The changing gravity field due to a superplume under the Tharsis Region

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Context

The Tharsis Region has been an interest of study for many years due to its large impact on the long wavelength gravity field and topography of Mars.

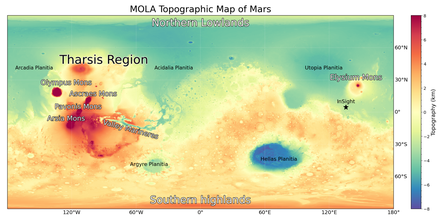


Figure 1. Topography of Mars from the Mars Orbiter Laser Altimeter data. The colorbar range is limited to ±8 km in order to show the global topographic features. The location of the InSight lander is indicated with a black star.

The leading theory on the origin of the volcanic region is a combination of both isostatic flexure of a thickened crust and a small contribution due to a (possible) large superplume residing in the upper mantle. The isostatic balance, on which previous studies have relied, does not adequately explain the long-wavelength gravity field spectra. These long-wavelength signals contribute to large scale features in the mantle. We consider the presence of **a dynamic mass anomaly below the Tharsis Region**. This could help explain the geological surveys of the relative young lava flows. By looking at mantle dynamic models we can explore the effect of a superplume that is actively rising in the mantle and changing the geoid over time.

Methods

After rotating Tharsis so that it comes to be under the North pole of an otherwise perfectly spherically symmetric planet, we ran a series of instantaneous axisymmetric Newtonian finite element models of Mars with varying plume and subsurface structural variables constrained by InSight. We run the model for 50 years, thereby accounting for the total duration of satellite data acquisition. The deformation in the model allows us to calculate the change in dynamic topography and gravity anomaly.

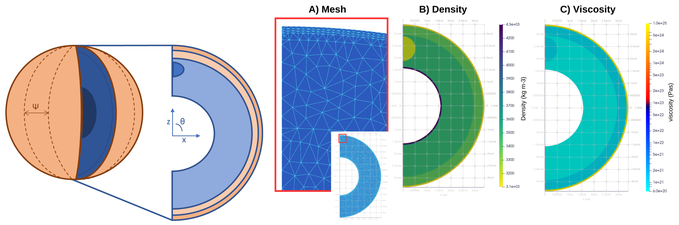
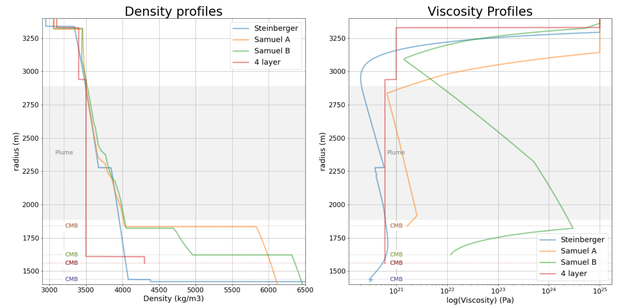


Figure 2. Left: geometry of the axisymmetric model. Right: FEM setup example with (A) Mesh representation with zoom in on upper right corner (h=80 km) (B) 4-layer homogeneous density distribution and (C) viscosity distribution.

Variable	Symbol	Value
Gravity Acceleration	g_0	3.72076 $\mathrm{m\,s^{-2}}$
Gravity measurement height	h_g	10 km
Planetary radius	R_{outer}	3389.5 km
Core radius	R_{inner}	1830 km
Core density	ρ_{core}	6200 $\mathrm{kg\,m^{-3}}$
Plume radius	R_{plume}	200 km
Plume depth	z_{plume}	2385 km
Plume density	ρ_{plume}	3200 $\mathrm{kg\,m^{-3}}$
Plume viscosity	η_{plume}	10^{21} Pa s

Density & viscosity profiles

We use 4 different density and viscosity profiles in our numerical experiments: one from Steinberger *et al* [1], two from Samuel *et al* [2], and one consisting of 4 layers:



Benchmark against ASPECT

Because our axisymmetric code Fieldstone is new, we benchmarked it against full 3D results obtained with ASPECT [3] for a model with an isoviscous background ($\rho_0 = 3700$ kg/m^3, $\eta_0 = 10^{21}$ Pa.s) and a plume sphere with radius 300 km ($\rho_{plume} = 3500$ kg/m^3 and $\eta_{plume} = 10^{22}$ Pa.s).

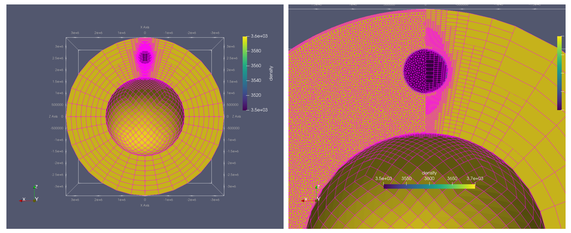


Figure 3. Left: Aspect mesh; Right: ASPECT mesh next to Fieldstone mesh.

With a maximum dynamic topography of 2091 km for Aspect and 2252 km for Fieldstone, this corresponds to a peak error of 2.6%. Further away from plume center the discrepancy does not exceed ±5 m or an error of 0.2%.

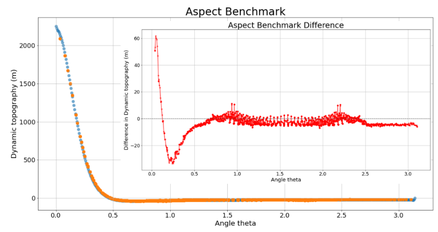


Figure 4. Dynamic topography at the surface. Fieldstone results are shown in blue and Aspect in orange. The difference between both is shown in red. Angle theta is given in radians.

Results

We have run extensive sets of tests [4]. The mantle anomaly (the 'blob') used in the results below has the following characteristics: Density of 3200 kg/m^3, depth of 1000 km, radius of 300 km.

The surface changes and gravity changes were calculated using the four different viscosity and density structures.

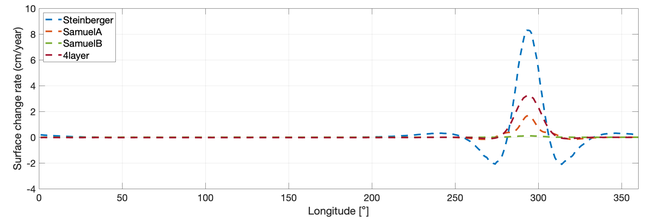


Figure 5. The surface changes due to a rising mantle anomaly underneath the Tharsis Rise.

The gravitational signal is mostly related to the dynamic topography changes, as can be seen in the following figure.

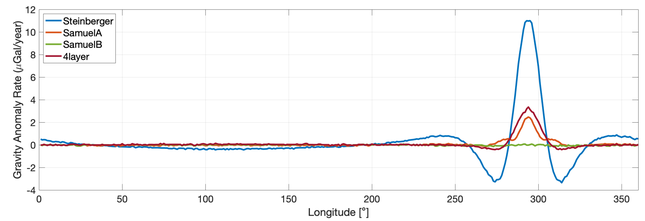


Figure 6. The gravity change after one year due to a rising mantle anomaly underneath the Tharsis Rise.

Conclusions

Our preliminary results show dynamic topography rates of a few centimetres per year and gravity rates in the order of 0.1-10 μGal per year. These gravity rates should fall within the precision of the Mars Reconnaissance Orbiter gravity field estimates, but are masked by other geological surface mass changes. **Our results show that with longer and dedicated gravity observations, we should be able to observe the large scale mantle dynamics of Mars.**

References

[1] Steinberger, B., Werner, S. C., Torsvik, T. H. (2010). Deep versus shallow origin of gravity anomalies, topography and volcanism on earth, venus and mars. Icarus, 207 (2), 564-577. https://doi.org/10.1016/j.icarus.2009.12.025

[2] Samuel, H., Ballmer, M. D., Padovan, S., Tosi, N., Rivoldini, A., Plesa, A.-C. (2021). The thermo-chemical evolution of mars with a strongly stratified mantle. Journal of Geophysical Research: Planets, 126 (4), e2020JE006613. https://doi.org/10.1029/2020JE006613

[3] https://geodynamics.org/resources/8

[4] M. Blasweiler (2023). From Finite Element Mantle Model to Martian Gravity Field - Determining dynamic topography and gravity rates by mantle plume under the Tharsis Rise on Mars, MSc thesis UU.