MODELING OF SURFACE AND SUBSURFACE LOADS FOR THE MAJOR MARTIAN VOLCANOES: IMPLICATIONS FOR DYNAMIC MANTLE PROCESSES ON THE PLANET

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In the absence of in situ geophysical measurements, modeling the relationship between gravity and topography is one of the few methods that can be used to constrain the properties of a planet's interior. In this study, we model the localized spectral admittance of the large Martian volcanoes by assuming that surface and subsurface loads are elastically supported by the lithosphere. We systematically investigate the misfit function for the entire multi-dimensional space, which includes the elastic thickness, crustal thickness, load density, crustal density, and ratio of surface to subsurface loading. We describe here the methodology developed in order to improve such kind of studies and the results obtained on the above mentioned parameters.

Theory developed in order to improve the computing of the lithospheric deflection

1. Computation of the gravity anomaly anywhere inside the planet:

Input:
- Surface topography
- Relief along any number of density interfaces
- Lateral variations of density

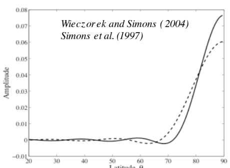
Output:
- g(r,θ,φ) and U (r,θ,φ) *at all points inside and on the surface* of the planet.

2 steps in the computation :
- calculation of U and g at an altitude R0 above the mean planetary radius (analogous to *Wieczorek and Phillips* 1998)
- downward propagation of U and g to each density interface

➢ U and g are calculated on the surface **as well as on any density interface within the planet.**

3. Improvement in the spatio-spectral localization

- The modeled gravity signal is then compared with the theoretical one in the spectral domain, using localized admittance.
- We use windows that are optimally concentrated within a spherical cap for a given value of L_{win}.

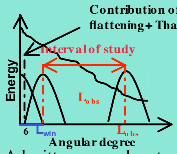


Spatial representation of the window of *Wieczorek and Simons*, 2004 and *Simons et al*., 1997 for a spatial diameter θ_0=15°.

Concentration of energy
- *Wieczorek and Simons, (2004)* : > 99 %
- *Simons et al. (1997)* : 93 %

Limitations when applying a localization window to a truncated spectra:

➢ Multiplying a dataset by a window is analogous to convolving the data in the spectral domain.



For each angular degree l, localized signal depends on degrees between l-L_{win} and l+L_{win}

➢Admittance can be studied for $L_{win}+6 \le l \le L_{obs}-L_{win}$, where $L_{obs} \sim 65$ for the jgm85h02 gravity field model.

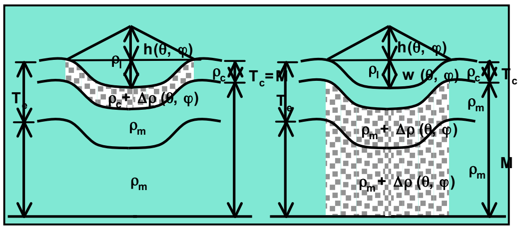
2.Improvement in the modeling of the lithospheric deflection

- **Model of lithospheric deflection including both surface and subsurface loads:**

A parameter *f* is defined corresponding to the ratio of surface to subsurface topography:
- *f < 0:* more dense material in the crust
- *f > 0:* less dense material in the mantle

$$f = \frac{\Delta\rho M}{(h+w)\rho_l}$$

➢All loads and deflections are assumed to be in phase (i.e coherence is close to unity).



•Deflection calculated without approximations on the gravitational potential inside the planet :

We have to solve the following set of two equations,

$$D\nabla^6 w + 4D\nabla^4 w + ET_E R^2 \nabla^2 w + 2ET_E R^2 w = R^4(\nabla^2 + 1 - \nu)q$$

$$q = -\frac{1}{R^2}\int \frac{dU(r,\theta,\phi)}{dr}\rho(r,\theta,\phi)r^2 dr - \rho_m U(R - T_E + w)$$

- The two equations are coupled
  - ➢ **They are solved iteratively**
- q depends on the potential *U* on each interface
  - ➢ **This method that computes *U* exactly on each interface prevents to use the mass sheet approximation as it is done in previous studies such as *Turcotte et al*, 1981, *Banerdt*, 1986 or *McGovern et al.*, 2002.**

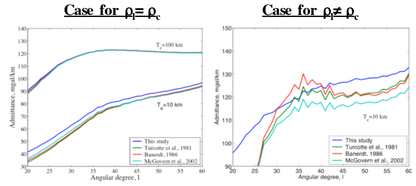
➢ ρ_l, ρ_c, T_e, T_c and f are then exhaustively sampled in order to determine their effect on the misfit between the observed and modeled gravity signal.

Results: Constraints obtained on the lithospheric parameters

1. Comparison with previous methods:

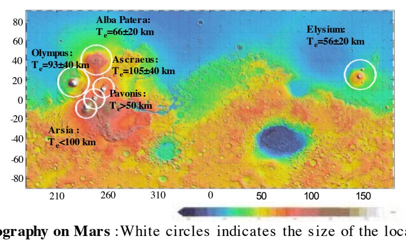
Localized admittance for Elysium

Case for $\rho_l = \rho_c$ — Case for $\rho_l \neq \rho_c$



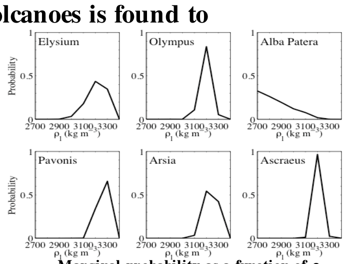
➢Discrepancies increase for small T_E or when $\rho_l \neq \rho_c$

2. No evident relationship was found between T_e and space or time



Global topography on Mars :White circles indicates the size of the localization window for the volcanoes studied here: Alba Patera,Elysium, Olympus, Arsia, Pavonis and Ascraeus Montes. Is shown here the results obtained for the elastic thickness T_e.

3. The density of the volcanoes is found to be ρ_l=3200±100 kg m^{-3}

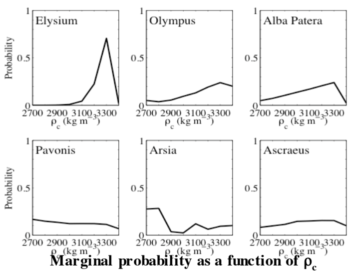


Marginal probability as a function of ρ_l

⇨ Higher densities than in previous studies

➢Density of volcanic loads are similar to the Martian meteorites (see also *Neumann et al.*, 2004).

4. The density of the crust is only constrained for Elysium, with ρ_c=3270±150 kg m^{-3}

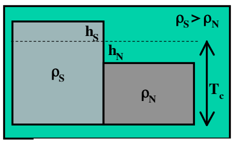


Marginal probability as a function of ρ_c

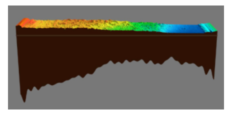
⇨ Is there a dichotomy in crustal composition?

- For Elysium, Alba Patera and Olympus Mons, we have obtained relatively high crustal densities of ~3200 kg m^{-3}.
- The only constraint that might come from the Southern hemisphere indicates a smaller value of ~3000 kg m^{-3} (Pathfinder measurement).

Pratt Compensation (density variation, constant "Moho" :



Crustal thickness profile assuming a constant crustal density:



Zuber et al., 2000

⇨ Is the difference in density between the northern and southern hemispheres consistent with Pratt compensation?

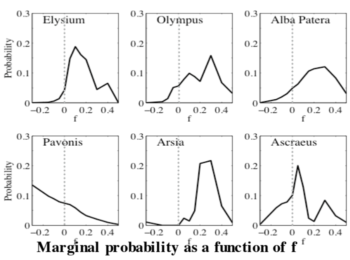
- Equilibrium equation for Pratt: $\rho_S(T_c + h_S) = \rho_N(T_c + h_N)$
- Expected density variation:
  - h_S=3 km and h_N = -3 km
  - ρ_S=3000 kg m^{-3}
  - 50 ≤ T_c ≤ 100 km

  } 3185 ≤ ρ_N ≤ 3382 kg m^{-3}

➢This is similar to our calculated value of ~3200 kg m^{-3}.

➢Pratt compensation for the difference in elevation between the northern and southern hemispheres implies that the average crustal thickness of the two hemispheres is nearly the same and would thus imply a Northern crustal thickness thicker than what was proposed in *Neumann et al.*, 2004.

5. For the major volcanoes a less dense material in the mantle is found (f > 0), except for Pavonis Mons and to a lesser extent for Ascraeus.



Marginal probability as a function of f

⇨2 possible interpretations of the induced density variation:
- ➢ Temperature variations
- ➢ Compositional variations as a result of the extraction of partial melt

$$\Delta\rho = -\rho_m[\beta \cdot F + \alpha\Delta T]$$

β: Coefficient of density reduction due to partial melting
F: Degree of depletion
α: Thermal expansion coefficient

⇨ Density variations obtained:
- Elysium : Δρ = 10-45 kg.m^{-3}
- Olympus : Δρ = 0-320 kg.m^{-3}
- Arsia : Δρ = 170-390 kg.m^{-3}

➢ Evidence for a dynamically active Martian interior?
- ⇨ For Arsia, Olympus and Elysium, either a mantle plume or depleted mantle composition is required.
- ⇨ Consistent with the evidence for recent volcanic activity
  - •Young radiometric ages of the Shergottites of ~175 Myr
  - • Cratering statistic: young lava flows (10-30 Myr)

References : **Banerdt**, W. (1986), *J. Geophys. Res.*, **91**, 403–419. **McGovern**, P. J., et al. (2002), *J. Geophys. Res.*, **107** (E12), 5136, doi:10.1029/2002JE001854. **Neumann**, G. A., et al. (2004), J. Geophys. Res., 109, E08002, doi:1029/2004JE002262. **Turcotte**, D. L., et al. (1981), *J. Geophys. Res.*, **86** (B5), 3951–3959. **Wieczorek, M. A., and R. J. Phillips** (1998), J. Geophys. Res., 103, 1715–1724. **Wieczorek**, M. A., and F. J. Simons (2004), *Geophys. J. Int.*, submitt.
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