculated from a multidisk mass model [*Wong et al.*, 1971, 1975] to invert for the depth of the lunar moho in 5x5 degree blocks. They assumed that the premare basins had achieved nearly complete isostatic balance through viscous relaxation [*Solomon et al.*, 1982] prior to being filled with mare basalts. The 2- to 4.5-km thicknesses of mare basalts inferred by Bratt et al. were insufficient to produce the measured positive gravity anomaly over the mare basins. They concluded that the mare basins were characterized by significant central uplift of mantle following impact.

Geophysical data from the Clementine mission and reanalysis of historical tracking have now shown that the lunar lithosphere had a variable mechanical structure and was, on average, more rigid during the period of basin formation than previously thought [*Zuber et al.*, 1994]. These data permit a consistent analysis and comparison of crustal structure of lunar basins, without isostatic assumptions. We apply a complete Bouguer correction to the lunar gravity field of F.G. Lemoine et al. (GLGM2: A 70th degree and order lunar gravity model from Clementine and historical data, submitted to *Journal of Geophysical Research*, 1995; hereinaftrer referred to as submitted manuscript), using the Clementine topography (D. E. Smith et al., The topography of the Moon

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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. E1, PAGES 1591-1611, JANUARY 25, 1997

Topography of the Moon from the Clementine lidar

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and Frank G. Lemoine[5]

Abstract. Range measurements from the lidar instrument carried aboard the Clementine spacecraft have been used to produce an accurate global topographic model of the Moon. This paper discusses the function of the lidar; the acquisition, processing, and filtering of observations to produce a global topographic model; and the determination of parameters that define the fundamental shape of the Moon. Our topographic model; a 72nd degree and order spherical harmonic expansion of lunar radii, is designated Goddard Lunar Topography Model 2 (GLTM 2). This topographic field has an absolute vertical accuracy of approximately 100 m and a spatial resolution of 2.5°. The field shows that the Moon can be described as a sphere with maximum positive and negative deviations of ~8 km, both occurring on the farside, in the areas of the Korolev and South Pole-Aitken (S.P.-Aitken) basins. The amplitude spectrum of the topography shows more power at longer wavelengths as compared to previous models, owing to more complete sampling of the surface, particularly the farside. A comparison of elevations derived from the Clementine lidar to control point elevations from the Apollo laser altimeters indicates that measured relative topographic heights generally agree to within ~200 m over the maria. While the major axis of the lunar gravity field is aligned in the Earth-Moon direction, the major axis of topography is displaced from this line by approximately 10° to the east and intersects the farside 24° north of the equator. The magnitude of impact basin topography is greater than the lunar flattening (~2 km) and equatorial ellipticity (~800 m), which imposes a significant challenge to interpreting the lunar figure. The floors of mare basins are shown to lie close to an equipotential surface, while the floors of unflooded large basins, except for S.P.-Aitken, lie above this equipotential. The radii of basin floors are thus consistent with a hydrostatic mechanism for the absence of significant farside maria except for S.P.-Aitken, whose depth and lack of mare require significant internal compositional and/or thermal heterogeneity. A macroscale surface roughness map shows that roughness at length scales of 10^1-10^2 km correlates with elevation and surface age.

Introduction

Topography is one of the principal measurements required to quantitatively describe a planetary body. In addition, when combined with gravity, topography allows the distribution of subsurface density anomalies to be mapped, albeit nonuniquely, yielding information on not only the shape, but also the internal structure of a planet. Such information is fundamental to understanding planetary thermal history. The limited coverage and vertical accuracy of previous topographic measurements have limited the characterization of lunar shape and structure, and thus interpretation of the implications for the thermal evolution of the Moon. Near-global topographic measurements obtained by the Clementine lidar should enable progress in all of these areas.

The Clementine Mission, sponsored by the Ballistic Missile Defense Organization with science activities supported by NASA, mapped the Moon from February 19 through May 3, 1994 [*Nozette et al.*, 1994]. The spacecraft payload included a light detection and ranging (lidar) instrument that was built by Lawrence Livermore National Laboratory [*Nozette et al.*, 1994]. This instrument was developed for military ranging applications and was not designed to track surface topography. However, by careful programming of instrument parameters, it was possible to cause the ranging device to function as an altimeter and to collect near globally distributed profiles of elevation around the Moon [*Zuber et al.*, 1994]. In this paper, we discuss the Clementine lidar investigation, including the function and performance of the sensor, the collection, processing, and filtering of data, and the development of global models for the geodetically referenced long wavelength shape and higher spatial resolution topography of the Moon. We compare our results to previous analyses of lunar topography and discuss the implications of the improved spatial coverage of the Clementine data as compared to previous data sets.

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A 70th degree lunar gravity model (GLGM-2) from Clementine and other tracking data

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Abstract. A spherical harmonic model of the lunar gravity field complete to degree and order 70 has been developed from S band Doppler tracking data from the Clementine mission, as well as historical tracking data from Lunar Orbiters 1-5 and the Apollo 15 and 16 subsatellites. The model combines 361,000 Doppler observations from Clementine with 347,000 historical observations. The historical data consist of mostly 60-s Doppler with a noise of 0.25 to several mm/s. The Clementine data consist of mostly 10-s Doppler data, with a data noise of 0.25 mm/s for the observations from the Deep Space Network, and 2.5 mm/s for the data from a naval tracking station at Pomonkey, Maryland. Observations provided Clementine, provide the strongest satellite constraint on the Moon's low-degree field. In contrast the historical data, collected by spacecraft that had lower periapsis altitudes, provide distributed regions of high-resolution coverage within $\pm 29°$ of the nearside lunar equator. To obtain the solution for a high-degree field in the absence of a uniform distribution of observations, we applied an a priori power law constraint of the form $15 \times 10^{-5}/l^2$ which had the effect of limiting the gravitational power and noise at short wavelengths. Coefficients through degree and order 18 are not significantly affected by the constraint, and so the model permits geophysical analysis of effects of the major basins at degrees 10-12. The GLGM-2 model confirms major features of the lunar gravity field shown in previous gravitational field models but also reveals significantly more detail, particularly at intermediate wavelengths (10^3 km). Free-air gravity anomaly maps derived from the new model show the nearside and farside highlands to be gravitationally smooth, reflecting a state of isostatic compensation. Mascon basins (including Imbrium, Serenitatis, Crisium, Smythii, and Humorum) are denoted by gravity highs first recognized from Lunar Orbiter tracking. All of the major mascons are bounded by annuli of negative anomalies representing significant subsurface mass deficiencies. Mare Orientale appears as a minor mascon surrounded by a horseshoe-shaped gravity low centered on the Inner and Outer Rook rings that is evidence of significant subsurface structural heterogeneity. Although direct tracking is not available over a significant part of the lunar farside, GLGM-2 resolves negative anomalies that correlate with many farside basins, including South Pole-Aitken, Hertzsprung, Korolev, Moscoviense, Tsiolkovsky, and Freundlich-Sharonov.

Introduction

Until the launch of Clementine, on January 24, 1994, the sources of tracking data for gravity models derived by U.S. investigators have been the Lunar Orbiters and the Apollo spacecraft. The Lunar Orbiters were inserted into elliptical orbits with periapses of 50 to 100 km above the lunar surface. The Apollo spacecraft were placed in near circular orbits at low inclinations with a mean altitude of 100 km, although some tracking was acquired from altitudes as low as 10 to 20 km. The tracking data sampled the gravity field of the Moon at a resolution unprecedented for orbiting spacecraft, at either the Earth, Venus, or Mars. However, the spatial coverage of the tracking was incomplete, with no direct tracking data available over large portions of the lunar farside. During the initial investigations, in the 1960s and 1970s, researchers were limited in the size of the spherical harmonic solutions that could be developed by the computers then available. Because of the power

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GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 17, PAGES 2183-2186, SEPTEMBER 1, 1997

Topography of the lunar south polar region: Implications for the size and location of permanently shaded areas

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Abstract. We analyze Clementine altimetry to constrain the size and location of proposed permanently shadowed regions in the vicinity of the lunar south pole. Long and short wavelength topography in the vicinity of the pole, in combination with measurements of depths of well-preserved craters and basins and the lunar topographic power spectrum, have direct bearing on the nature of elevations in the south polar region. A criterion based on geometric considerations and altimetry demonstrates that the existence of permanent shadowing is not very sensitive to the elevation of the south pole. In addition, permanent shadowing cannot be a consequence of large structures such as the South Pole-Aitken Basin and/or a 300-km degraded polar basin. Perennially dark regions, if they exist, are most likely associated with craters or other axisymmetric features with diameters of at most 80 km centered at the pole. For structures displaced 2° from the pole the maximum allowable diameter decreases to ~30 km.

Introduction

The recent possible detection of water ice at the lunar south pole from the Clementine bistatic radar experiment [*Nozette et al.*, 1996] has potentially major implications for future lunar exploration initiatives. The basis for the potential finding is the recognition of backscatter and polarization enhancement of radar echoes transmitted by the spacecraft that interacted with a region of the lunar surface near the pole, outlined in Fig. 1. The unusual radar signature has been interpreted as being due to coherent backscatter of a high volume scattering substance, most likely water ice [*Nozette et al.*, 1996], though lunar surface roughness near the radar wavelength has been offered as an alternative explanation on the basis of analysis of higher spatial resolution Earth-based observations [*Stacy et al.*, 1997]. The retention of near-surface ice, presumably deposited by cometary or asteroidal impacts, would require areas of the lunar surface to have been shadowed from sunlight over geological timescales [*Watson et al.*, 1961; *Arnold*, 1979; *Ingersoll et al.*, 1992].

Continuous shadowing in the lunar south polar region has been identified on the basis of the Clementine south pole image mosaic [*Shoemaker et al.*, 1994; *Spudis et al.*, 1995], which was assembled from two months of orbital imaging. However, dark regions in the mosaic do not necessarily imply permanent shadowing [*Shoemaker et al.*, 1994]. The Clementine observations were obtained during southern hemisphere winter, when the tilt of the Moon's rotation axis was ~1.5° from pole of the ecliptic in the direction away from the sun. An increase of the sun's elevation above the south polar horizon of over 3° will occur during southern summer at some time during the year, and it is probable that at least some of the darker areas seen in the Clementine mosaic will then be illuminated.

Surface topography, defined as elevation with respect to the geoid, is another essential observation required to distinguish the location and physiographic context of permanently shadowed regions. Unfortunately a definitive analysis of topographic constraints is not possible because there are currently no direct measurements of lunar topography at either pole. However, there are well-constrained indirect topographic observations that provide insight into the distribution and character of south polar elevations. These include: long wavelength lunar topography, near-polar short wavelength topography, measured depths of craters and basins distributed over the lunar surface, and the global topographic power spectrum. Because of the unique contribution of

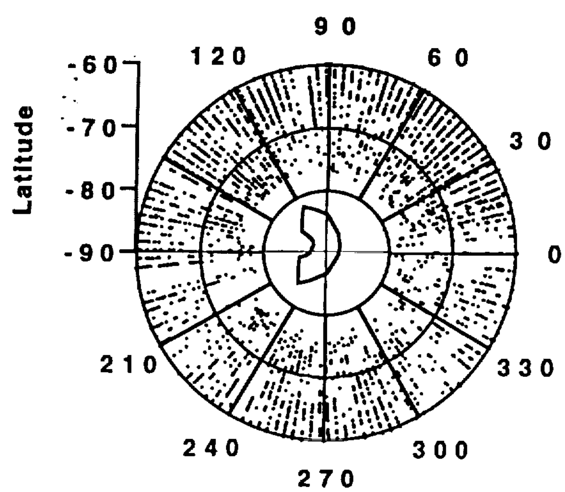

Figure 1. Distribution of surface elevations from Clementine altimetry between latitude -60° and the south pole. The semi-circular area near the pole is the region of enhanced radar backscatter recognized by *Nozette et al.* [1996]. Proposed regions of permanent shadowing within this area have been interpreted as containing ice and/or other frozen volatiles [*Nozette, et al.*, 1996]. In the figure the direction of Earth is to the right.

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II

Measurement and Analysis of Lunar Basin Depths from Clementine Altimetry

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Collisional physics

in press

ABSTRACT

Altimetric profiles from the Clementine LIDAR are used to calculate the depths of 29 large craters and basins on the Moon. Plotting the depths of the best preserved structures together with values for simple and complex craters measured in pre-Clementine studies reveals ~~a second~~ two inflections in the depth/diameter (d/D) curve. ~~This~~ The larger inflection occurs in the diameter range that corresponds to the morphologic transition from complex crater to basin. The best empirical power law fit for basin depths is $\log_{10}(d) = 0.4092*[\log_{10}(D)]^{0.5654}$. This relationship is characterized by a lower slope than that for complex craters, demonstrating that this morphologic transition corresponds to a further decrease in the depth of an impact structure relative to its diameter with increasing size. Qualitative consideration of possible causes for the second inflection leads to the conclusion that it is most likely a consequence of a short-term modification mechanism that influences fundamental crater morphology, such as the increasing influence of gravity with diameter. Thicknesses of maria in the major basins are calculated by assuming that their unfilled depths would follow the d/D relation. Results are compared with previous estimates and yield thicknesses that are generally greater than those determined by studies of flooded craters and less than those obtained from analysis of gravity.

Tectonic Evolution of Bell Regio, Venus:
Regional Stress, Lithospheric Flexure, and Edifice Stresses

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Abstract. In order to understand the relationship between volcanic and tectonic processes and the Venus stress state we analyzed the stress environments and resulting tectonic features associated with the major volcanic edifices in Bell Regio, Venus, using Magellan synthetic aperture radar (SAR) images and altimeter measurements of topography. The major volcanoes of Bell Regio, Tepev Mons and Nyx Mons, exhibit tectonic characteristics that are unique relative to other volcanic edifices on Venus. The most prominent distinction is the lack of large rift zones within the overall highland uplift, which characterize many other highland rises on Venus. Also, previous studies have determined that many large Venus volcanoes exhibit radial tectonic structures on their flanks, but generally lack the circumferential graben which surround volcanoes on Earth and Mars, and are thought to be indicative of lithospheric deformation. Tepev and Nyx Montes exhibit both the radial tectonic features associated with other Venusian edifices and numerous concentric graben. Nyx Mons implies a more distributed magmatic system by its broad shape, radial chains of pit craters, and expansive flow fields, whereas Tepev Mons is a more centralized volcanic system, with limited associated long flows. We investigate the regional stresses associated with Bell Regio and structural features believed to be a consequence of lithospheric flexure due to volcanic loading, modeling both Nyx Mons and Tepev Mons as axisymmetric loads with Gaussian mass distributions on an elastic plate. The relationship between the tectonic features surrounding Tepev Mons and stresses associated with magma chamber inflation are also examined through finite element analysis. Using topography data to model the shape of the volcano, we determine that a horizontally ellipsoidal chamber or sheet-like reservoir at a depth of approximately 18 km best fits the locations of graben formation observed in Magellan images. These results imply a shift in volcanic style within Bell Regio from an early phase of broad, low shield formation to later steep-sided, more centralized edifice development. Such changes are consistent with an increase in the thickness of the lithosphere over time.

P. G. Rogers • M. T. Zuber • B. A. Campbell

Crossflow Topographic Effects on the Emplacement of Leveed Lava Flows

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Submitted

Abstract

To understand the factors that affect the emplacement of lava flows, we integrated field measurements with theoretical modeling to examine how downflow and crossflow topography influences the development of marginal levees. Levee dimensions reveal important information about the rheology and emplacement characteristics of a flow. We examined two end member basalt flows in Hawaii to evaluate the validity of the Hulme model for lava rheology and found that a theoretical extension of the model is necessary to account for the crossflow slope. Even small crossflow slopes are shown to have a significant effect on the lateral dimensions of the levees. The effect of the crossflow slope becomes more pronounced as the downflow slope diminishes. We then applied this model to lava flows on Venus, which in many cases traveled great distances (order 10^2 km) over very shallow slopes. Analysis of possible leveed flows on Venus shows that application of a simple Bingham flow model leads to an apparent dependence of derived yield stress on downflow slopes. We interpret this result to indicate the possible existence of crossflow confining slopes beneath most of the Venus leveed flows. Further applications of common rheologic models to Venus are shown to be limited by the coarse topographic sampling of the Magellan radar altimeter.

Key words Volcanism • lava flows • Kilauea • flow modeling • Venus • rheology • topography • levees

Introduction

Knowledge of a lava flow's rheologic properties, and how these properties vary in space and time, is fundamental to understanding flow dynamics and morphology. Through lava flow modeling, one hopes to relate a flow's final morphology to rheologic and emplacement conditions and thereby develop a method to predict flow growth (Hulme, 1974; Pinkerton and Sparks, 1978; Guest et al., 1987; Fink and Zimbelman, 1990). Such models are important for

Flow and convective cooling in lava tubes

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Abstract

Tube-fed basaltic lava flows with lengths ranging from 10 km to 200 km are inferred to exhibit similar amounts of cooling. To explain the wide range of implied cooling rates, we consider forced convection as a dominant cooling process in lava tubes and present solutions that express mean temperature versus distance down the tube as a function of flow rate and flow cross-section. Our models treat forced convective thermal losses in steady laminar flow through a lava tube with constant temperature walls and constant material properties. We explore the effects of different wall temperature and heat flux rate boundary conditions for circular tube and parallel plate flows over a range of tube sizes, plate spacings, eruption temperatures and volume flow rates. Results show that nonlinear cooling rates over distance are characteristic of constant wall temperature for a piece-wise parallel plate/circular tube model. This provides the best fit to temperature observations for Hawaiian tubes. Such a model may also provide an explanation for the very low (~10°C) cooling observed in ~10-km long Hawaii tube flows and inferred in longer ~50-150 km tube-fed flows in Queensland. The forced convective cooling model may also explain similar flow morphologies for long tube-fed basaltic lava flows in a wide variety of locations, since small variations in eruption temperature or flow rate can accommodate the entire range of flow lengths and cooling rates considered. Our results are consistent with previous suggestions that long basaltic flows may be a reflection of low slopes, a particularly steady, moderate, eruption rate, and well-insulated flow, rather than of high discharge rates.