Geophysical evidence for a compositionally stratified Martian mantle

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1. Motivations

The identification of deep reflected S-waves on Mars has led to the first seismic estimation of a core size of 1830±40 km [1]. However, this relatively large core size requires light element contents incompatible with experimental petrological constraints.In addition, this core size estimate assumes a compositionally homogeneous Martian mantle, at odds with measurements of anomalously slow propagating P-waves diffracted along the core-mantle boundary [2].

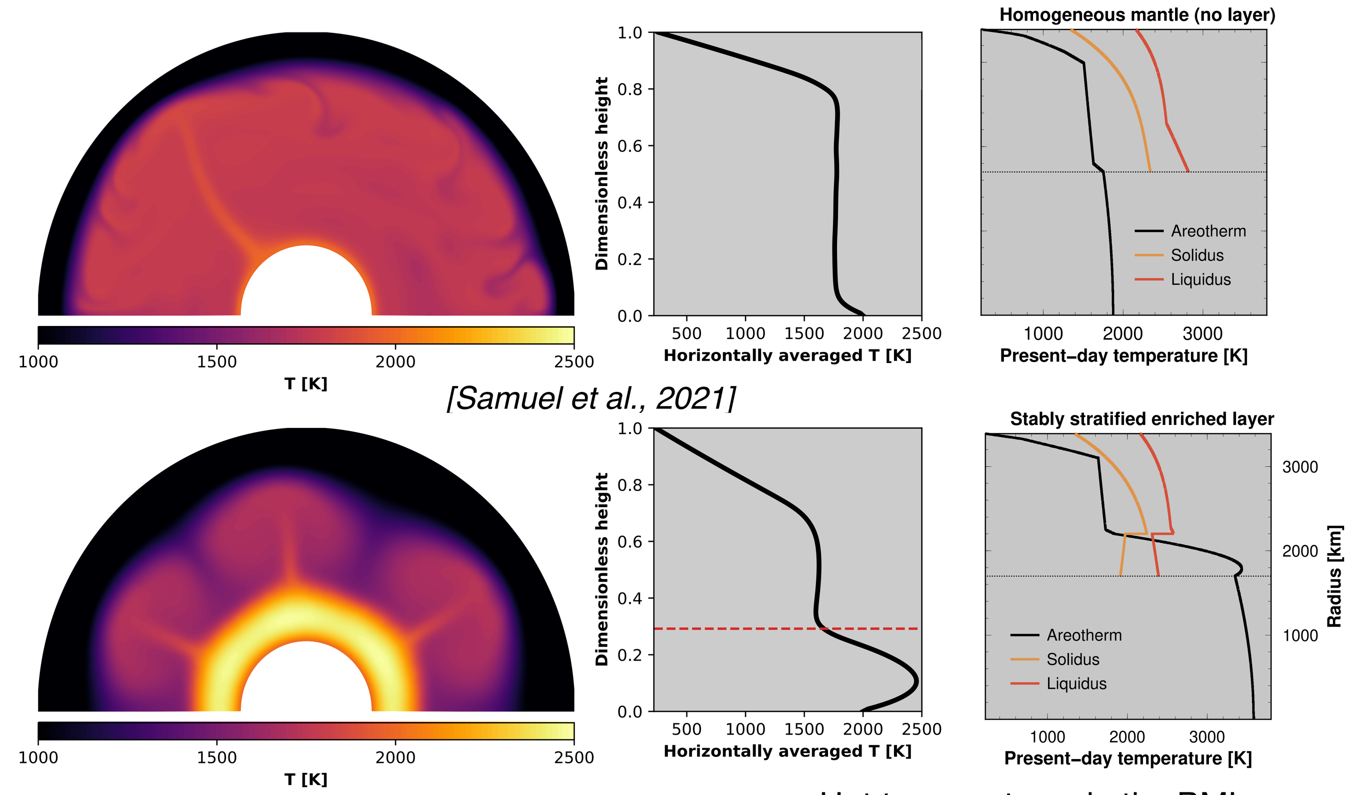
Alternatively, Mars' mantle may be heterogeneous as a result of a magma ocean solidification that formed a basal layer enriched in iron and heat-producing elements [3], resulting in the the presence of a molten silicate layer above the core, overlain by a partially molten layer [4].To determine the planet structures compatible with observations, we performed a probabilistic inversion of seismic data. Our inversion relies on a parameterisation in terms of quantities that influence the thermo-chemical evolution of the planet composed of a liquid iron core, a silicate mantle (with or without a enriched Basal Mantle Layer), and an evolving lithosphere and crust [5].

We show that such a layered Martian mantle is compatible with all geophysical data including (*i*) deep reflected and diffracted seismic phases from the mantle, (*ii*) weak shear attenuation at seismic frequencies, and (*iii*) Mars' dissipative behaviour at Phobos tides.

In particular, our results point to a revised core size of 1650±20 km implying a density of 6.5 g/cm3, 5-8% larger than previous seismic estimates. Using a core equation of state that reproduces experimental data, we show that Mars' core can be explained by fewer, and less abundant, alloying light elements than previously required, in amounts compatible with experimental and cosmochemical constraints. The new density structure is compatible with measurements of Mars' rotation [6].

The layered mantle structure requires external sources to generate the magnetic signatures recorded in Mars' crust.

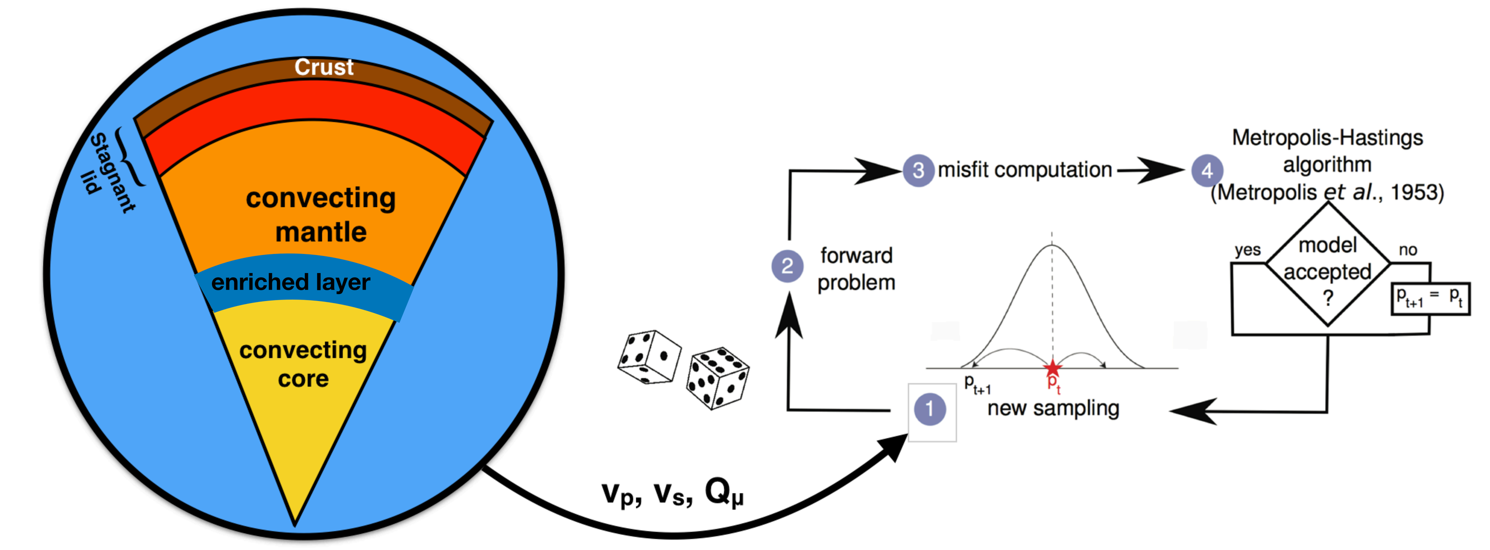
2. Homogeneous vs. layered mantle evolution



Basal mantle layer (BML) = heat buffer
➪ Reduces heat transfer efficiency
➪ Affects heat flux, crustal thickness…

Hot temperatures in the BML
➪ Partial and/or complete melting
➪ Can affect seismic structure

3. Geodynamically-constrained inversion of seismic data

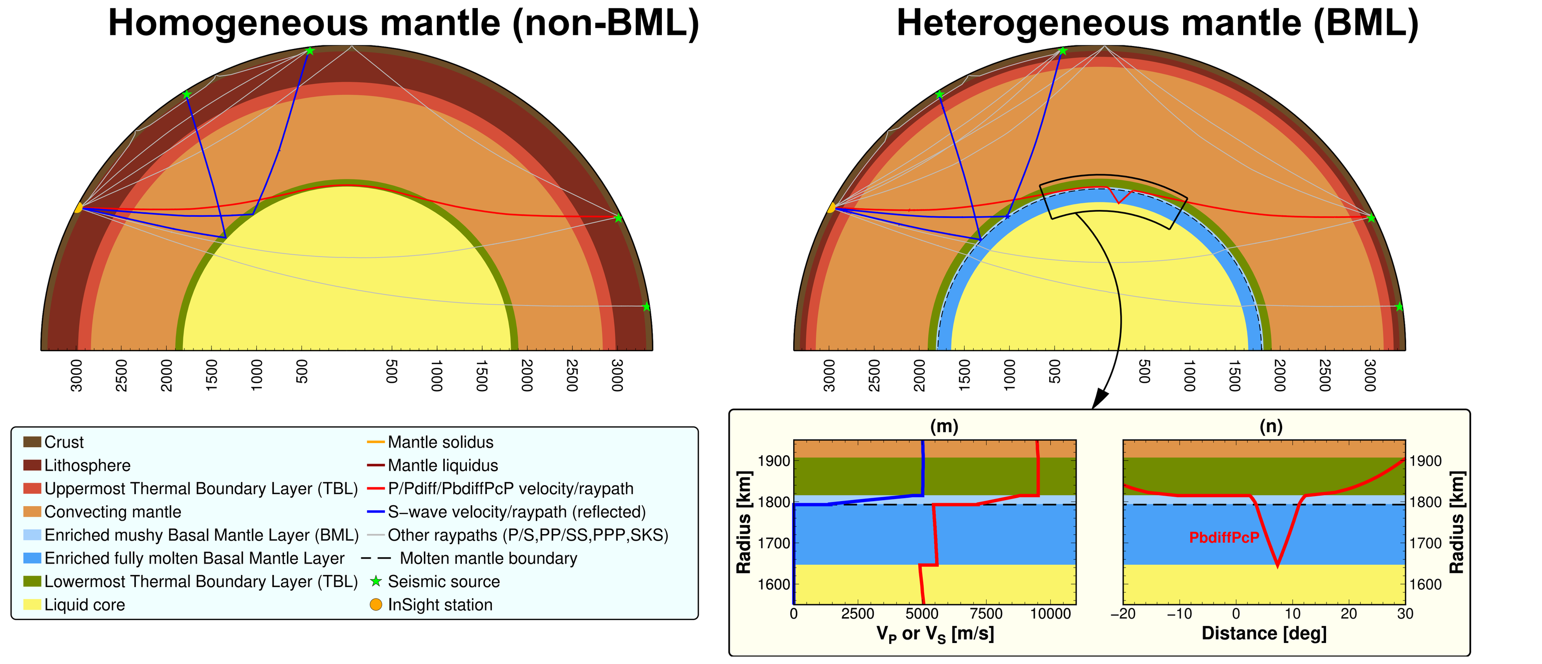


✓ MCMc inversion (*e.g.*, [5])
✓ Rely on the evolution of a Mars-like planet for 4.5 Gyr instead of present-day v_P,v_S, and density profiles
✓ Parameter space sampled: mantle rheology, initial thermal state, core size, HPE crustal enrichment
✓ The resulting present-day state is converted into v_P,v_S, and density profiles
✓ Models satisfy Mars' mass, k_2, crustal thickness and MoI constraints

➪ Smaller parameter space than that of classical inversions in terms of v_P,v_S, and density
➪ Resulting seismic structure more constrained and consistent
➪ Provides information on the entire thermo-chemical history of the planet and on additional present-day features

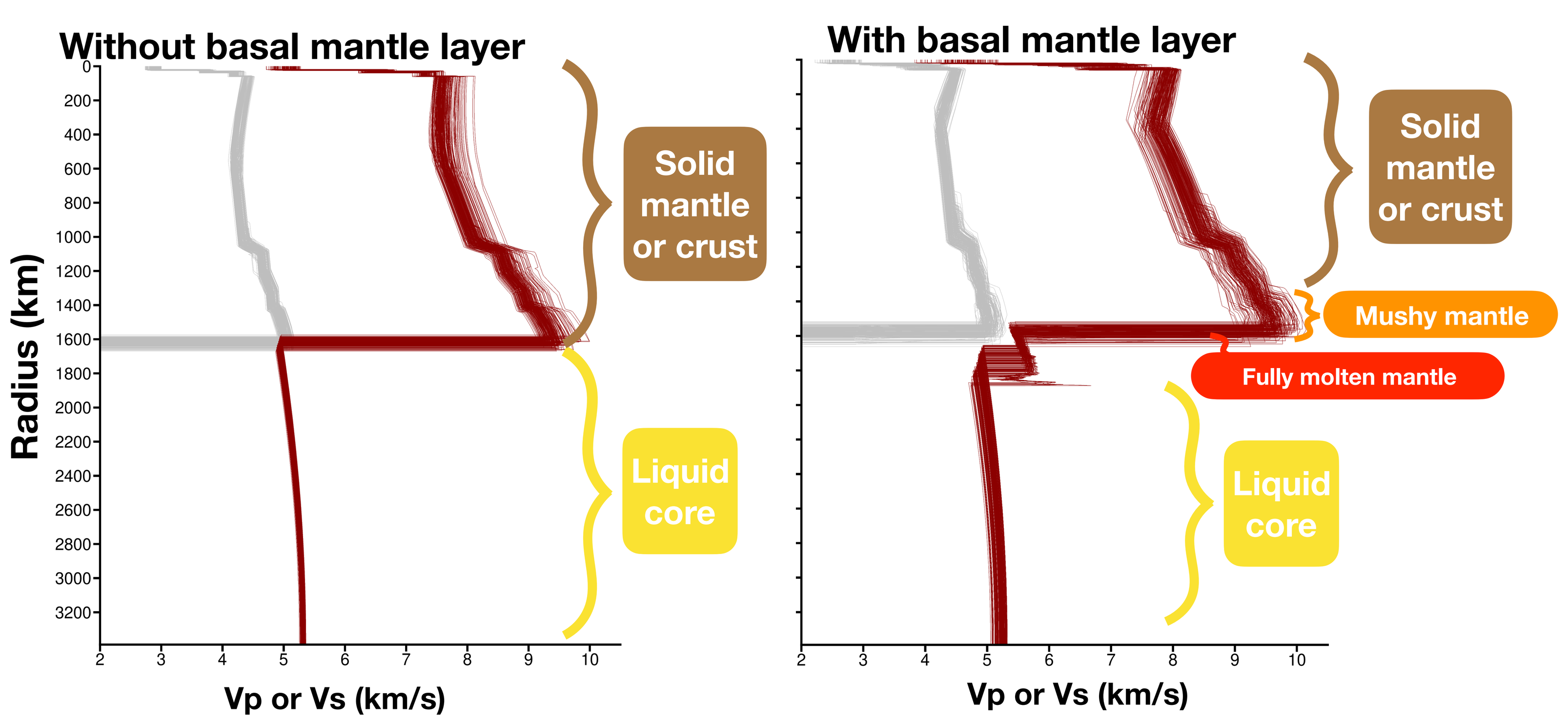
4. Inversion sets, seismic structures, and data fit

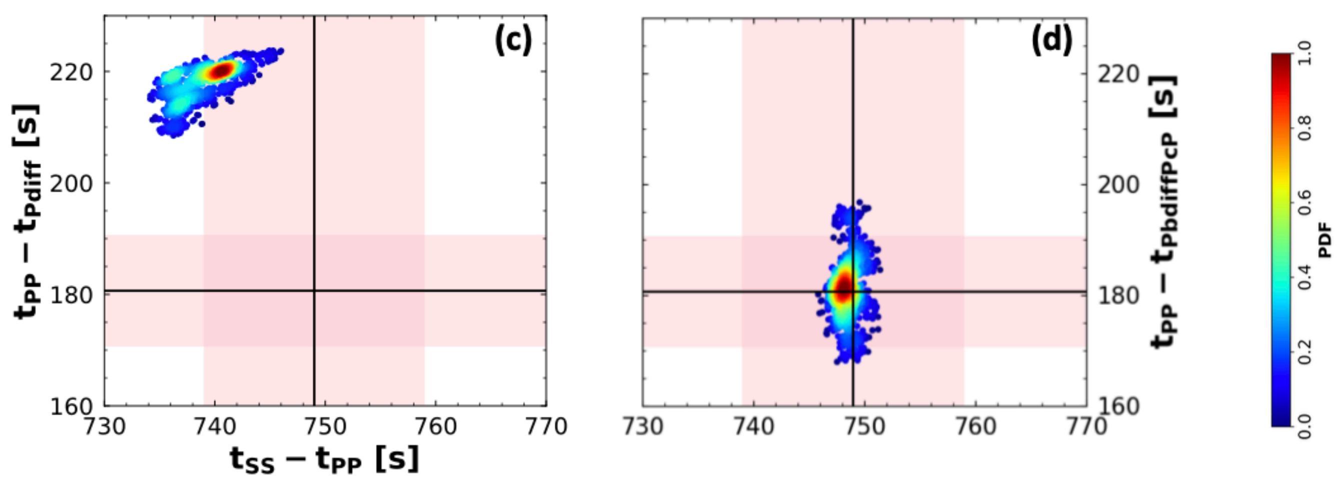
Homogeneous mantle (non-BML) | **Heterogeneous mantle (BML)**



√S waves reflected at the CMB
√Pdiff above the CMB

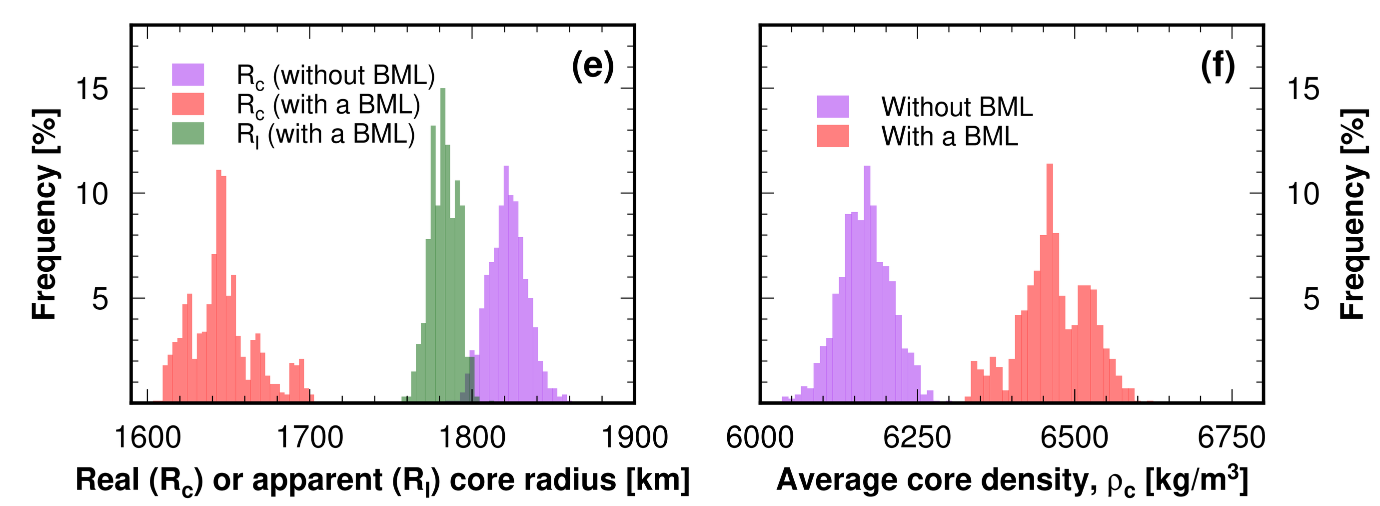
√S waves reflected above molten BML
√Pdiff travels within the BML: **PbdiffPcP**

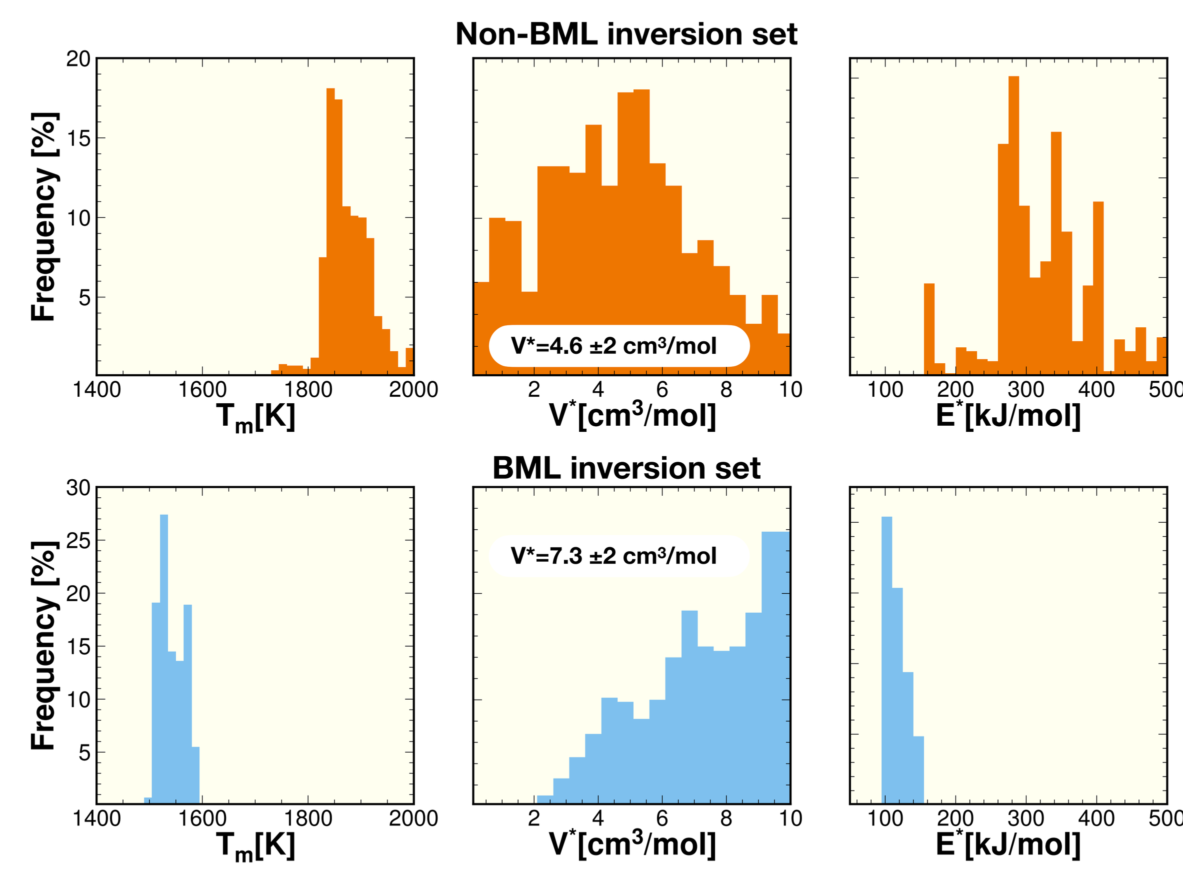




Homogeneous mantle models fail to explain the travel time observation for P-diffrated phases

5. Revised core size and composition



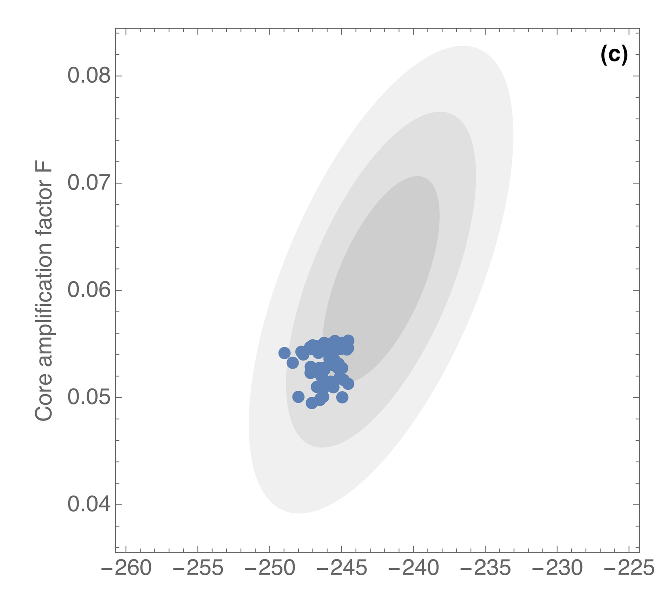


Mars' core is ~ 150-200 km smaller when a BML is present

Present-day BML mantle ~340 K colder

BML depth-dependent viscosity ~60% larger

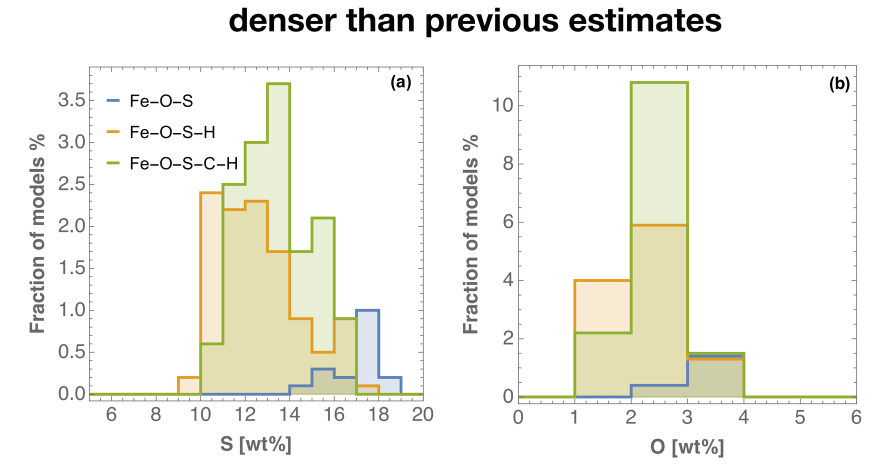
BML temperature-dependent viscosity ~3 times smaller



[Le Maistre et al., 2023]

BML compatible with geodetic data: k_2, FCN, Core amplification factor (~MoI_{core} / MoI_{mantle})

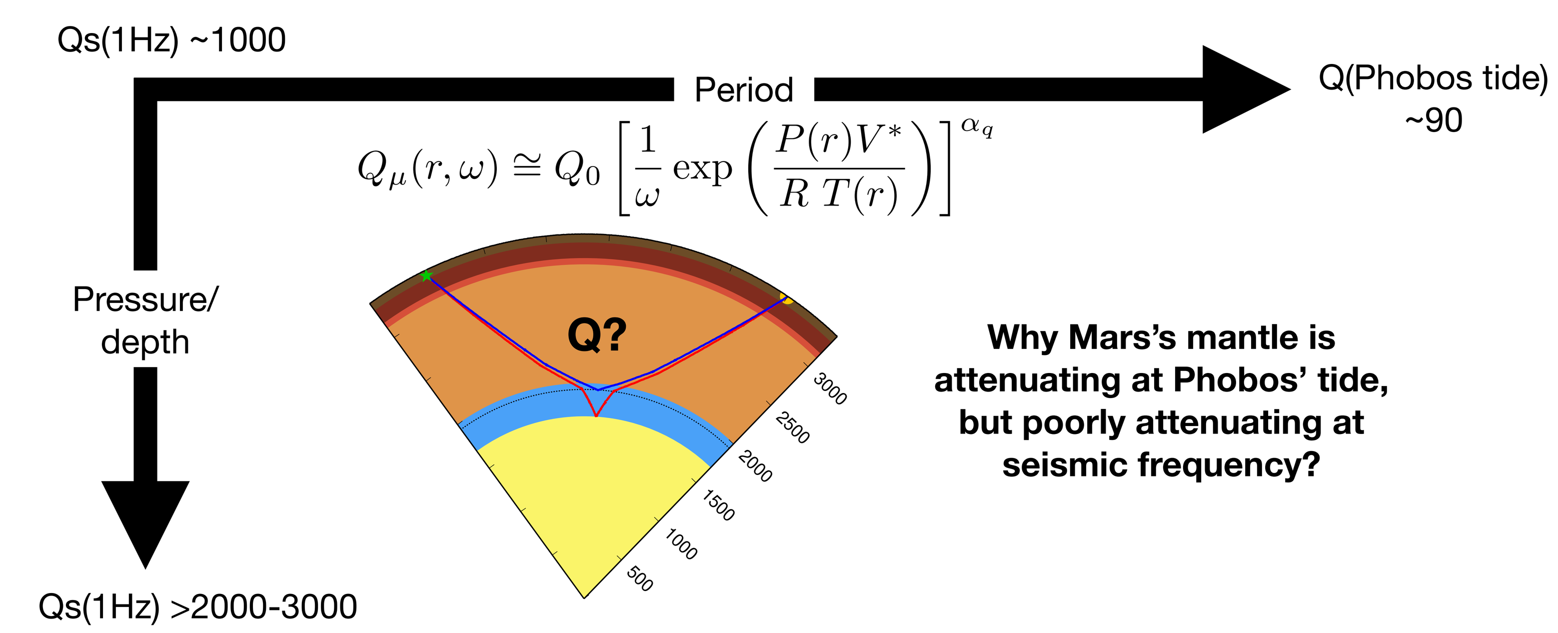
Revised core ~30% smaller and ~5-8% denser than previous estimates



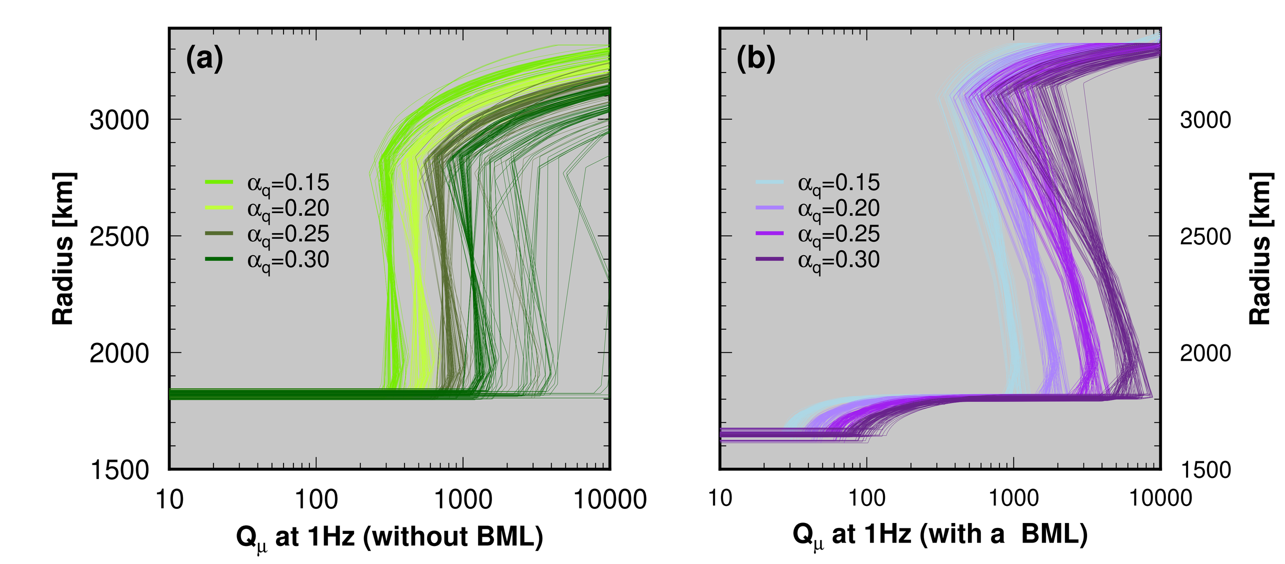
➪ Simpler mixtures with fewer, and smaller amounts of light elements (*e.g.*, Fe + 17% S and 3% O), or more complex mixture of S, O, H and C in smaller proportions

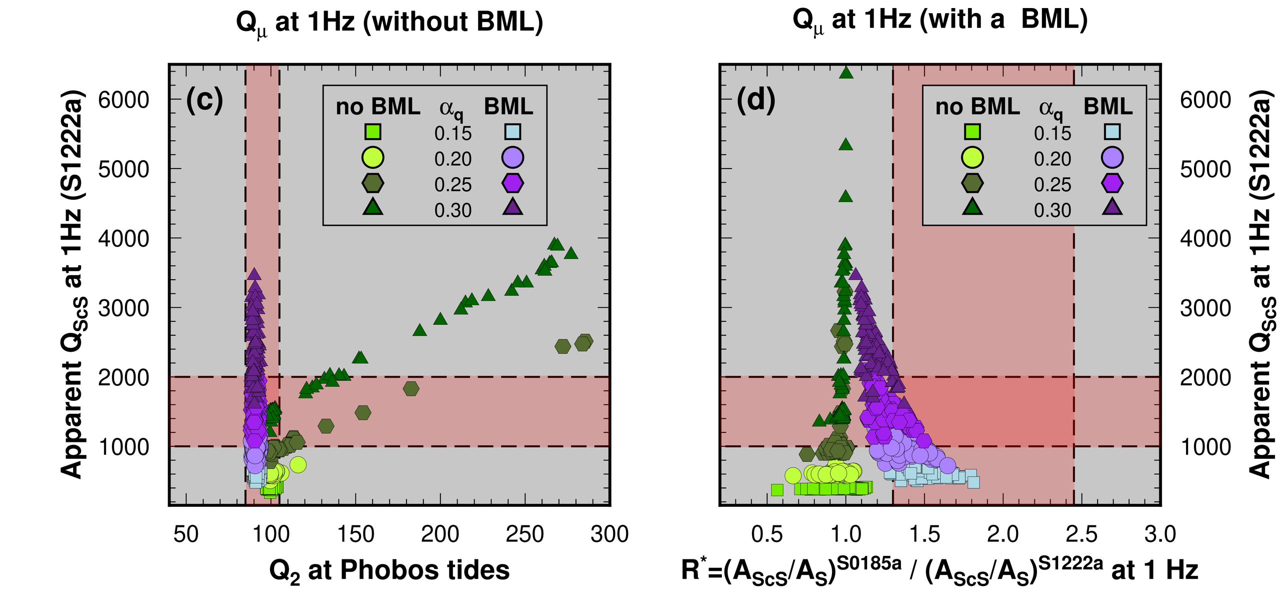
➪ **The core thermal blanketing of the BML requires external sources to power an early magnetic field**

6. Attenuation structure of Mars's mantle



Why Mars's mantle is attenuating at Phobos' tide, but poorly attenuating at seismic frequency?





✓ BML models can more easily explain attenuation at seismic frequencies and at Phobos main tide
✓ Only BML models can explain the slope of *Q* (*R**)
✓ One can constrain the frequency dependence of *Q*: α_q = 0.2-0.3

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[2] Posiolova L. et al. *Science*, **378** (2022)
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[6] Le Maistre et al., *Nature*, doi:10.1038/s41586-023-06150-0 (2023)
[7] H. Samuel, et al., Geophysical evidence for an enriched molten silicate layer above Mars' core, *Nature*, **622**, doi: 10.1038/s41586-023-06601-8, 2023