

Note

Complementary analyses further support a molten Basal Mantle Layer on Mars: A reply to Russell et al. (2026)

Henri Samuel ^{a,*}, Mélanie Drilleau ^a, Vedran Lekić ^b, Jessica C.E. Irving ^c, Zongbo Xu ^a, Quancheng Huang ^d, Raphaël F. Garcia ^e, Attilio Rivoldini ^f, James Badro ^a, Philippe H. Lognonné ^a, James A.D. Connolly ^g, Taichi Kawamura ^a, Tamara Gudkova ^h, William B. Banerdt ⁱ

^a Planetology and Space Sciences, Université Paris Cité, Institut de physique du globe de Paris, CNRS, 1 rue Jussieu, Paris, 75005, France

^b University of Maryland, College Park, USA

^c School of Earth Sciences, University of Bristol, Bristol, UK

^d Geophysical R&D Institute, China Oilfield Service Ltd, Tianjin, China

^e Institut Supérieur de l'Aéronautique et de l'Espace ISAE-SUPAERO, 10 Avenue Édouard Belin, Toulouse, France

^f Royal Observatory of Belgium, Brussels, Belgium

^g ETH Zurich, Zürich, Switzerland

^h Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, Russia

ⁱ Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA

ARTICLE INFO

Keywords:

Mars
Basal Mantle Layer
Geophysics
Planetary dynamics

ABSTRACT

Seismic data offer a unique window into planetary interiors. Here, following a note from Russell et al. (2026), we provide further analysis to solidify our identification of a seismic phase detected by the InSight mission as one which interacts with a basal mantle layer (BML) on Mars (Samuel et al., 2023a). We show that other mantle discontinuities or other seismic structures invoked in the aforementioned note are unlikely to produce this seismic signal. We further illustrate how our proposed layered structure is compatible with other available geophysical observations and geodynamical constraints, and can be used to make inferences about Martian evolution.

1. CMB-interacting phases on Mars

In Samuel et al. (2023a) we proposed that the seismic signal arriving ~ 176 s before the PP phase arrival is a compressional wave which both diffracts along the boundary between the solid mantle and a liquid basal mantle layer (BML), and is also reflected at the core–mantle boundary (a liquid–liquid interface). We label the seismic phase $Pb_{diff}PcP$ to indicate these important elements of the wavepath, while noting that the amplitude of the observed phase results from the simultaneous arrival of waves traveling along multiple paths, with diffraction occurring before and/or after reflection at the CMB (Supplementary Figs. 4–5 and our public response to reviewers (Samuel et al., 2023b)). We welcome the synthetic sensitivity kernel computed by Russell et al. (2026), using tools from Nissen-Meyer et al. (2014) and Stähler et al. (2016). These kernels corroborate our identification of the signal recorded for event S1000a. Additionally, they rule out the existence of the P_{diff}^{CMB} , which is consistent with our findings (Samuel et al., 2023b) and our inversion approach. The kernel clearly illustrates

the uniform sensitivity of the phase we label $Pb_{diff}PcP$ to the entire BML along the diffracted path. It also shows that any seismic arrivals coincident with $Pb_{diff}PcP$ would be sensitive to the mantle; we explore feasible mantle signals in Section 3.

We agree with Russell et al. (2026) that the BML structure we propose would also generate a wave which diffracts along the solid–liquid boundary at the top of the BML (Pb_{diff}). However, this phase is not “absent” in Samuel et al. (2023a): it is clearly visible and labeled in supplementary Figure 5(d–f). We (Samuel et al., 2023a) did not include the corresponding arrival time in our inversions, as they were less robust observations (similarly, this wavepacket was not identified or employed in Duran et al., 2022 or Horleston et al., 2022). We mark the arrival of a wavepacket that we label as Pb_{diff} , and another we label as $Pb_{diff}PcP2$ which has an extra reverberation in the BML, on Fig. 1. The amplitude and arrival times of these BML-interacting phases are discussed in detail in Section 3.

* Corresponding author.

E-mail address: samuel@ipgp.fr (H. Samuel).

<https://doi.org/10.1016/j.icarus.2026.117148>

Received 12 January 2026; Received in revised form 3 April 2026; Accepted 30 April 2026

Available online 12 May 2026

0019-1035/© 2026 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Russell et al. (2026) claims that BML interface topography is expected, and that it is likely to be large enough to increase $Pb_{\text{diff}}/Pb_{\text{diff}}PcP$ amplitude ratios. We do not find evidence to support these claims. First, we expect that the strong density jump at the BML caused by its iron enrichment would prevent significant topography of its surface, as shown in Samuel et al. (2021). Second, although the BML topography might reduce the relative amplitude of $Pb_{\text{diff}}PcP$, the opposite effect is also entirely possible (Emmerich, 1993; Shen et al., 2016; Wu et al., 2014; DeSilva et al., 2018), and Russell et al. (2026) did not provide arguments for why amplitude reduction is more likely to impact $Pb_{\text{diff}}PcP$. How the BML topography impacts $Pb_{\text{diff}}/Pb_{\text{diff}}PcP$ ratios depends on the spatial distribution and amplitude of the topography: parameters that are unknowable given the paucity of seismic observations on Mars, and are uncertain even for interfaces within the Earth (e.g., Koelemeijer, 2021).

2. Observational evidence for BML interacting signals

InSight seismic recordings consist of low amplitude signals prone to contamination by environmental noise, particularly wind, requiring careful analysis (Lognonné et al., 2020; Scholz et al., 2020; Kim et al., 2021; Ceylan et al., 2021; Stott et al., 2023, 2025). $Pb_{\text{diff}}PcP$ is a compressional wave, most prominently observed on the vertical component. Its identification included an analysis of the relative amounts of vertically- and horizontally-polarized motion (supplementary Figure 2 in Samuel et al., 2023a).

In Fig. 1a, we plot the particle motion around the $Pb_{\text{diff}}PcP$ phase in the frequency range where both signals and rectilinear motion are clearest: 0.5–0.8 Hz range and the first 6 s after the arrival (indicated by dashed lines in Fig. 1c–d). It is evident that the phase in question is characterized by vertically polarized linear motion; motion on the transverse component is approximately five times smaller than that on the vertical component, and half the size of that on the radial. The hodogram (Fig. 1a) clearly illustrates that the signal in question is characterized by P-type particle motion of a wave arriving with a steep angle of incidence, as expected for $Pb_{\text{diff}}PcP$. The low, but non-zero motion on the horizontal components is both consistent with a wave that is close to vertical incidence and explains why determining a stable backazimuth is challenging (e.g., Horleston et al., 2022).

The frequency range for the analyses in Samuel et al. (2023a) is chosen to avoid frequencies known to be impacted by wind noise (Clinton et al., 2021; Ceylan et al., 2021; Stott et al., 2023), while including those with strongest rectilinear motions. Environmental noise, as well as scattering by mantle heterogeneity, are expected to come from a range of different directions, so that their overall contribution is to render the particle motions more random and less rectilinear. This expectation runs contrary to Russell et al. (2026)'s interpretations that attribute the entire time-series, including time–frequency windows with prominent rectilinear motions, as resulting from mantle scattering. This is the reason why we underpin our interpretations with results from frequency-dependent polarization analysis – which has been workhorse of InSight data analysis (e.g., Stähler et al., 2021; Irving et al., 2023) – to identify time–frequency windows in which the signals are least likely to be contaminated by scattered energy (indicated in Fig. 1d–f).

Synthetic seismograms computed for models containing a BML (Section 3, Fig. 2b,d), predict three distinct arrivals (Pdiff, $Pb_{\text{diff}}PcP$, $Pb_{\text{diff}}PcP2$). The association of the observed arrivals (Fig. 1, Fig. 2a in Russell et al. (2026), Supplementary Figure 2 in Samuel et al. (2023a)) with these three phases is strongly supported by the equal time separation between them, as they differ only by the number of reverberations in the BML. Additionally, hodograms reveal that all three phases are dominated by vertical particle motions, as expected for P waves reaching the base of the mantle, but the phases that we did not invert in Samuel et al. (2023a) have slightly more energy on the transverse component (see Fig. 1e), which could indicate environmental noise and/or path complexity. The observed larger amplitude

of the $Pb_{\text{diff}}PcP$ phase compared to Pb_{diff} is consistent with synthetic waveforms produced in both Samuel et al. (2023a) (Supplementary Figure 5f) and Russell et al. (2026) (Figure 1d). The one notable difference between the data (e.g., Fig. 1 b–d) and our synthetics is the differential travel time between consecutive phase pairs ($Pb_{\text{diff}}PcP$ -Pdiff and $Pb_{\text{diff}}PcP2$ - $Pb_{\text{diff}}PcP$) is ~ 60 s in the S1000a data, and ~ 40 s in our synthetics. As we explained above, we did not use Pb_{diff} and $Pb_{\text{diff}}PcP2$ to develop the models in Samuel et al. (2023a), thus is unsurprising that their relative arrival times are not predicted. However, future inversions that include these different travel times could fit the ~ 60 s gap by increasing the thickness of the BML, or by decreasing its V_p , or a combination of the two.

3. Potential shallower mantle-generated seismic signals

Typically, seismologists have followed a parsimonious approach to building Earth models, ascribing seismic signals (and delay times) to radially varying structure before attempting to justify more complex laterally-varying heterogeneities. Additionally, seismological interpretations often build on complementary prior constraints from other fields. In particular, the presence of phase transitions leading to global (1D) seismic discontinuities at various depths in the solid Martian mantle is expected, making these transitions a well-motivated potential explanation for the seismic signals observed on Mars. We therefore considered in Samuel et al. (2023a) the possibility that the observed arrival(s) originated from mantle reflections, but concluded that shallower seismic phases generated by mineral phase transitions fail to explain the observations.

Mineralogical transformation of *olivine-to-wadsleyite* and *orthopyroxene-to-high-pressure-clinopyroxene* result in velocity contrasts at depths which correspond to zones of sensitivity in Russell et al. (2026)'s kernels. Alternative methods of examining InSight data have reported signals corresponding to mid-mantle mineralogical phase transitions on Mars (e.g., Huang et al., 2022; Deng and Levander, 2023). Predicted underside reflections from these contrasts, called PolP and PpvP, respectively, are shown in cyan and green in synthetic seismograms (Fig. 2a–d), and supplementary Figure 5 of Samuel et al. (2023a). In our simulations with and without a BML, neither PolP nor PpvP produces seismic signals large enough to be clearly identified. Without a BML, only Pdiff is observable (Fig. 2a, c).

Attributing the three phases arriving at 60 s intervals to precursors corresponding to different mineralogical phase transitions in the Martian mantle is not feasible: (i) A hotter mantle sharpens the *olivine-to-wadsleyite* transition on the V_p profile, enhancing PolP amplitudes, but it also causes the *orthopyroxene-to-high-pressure-clinopyroxene* transition to occur at similar depths (Fig. 2e–f). Therefore, only two phase arrivals are possible (Pdiff and PolpyP), with a PolpyP-Pdiff differential time hardly exceeding ~ 40 s. (ii) For a colder mantle, shallow mineralogical transitions occur at distinct depths, and three distinct arrivals are possible: Pdiff, PpvP, and PolP (Fig. 2c–d). However, even if scattering could amplify the amplitude of mid-mantle reflected phases, it would require excessive mantle cooling for these phases to reach a ~ 60 s differential time. Although, as highlighted in Russell et al. (2026)'s note, the seismic phases examined by Samuel et al. (2023a) are “approximately coincident with underside reflections from proposed mantle discontinuities independently inferred from InSight data”, such mid-mantle underside reflections cannot account for the S1000a signal, neither in arrival times nor in wave amplitudes. Therefore, BML models remain the strongest candidates to explain the coherent seismic arrivals of S1000a seismic event.

Russell et al. (2026) disagree with our interpretation that coherent, rectilinearly-polarized seismic phases arise from interaction with a BML on Mars, and suggests instead that scattering from heterogeneities in Mars's mid to lower mantle could generate the entire observed wave-train. While it is plausible that the Martian mantle contains sufficient

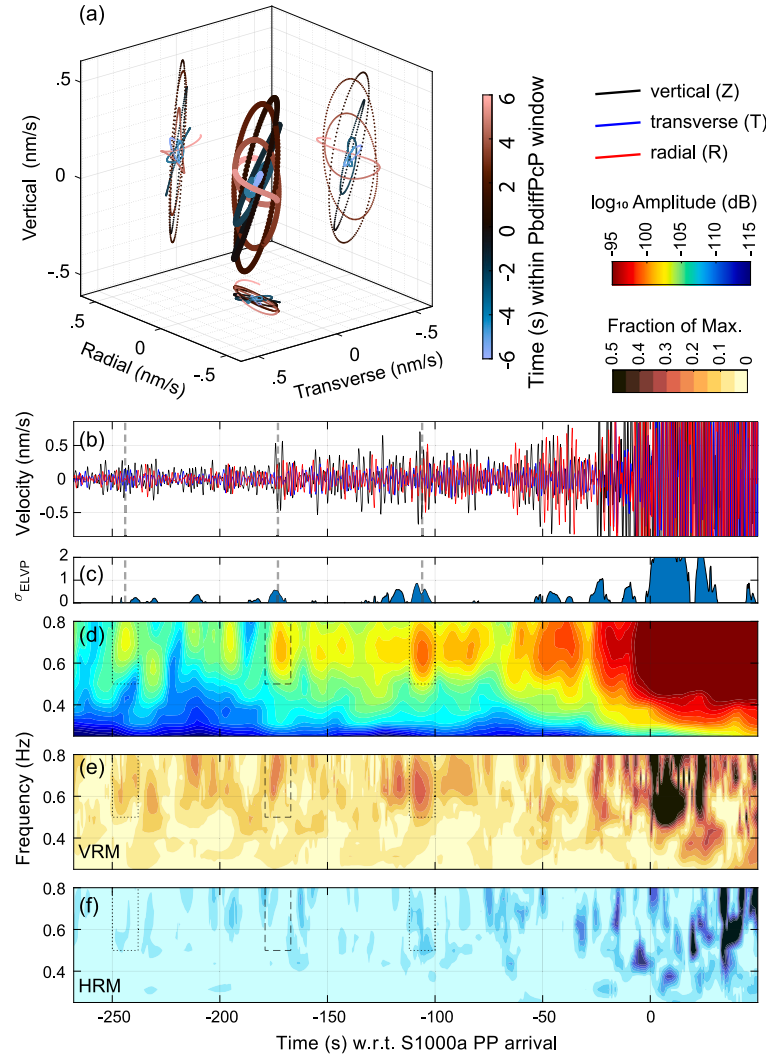


Fig. 1. Polarization analysis for event S1000a. (a) 3-D particle motion plot (hodogram) showing the primarily vertical polarization of the $Pb_{diff}PcP$ phase in the 0.5–0.8 Hz frequency range (corresponding to dashed rectangle in panels d–f). Before $Pb_{diff}PcP$ (blue), the amplitudes are smaller. As $Pb_{diff}PcP$ arrives (black), polarization becomes linear in the vertical and radial components. After $Pb_{diff}PcP$ (pink) the signal becomes more elliptical. (b) Velocity seismograms showing the three components of motion filtered in 0.5–0.8 Hz range. (c–f) Results of frequency dependent polarization analysis show that the $Pb_{diff}PcP$ signal (~176 s before PP arrival and indicated by the gray line) has strong amplitude (d) in the 0.5–0.8 Hz band and is characterized by an excess (c) of vertically-oriented (e) and near total absence of horizontally-oriented (f) rectilinear motion. Potential arrivals Pb_{diff} and $Pb_{diff}PcP2$ (dotted rectangles in panels d–f) arriving before and after $Pb_{diff}PcP$ show weak amplitudes and non-negligible horizontally-oriented rectilinear motion, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

structural variability to produce scattered seismic energy (e.g., Charalambous et al., 2025), such scattering would be expected to generate a diffuse coda distributed across all three components, rather than discrete, rectilinear arrivals. To support their argument, Russell et al. (2026) present a terrestrial example of “unambiguous scattering” from the 1993 Mw 7.5 earthquake south of the Mariana Islands recorded at station BFO. Although the three-component seismograms for this event are complex (Appendix Fig. A.1a–b), and we agree that they contain scattered arrivals, frequency-dependent polarization analysis (Appendix Fig. A.1c–f) reveals multiple, distinct arrivals with vertically polarized, rectilinear motion. As expected, the most prominent of these wavepackets correspond to Pdiff and PP. Other prominent vertically-polarized arrivals – which can appear with relatively restricted frequency ranges — correspond to interactions of Pdiff and PP with known 1D structures, including depth phases, receiver-side crustal multiples and interactions with mantle discontinuities, such as the 410. Of course, unlike terrestrial earthquakes, S1000a is a surface impact (Posiolova et al., 2022), precluding the existence of depth phases. Thus, the seismograms presented in Russell et al. (2026) demonstrate

that even on Earth, where we might not choose to interpret seemingly complex waveforms on individual records, prominent, rectilinearly-polarized arrivals within the scattered wavefield can be attributed to known 1D discontinuities. We suggest that this is also the case for the seismic signals we observe on Mars.

Importantly, although the examples selected by Russell et al. (2026) illustrate scattering on seismograms observed on Earth, they cannot be directly tested against Mars’s seismic record, in particular event S1000a, because the context is different and the true mantle and crustal structure is not known. As such, these selected examples represent qualitative empirical analogies with terrestrial observations. Only synthetic examples such as the ones displayed in Fig. 2 and in Samuel et al. (2023a), where the potential of alternative structures to explain the S1000a signals can be investigated, allow quantitative testing of possible structural scenarios. However, such tests are absent in Russell et al. (2026)’s note.

Finally, we stress that explaining the observed Pdiff-related phases with a 1D layered structure is simpler and provides testable predictions in a way that fortuitous scattering by 3D mantle structure cannot. The

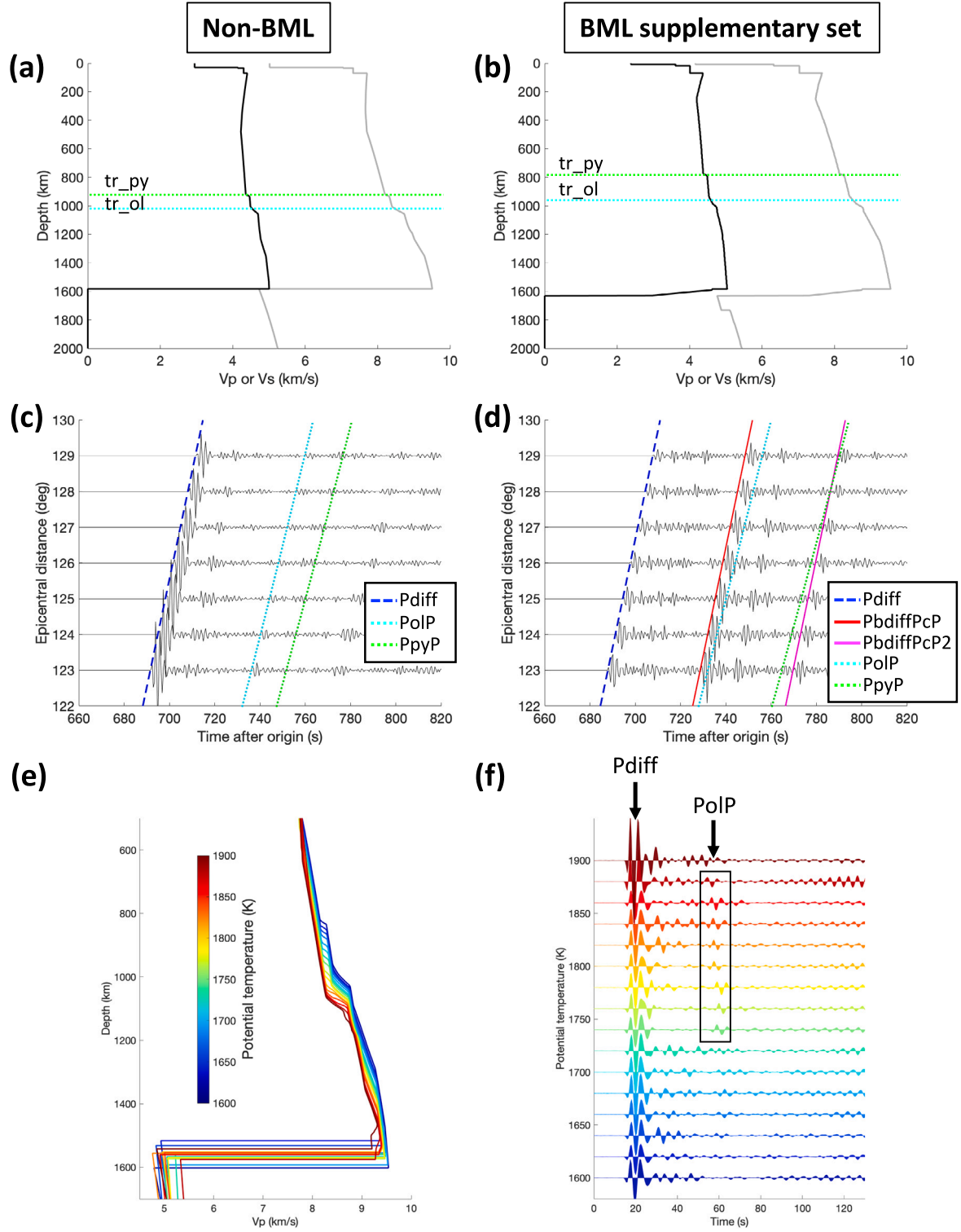


Fig. 2. Velocity models and synthetic seismograms. Panels (a–d) are modified from Samuel et al. (2023a)’s Supplementary Figure 5. Examples of velocity models of the non-BML (a) and supplementary BML inversion sets (b). (c,d) synthetic seismograms with predicted arrival times displayed with colored lines. We have added the arrival times of seismic phases reflected at the seismic discontinuities related to the *olivine-to-wadsleyite* and from *orthopyroxene-to-high-pressure-clinopyroxene* mineralogical transformations, shown in cyan and green, respectively. (e) and (f) present a suite of V_p profiles for non-BML models together with their corresponding waveforms, where each color represents a different potential temperature, ranging from 1600 K (dark blue) to 1900 K (dark red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

BML model sensitivity kernel shown in Russell et al. (2026) exhibits strong oscillatory behavior in the mid-mantle; this means that the contribution of putative extended structures that could give rise to the observed $P_{\text{diff}}P_{\text{cP}}$ arrival through scattering would tend to cancel out.

This is, in fact, the basis for the often-used stationary phase approximation in seismology (e.g., Romanowicz et al., 2008). In other words, for a mantle scatterer to produce the observed arrivals, it would have to have a serendipitously contorted shape that aligns with the lobes in

the oscillatory portion of the kernel. Such an alignment would only be expected for the specific path from the S1000a impact to the InSight lander. Because the patterns of kernel oscillations are path-dependent, the explanation in terms of mantle scattering would have no predictive power for other source–receiver pairs. As explained above, our preference for interpreting the observed signals in terms of 1D structure is consistent with standard practice in seismology; seismologists have historically proceeded to model the 1D structure of Earth prior to analyzing 3D velocity variations. Of course, other, less rectilinearly-polarized signals seen in the S1000a record, visible as complexity in Fig. 1b–f, could very well result from scattering by 3D structure (e.g., Karakostas et al., 2021; Menina et al., 2023; Charalambous et al., 2025).

4. Ancient dynamo

Russell et al. (2026) argue that the presence of a stably stratified BML would prevent core cooling and is thus incompatible the existence of a transient ancient magnetic field for several hundred millions years recorded in Mars's crust (Acuña et al., 1998; Johnson et al., 2020; Mittelholz et al., 2020). They rejected the alternative dynamo mechanisms (Acuña et al., 1998; Johnson et al., 2020; Mittelholz et al., 2020) put forward in Samuel et al. (2023a) and in Samuel et al. (2021), claiming that these could not generate the magnetic record for sufficiently long times, or could even prevent the dynamo from operating.

Regardless of the planet's structure, predicting dynamos is challenging because even state-of-the-art modeling is restricted to parameter spaces far from planetary core conditions (Christensen, 2010; Gastine et al., 2016). However, our simulation-based proposed mechanisms can quantitatively explain the longevity of Mars's dynamo. For example, elliptical instabilities triggered by ancient satellites that would have orbited the early Mars before impacting the planet (Arkani-Hamed, 2009) are well described in the literature (Cébron and Hollerbach, 2014; Kerswell, 2002; Sauret et al., 2014; Landeau et al., 2022), can sustain dynamos for hundreds of millions of years, and are supported by crater observations. Arkani-Hamed (2009), along with others cited in Samuel et al. (2021, 2023a), asserts magnetic field generation based on ohmic dissipation. This criterion is physically sound, widely used in the literature (Buffett, 2002; Gubbins, 1977; Labrosse, 2003; Stevenson et al., 1983), and represents a more restrictive condition than the sole outgoing core heat flux value frequently considered for Mars (Breuer and Spohn, 2003, 2006; Nimmo and Stevenson, 2000), which may be insufficient for powering thermal dynamos (Buffett, 2002; Monteux et al., 2011; Landeau et al., 2022).

Our proposed dynamo mechanisms constitute neither an exhaustive nor a definitive list. An alternative not discussed in Samuel et al. (2023a) would be that the BML formed hundred Myrs after Mars's accretion if the solidification of Mars's silicate magma ocean was delayed, for example as a result of a thicker and opaque early atmosphere (Kite, 2019). A thermal dynamo could have then operated on Mars prior to the genesis of the BML and its thermal blanketing of the core.

When summarizing our inversion approach that accounts for an enriched BML, Russell et al. (2026) mentioned that Samuel et al. (2023a) “argue for HPE enrichment and stable stratification” to “keep this layer molten”, which could be misleading as it may suggest that such a structure was manufactured and justified *a posteriori* to explain seismic data. We take this opportunity to clarify that the layer's molten state was originally an unpredicted outcome of our thermochemical evolution modeling (Samuel et al., 2021). This evolving state is embedded in our inversion approach (Drilleau et al., 2021), where the mantle is initially stratified and entirely at solid state, but was found to frequently evolve towards a fully and partially molten state in the lowermost mantle. Moreover, the formation of this stratified layer is also a natural outcome of early differentiation processes in planetary mantles (Boukaré et al., 2025; Ballmer et al., 2017; Maurice et al.,

2017). This is why the hypothetical implications of such BML on the interpretation Mars's seismic, geodetic and expected heat flow data were discussed in a modeling study (Samuel et al., 2021) prior to the first seismic detection of the Martian core (Stähler et al., 2021), and predating the detection of seismic signals attributed to deep mantle phases (Horleston et al., 2022).

5. HPE crustal content

Russell et al. (2026) claimed that Mars's crust contains at least half of the Bulk Silicate Mars (BSM) HPEs. This statement is based on Gamma-Ray Spectrometer (GRS) data that suffer from resolution issues, but also from critical assumptions, which could be revised in the frame of the BML scenario. As the commenters acknowledged in their note and in their previous works (Plesa et al., 2016, 2018), GRS data only probe Mars's sub-surface, leaving large uncertainty for deeper parts (Smrekar et al., 2019). Indeed, a considerable extrapolation from depths of few centimeters to tens of kilometers is necessary to infer Mars's crustal HPE content. Additionally, Mars's surface, including deep basins, is covered by dust, complicating the interpretation of GRS data. Importantly, despite occurring early in the planet's history crustal formation was probably gradual; it is unlikely that Mars's crust is homogeneous either laterally or with depth (Baratoux et al., 2014).

GRS data resolution is coarse ($5^\circ \times 5^\circ$ pixels, 90,000 km² Hahn et al., 2011), which masks HPE surface variability. Despite this, GRS data show variation in HPE ratios of a factor ~ 3 (Taylor et al., 2007). This variability is further underestimated by scale effects, as demonstrated on Earth by the large differences between HPE airborne measurements and *in situ* analyses (Baratoux et al., 2021), implying that HPE surface variations could be as large a factor of ~ 30 . Finally, inferring Mars's HPE crustal fraction requires making assumptions on BSM composition, which is also prone to uncertainties and assumptions, as illustrated by the variety of compositions in the literature (Khan et al., 2022; Lodders and Fegley, 1997; Morgan and Anders, 1979; Sanloup et al., 1999; Taylor, 2013; Treiman et al., 1986; Wanke and Dreibus, 1994; Yoshizaki and McDonough, 2020). Altogether, this suggests that GRS data alone may not unequivocally constrain relative or absolute crustal HPE content.

Finally, while the BML in Samuel et al. (2023a) was assumed to contain a major fraction of Mars's HPEs, more modest BML HPE enrichment (and hence, a crust more enriched in HPEs) would not necessarily prevent the basal layer from being molten, because its iron enrichment would still shift liquidus and solidus to colder temperatures, allowing most of this layer to remain above the melting curves. Additionally, the iron enrichment of the BML would reduce its thermal conductivity (Hsieh et al., 2018). That would lead to higher temperatures, which was not considered in Samuel et al. (2023a). Therefore, a more modest HPE enrichment of the BML (Cheng et al., 2025) could be investigated in future inversions of geophysical data.

6. Present-day lithospheric thickness

Using one model displayed in Samuel et al. (2023a), Russell et al. (2026) estimated a corresponding elastic thickness (T_e) that is less than 200 km, and claimed that this T_e value would be too thin to explain estimates obtained at the North polar cap (Broquet et al., 2025). Russell et al. (2026) further contrasted this value with previous models without a BML shown in Samuel et al. (2023a) and in work relying on thermal evolution modeling in 3D spherical geometry with a homogeneous mantle and a large core (Plesa et al., 2018), arguing that they better satisfy constraints on the present-day T_e . Estimating T_e requires making a number of assumptions, for example on the values of deformation time scales, or the lithospheric yield strength (Grott and Breuer, 2008, 2010; Thiriet et al., 2018; Plesa et al., 2018) – quantities that are not well constrained, and which can vary significantly depending on the location – or even to account for viscoelastic effects (Broquet et al.,

2025). Instead, Samuel et al. (2023a), provided average values for the thermal lithosphere thickness, which is expected to be larger than T_e , as illustrated by Russell et al. (2026)'s estimate.

We first remark that the present-day thermal lithosphere thickness range provided in Samuel et al. (2023a) corresponds to a one-standard deviation (σ) interval, therefore the global 3- σ range is broader: 200–320 km for the main BML inversion set (which we recall covers the best 1000 models only, not the entire population of retained output models). Consequently, the corresponding T_e estimate range is expected to be broader, and Figure 4 in Russell et al. (2026) that compares one model from Samuel et al. (2023a) with an envelope of models from Broquet et al. (2025) is therefore misleading (as also illustrated in our Fig. 3).

More importantly, because our model assumes 1D spherical symmetry, the lithospheric ranges given above correspond necessarily to global averages. Therefore, the requirement on local T_e values mentioned in Russell et al. (2026) is irrelevant since by construction the models in Samuel et al. (2023a) do not account for lateral variability in crustal and lithospheric thicknesses. The range of lithospheric thickness is known to be large for Mars, in particular there are contrasts between the Northern and the Southern hemispheres, as reported in the literature (e.g., Wieczorek et al., 2022; Knapmeyer-Endrun et al., 2021; Thiriet et al., 2018; Grott and Breuer, 2008; Plesa et al., 2018; Smrekar et al., 2019, and references therein) and illustrated in Fig. 3. Constraints on present-day T_e on Mars point to values ranging between 330 and 450 km in the Northern polar cap (Broquet et al., 2020), with possible T_e variations in the rest of the Northern hemisphere. In the Southern hemisphere, however, the present-day T_e have been constrained to considerably smaller values: with a best fit average value of 161 km under the South polar cap (Wieczorek, 2008) and a global range of 100–140 km (Grott and Breuer, 2008, 2010). Overall, this lateral variability results in a present-day average T_e value close to 150–200 km, as pointed out in Plesa et al. (2018) and reproduced in Fig. 3. This average value is compatible with the results in Samuel et al. (2023a) with a BML, and with the corresponding estimate given in Russell et al. (2026).

While Russell et al. (2026) acknowledged that the models in Samuel et al. (2023a) are one-dimensional, they claimed that lateral temperature and viscosity variations could not significantly affect the average T_e value, because in the 3D thermal models used to make inferences on the viscosity of the Martian mantle, their global viscosity profile is similar to the average value below the Northern cap (Fig. 4 in Russell et al. (2026)'s note). However, Russell et al. (2026)'s reasoning is flawed by the underlying assumptions made in Broquet et al. (2025), which neglected in particular (i) lateral crustal variations in HPEs, (ii) the progressive formation of the Martian crust, (iii) lateral variations in visco-elastic deformation, or (iv) the possibility of mantle compositional stratification.

It has been suggested that the Martian Southern crust could be enriched in HPEs by up to about a factor of two compared to that of the thinner Northern crust (Thiriet et al., 2018) (see also Section 5). Both 1D parameterized and dynamic modeling in 2D cylindrical and 3D spherical geometry have shown that this non-uniform HPE crustal enrichment can cause strong lateral differences in crustal and lithospheric thermal states (Thiriet, 2018), with a present-day Southern temperature profile 300 K hotter over more than 250 km depth than that of the Northern hemisphere. This also implies a Southern thermal lithosphere 150–200 km thicker than that of the Northern hemisphere (Thiriet et al., 2018; Bonnet-Gibet et al., 2022) (Fig. 4a), which would then affect the shallow viscosity structure of the Martian mantle. Even with a uniform HPE enrichment, similar behavior is observed (Thiriet et al., 2018) (Fig. 4b), at odds with what is claimed in Russell et al. (2026)'s note. Unfortunately, the possibility of non-uniform HPE content was not considered by Russell et al. (2026) and the influence of the North–South dichotomy was further hindered by computing the visco-elastic structure using 1D averages of their 3D dynamic modeling. Moreover,

in contrast to Samuel et al. (2023a) where both BML and non-BML structures were considered, the possibility of a compositionally stratified mantle in addition to a homogeneous mantle was not explored in Broquet et al. (2025). This set of *a priori* assumptions therefore unavoidably reduces the applicability of their constraints on Mars's lithospheric and viscosity structure.

While the models in Samuel et al. (2023a)'s inversions do not handle lateral variations, they account for the progressive formation and growth of the Martian crust inferred by observations (Greeley and Schneid, 1991; Nimmo and Tanaka, 2005; Solomon et al., 2005) via shallow melting and extraction. This two-way coupling between thermal state and crustal production is sometimes neglected in 3D studies, such as those quoted in Russell et al. (2026)'s note (Plesa et al., 2018; Broquet et al., 2025). Accounting for self-consistent crustal formation along with considering constraints on the present-day crustal thickness significantly reduces the population of plausible interior models for Mars (Knapmeyer-Endrun et al., 2021; Samuel et al., 2019, 2021; Drilleau et al., 2021, 2022, 2024), which likely impacts other characteristics of retained models, such as the present-day thermal state and lithospheric structure (e.g., Spohn, 1991; Breuer and Spohn, 2003; Schumacher and Breuer, 2006; Morschhauser et al., 2011; Thiriet et al., 2018; Huang et al., 2022). For these reasons, despite their simplicity, 1D models in Samuel et al. (2023a) may exhibit a higher level of self-consistency than inferences from 3D spherical models that prescribe a fixed Martian crust thickness from the beginning, at odds with the diversity of Mars crustal ages (Solomon et al., 2005).

Overall, the lithospheric thickness constraints considered in Russell et al. (2026)'s note are bounded by a number of aforementioned critical assumptions made for the thermal modeling and visco-elastic calculations, limiting their application at best to a narrow parameter space, where crustal formation and thermal evolution are decoupled, and where the Martian mantle can only be compositionally homogeneous.

Finally, the inversions in Samuel et al. (2023a) imposed no constraints on the present-day lithospheric thickness. We conducted a new inversion set with a BML, where only output models with present-day thermal lithosphere thicknesses (D_l , excluding the more deformable thermal boundary layer beneath it) thicker than 330 km are retained. The results displayed in Fig. 5 show that it is possible to have models that satisfy simultaneously seismic and geodetic data, along with constraints on the present-day crustal thickness (Knapmeyer-Endrun et al., 2021), with global D_l reaching values as high as 370 km, and even more if one includes the thermal boundary layer at the base of the lithosphere.

7. Present-day thermal state

Russell et al. (2026) pointed out differences in the thermal state of the solid mantle between Samuel et al. (2023a) and Khan et al. (2023). The fact that the present-day mantle in Samuel et al. (2023a) lies below Mars's solidus is not accidental. It essentially results from the fact that these models account for mantle melting and the consequent reduction on seismic velocities. Global shallow melting due to hot temperatures would reduce P and S seismic velocities by several tens of percents, thereby preventing matching the observed travel times for seismic events. In addition, similar to Knapmeyer-Endrun et al. (2021) the inversion performed in Samuel et al. (2023a) also checked for the occurrence of shallow melting that would produce widespread volcanism that would be at odds with observations.

Additionally, Russell et al. (2026) raised a concern about the differences in the thermal states inferred in Samuel et al. (2023a) (and Khan et al., 2023) with previous estimates based on less extensive seismic datasets (i.e., Huang et al., 2022; Drilleau et al., 2022; Khan et al., 2021; Duran et al., 2022). They attempted to underline these differences in their Figure 3, however this does not show the full story because it compares only two thermal profiles selected from the posterior distributions of two inversions sets, with ranges proposed in previous studies.

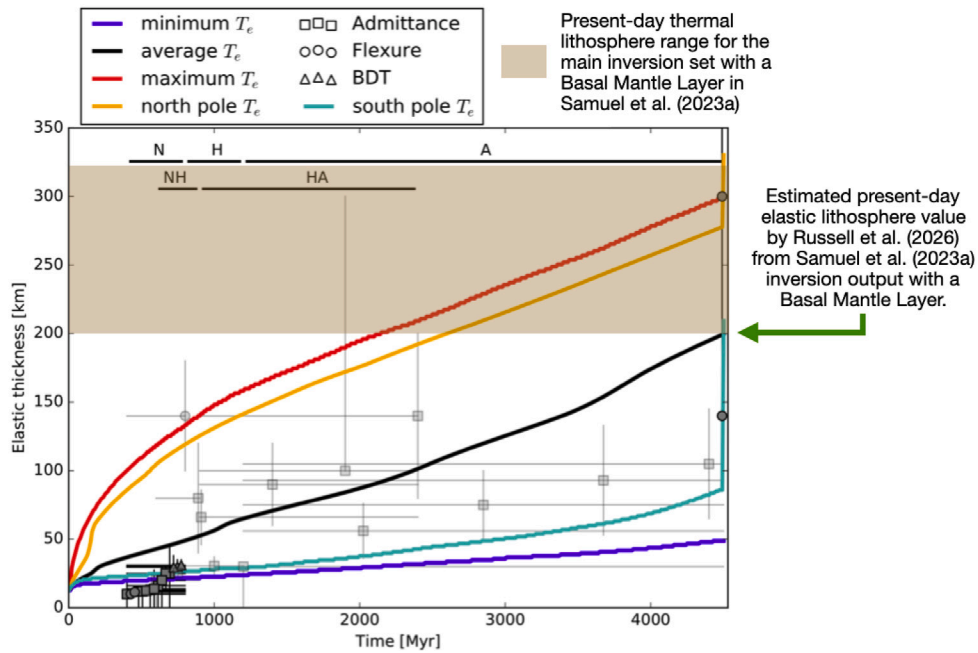


Fig. 3. Modified from Plesa et al. (2018) Supp. Figure 1 (a similar plot is also displayed in Fig. 7b in Smrekar et al., 2019). Evolution of the elastic lithosphere thickness (T_e) for a successful representative model (reference case 85 in Tables 1, 2 and 3 in Plesa et al., 2018) that agrees with small elastic thicknesses during the Noachian epoch and the present-day values for the north and south pole of Mars (full symbols). Other elastic thickness estimates are shown by transparent gray color, however, such estimates have not been used since they show large uncertainties. The jump shown by the colored lines for the north and south pole is due to the fact that to compute T_e for the present-day north and south pole Plesa et al. (2018) use deformation timescales associated with the deposition of the polar caps (and hence a strain rate of 10^{-14} s^{-1}), while for the evolution of the elastic thickness we use mantle convection timescales (of 10^{-17} s^{-1}). The letters “N”, “H”, “NH”, “HA” and “A” indicate Noachian, Hesperian, Noachian-Hesperian, Hesperian-Amazonian and Amazonian geological ages, respectively. Added items: range of present-day thermal lithosphere thicknesses derived from the main inversion set in Samuel et al. (2023a) is indicated in brown. The upper bound elastic lithosphere thickness claimed in Russell et al. (2026)’s note to be estimated from Samuel et al. (2023a) inversion output with a BML is indicated by a green arrow, closely coincides with the present-day average value (black line) of the reference model in Plesa et al. (2018), and lies well within the various estimates available (symbols). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

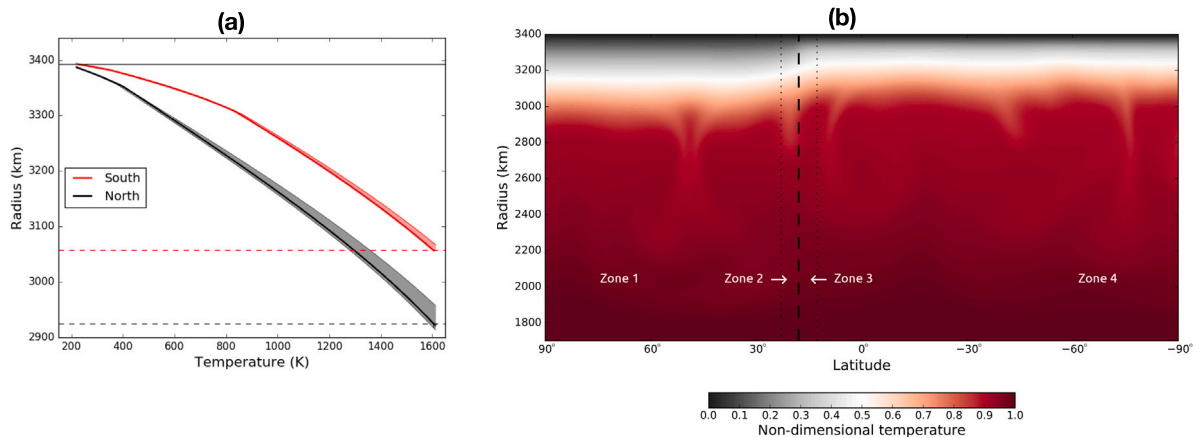


Fig. 4. Modeling results considering non-uniform crustal enrichment and/or crustal thickness for a Mars-like planet after 4.5 Gyr of evolution. (a) Parameterized convection evolution from Fig. 11 in Thiriet et al. (2018). Present-day temperature profile in the North (black) and in the South (red), for best models considered in Thiriet et al. (2018). The temperature profiles of the reference model are shown in bold lines. The Southern surface altitude is illustrated by the horizontal black line and the base of the stagnant lid by the dashed lines. The shaded areas correspond to the range of temperature profile obtained in the simulations that have the best fit to the constraints considered for both a uniform Crustal Model and Non-Uniform Crustal Model simulations. (b) Results of a (flattened) 2D cylindrical simulation considering a uniform crustal enrichment model but distinct Southern and Northern crustal thicknesses reproduced from Fig. 4.14 in Thiriet (2018). Zones 2 and 3 delimit of the Northern and Southern transition zones, respectively. The Northern and Southern hemispheres correspond to zones 1 and 4. The boundary of the North/South dichotomy (large dashed line) and the limits of the transition zones in the two hemispheres (dotted lines) are represented on a cross section of the mantle at the present-day from 90°N to 90°S. The color scale corresponds to the non-dimensional temperature. A similar outcome is also observed in simulations in 3D spherical geometry with either uniform or non-uniform crustal HPE enrichment (Fig. 4.13 in Thiriet, 2018). Panels (a) and (b) show that a significantly distinct thermal a viscous structures can exist beneath the two Martian hemispheres. In the models displayed in panels (a) and (b) the crustal thickness is fixed from the beginning of the simulations. Models that account for progressive crustal growth exhibit comparable differences in present-day lithospheric thicknesses (Bonnet-Gibet et al., 2022; Bonnet-Gibet et al., 2025). The North/South dichotomy in thermal states seen in both panels shows that very large lateral variations in viscosity are expected on Mars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

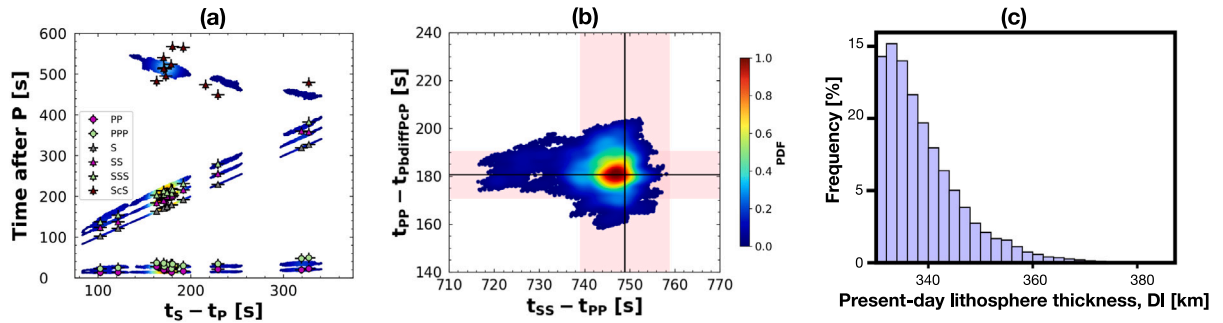


Fig. 5. Inversion results for a mantle with a BML and using the same data and approach as in Samuel et al. (2023a), with additional constraints on present-day lithospheric thickness D_l (i.e., $D_l > 330$ km). The results are displayed in terms of probability density functions (PDFs). Blue and red colors show small and large probabilities, respectively. (a) Body wave differential times with respect to P waves as a function of the travel time difference $t_S - t_P$ (subscripts refer to seismic phases). Markers and error bars represent observed differential arrival times and their uncertainty, respectively. (b) $t_{PP} - t_{PdiffPcP}$ as a function of $t_{SS} - t_{PP}$ for event S1000a. The observed differential travel time measurements are displayed with black lines. The pink bands indicate uncertainties on the measurements. (c) Present-day lithospheric thickness (excluding the thermal boundary layer at the uppermost mantle). Note that the models also satisfy constraints on the present-day crustal thickness and on Mars's k_2 love number, average density, and moment of inertia, as in Samuel et al. (2023a). Panels (a–b) show that it is possible to satisfy seismic constraints with large D_l (panel c) just as well as for the BML models Samuel et al. (2023a) that are associated with smaller D_l . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

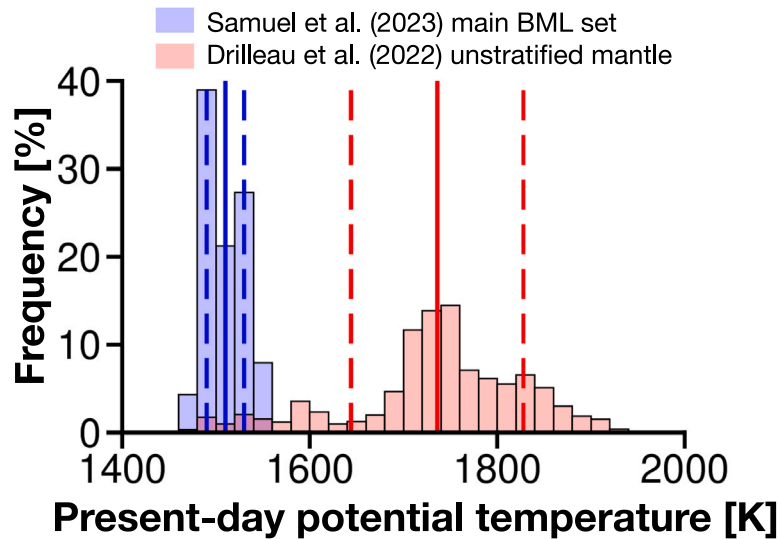


Fig. 6. Inversion outputs from Drilleau et al. (2022) (red) and Samuel et al. (2023a) main inversion set with a BML (blue). The histograms represent the posterior distributions for present-day mantle potential temperatures ranges, T_p , with the average value marked by solid vertical lines and the $1-\sigma$ range represented by vertical dashed lines for each distribution. Both inversions rely on the same approach (Drilleau et al., 2021) and use the same non-seismic constraints, but differ in that Drilleau et al. (2022) considers a homogeneous mantle and a smaller seismic dataset (i.e., notably with no deep mantle and core phases from event S1000a). The BML set is composed only of the 1000 best output models, as discussed in Samuel et al. (2023a), while the non-BML set from Drilleau et al. (2022) contains all (i.e., 20,000) retained models. While the $1-\sigma$ ranges of each distribution do not intersect, an overlap exists for T_p colder than ~ 1550 K. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Since the different studies quoted above do not necessarily rely on the same type of constraints or approaches (the paragraph above shows that the parameterization in the inversion does play a role), we will focus our demonstration below on the differences between the output from inversions we conducted (i.e., Drilleau et al., 2022; Samuel et al., 2023a). In contrast to the limited depiction in Russell et al. (2026)'s Figure 3, the entire range of potential mantle temperatures (T_p) inferred by Samuel et al. (2023a) is 1470–1550 K. Similarly, the entire T_p range from the inversions in Drilleau et al. (2022) is 1490–1940 K.

Therefore, as shown in Fig. 6, the two studies T_p distributions actually overlap. This is not visible in Russell et al. (2026)'s Figure 3 because the authors opt to display a single profile and narrower ($1-\sigma$) ranges. Thus, their figure does not indicate a lack of consistency among the results of different inversion studies, since these ranges constitute only a portion of the posterior distributions, and do not necessarily

correspond to models with the lowest misfit to the data because output distributions are multi-modal (Fig. 6). Instead, the gap and the differences between $1-\sigma$ ranges simply indicate that, fortunately, the available data play a dominant role in driving the results of inversions. It is therefore to be expected that the results of inversions using distinct datasets are not identical. A prime and obvious illustration of this reassuring fact is the contrasting layered mantle structure with molten BML above the Martian core, which gained support from the additional data from event S1000a, that was either absent from the datasets used in studies prior to 2023, or unexplained in the frame of an entirely solid Martian mantle (Horleston et al., 2022; Duran et al., 2022). Therefore, similarly to the viscous structure (see previous Section), it is worth realizing that several previous constraints on the thermal structure of the Martian mantle (e.g., Plesa et al., 2018; Khan et al., 2021; Pou et al., 2022; Huang et al., 2022) have been derived under the exclusive

assumption of a homogeneous Martian mantle. Consequently, for completeness these studies may need to be re-asserted in the frame of the presence of a BML. This would allow these model-dependent constraints to be properly confronted to compositionally stratified Martian mantle models.

It is also worth mentioning that in addition to the fact that a layered Martian mantle is a natural consequence of early planetary differentiation (see Section 4), the presence of a BML is not only supported by seismological data. A homogeneous Martian mantle favored by Russell et al. (2026) would result in a large metallic core (Stähler et al., 2021; Irving et al., 2023) with a low density, requiring high abundances of light elements that are not supported by cosmochemical considerations and petrological experimental data (Samuel et al., 2023a; Khan et al., 2023; van Driel et al., 2025). This documented central issue of the overabundance of light elements in the core associated with homogeneous Martian mantle is neither addressed nor mentioned in Russell et al. (2026)'s note.

8. Summary

The concerns raised by Russell et al. (2026) have underlined several critical differences in the inversion approach and the output models between Samuel et al. (2023a) and Khan et al. (2023). Notably, they confirmed that the interpretation of the seismic signals recorded on event S1000a as a Pb_{diff}PcP phase that sampled Mars's lowermost mantle is consistent with seismic sensitivity kernels. We further confirm this with a polarization analysis presented in this work. Russell et al. (2026)'s comments further allow us to point out that the present-day thermal structure inferred in Samuel et al. (2023a) for a Martian mantle with a BML is consistent with geophysical constraints, and does not result in shallow widespread global scale melting — as would occur with the hot areotherms — which is not observed today.

Other more specific comments made by Russell et al. (2026) offered us the opportunity to clarify that Mars's layered structure proposed in Samuel et al. (2023a) is compatible with geophysical, petrological, and geo-cosmochemical data available. We confirmed that several external mechanisms documented in the literature, and the protracted formation of the BML can explain the early transient magnetic field recorded in Mars's crust, that the HPE enrichment in the BML is not incompatible with GRS data that samples only the first few centimeters of Mars, and is prone to resolution and scale limitations.

We showed that the average lithospheric thickness provided in Samuel et al. (2023a) is consistent with the average present day elastic thickness. More importantly, we showed that despite its simplicity the 1D internal structures of Mars inferred in Samuel et al. (2023a)'s inversions stem from an approach accounting self-consistently for first-order feedback effects between thermal evolution, crust formation, and lithospheric thickening, sometimes neglected in more sophisticated 3D modeling used to derive the present-day thermochemical and viscous structure of Mars, such as those considered in Russell et al. (2026).

We clarified that the refined thermal structure proposed in Samuel et al. (2023a) is consistent with previous inversions (Stähler et al., 2021; Drilleau et al., 2022; Irving et al., 2023) relying on smaller data sets but conducted with a similar approach optimized for InSight's single-station multiple event context (Drilleau et al., 2020, 2021), and that the differences between the inversion output result from the distinct data set considered.

Finally, we further showed that alternative explanations to the Pb_{diff}PcP for the seismic signals recorded on event S1000a as phases interacting with two main, shallower, mantle discontinuities predicted by mineral physics are unable to reproduce the seismic observations.

While we welcome the calculations and constructive criticism raised in their note as an important part of the scientific process, Russell et al. (2026) did not provide a testable and quantitative alternative explanation for the seismic observations in the frame of all other available data and constraints on Mars. We nevertheless take this opportunity to

stress that although we confirmed that geophysical observations along with geodynamical constraints and experimental petrological data are best explained by the presence of an enriched BML, there is a need to pursue multi-disciplinary avenues of investigations to further unravel the puzzle of Mars's origin, formation and long-term evolution.

CRedit authorship contribution statement

Henri Samuel: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Mélanie Drilleau:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Conceptualization. **Vedran Lekić:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Jessica C.E. Irving:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Zongbo Xu:** Writing – review & editing, Methodology, Investigation. **Quancheng Huang:** Writing – review & editing, Methodology, Investigation. **Raphaël F. Garcia:** Writing – review & editing, Methodology, Investigation. **Attilio Rivoldini:** Writing – review & editing, Validation. **James Badro:** Investigation. **Philippe H. Lognonné:** Project administration, Investigation, Funding acquisition. **James A.D. Connolly:** Software, Investigation. **Taichi Kawamura:** Investigation. **Tamara Gudkova:** Investigation. **William B. Banerdt:** Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors are grateful to an anonymous reviewer and the editor for fruitful exchanges, and to Benoit Tauzin for his help with the synthetic seismogram calculations shown in Figure 2.

We acknowledge NASA, Centre National d'Etudes Spatiales (CNES), partner agencies and institutions (UK Space Agency, SSO, Deutsches Zentrum für Luft- und Raumfahrt, Jet Propulsion Laboratory, Institut de Physique du Globe de Paris - Centre National de la Recherche Scientifique, Eidgenössische Technische Hochschule Zürich, Imperial College London, and Max Planck Institute for Solar System Research (MPS-MPG)), and the operators of Jet Propulsion Laboratory, SEIS on Mars Operation Center (SISMOC), Mars Seismic Data Service (MSDS), EarthScope Data Management Center (DMC), and Planetary Data System (PDS) for providing Standard for the Exchange of Earthquake Data (SEED) SEIS data.

Co-authors affiliated to French laboratories thank the French Space Agency CNES and Agence Nationale de la Recherche fund (ANR-19-CE31-0008-08). JB acknowledges support from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement no. 101019965—ERC advanced grant SEPTiM). Additional support was obtained from IdEx Université Paris Cité ANR-18-IDEX-0001 for HS, ZX, PL, JB and TK. VL acknowledges support from NASA, United States grant 80NSSC18K1628 and NASA SSERVI Cooperative Agreement 80NSSC19M0216. JI acknowledges UK Space Agency, United Kingdom grant ST/W002515/1.

A. Rivoldini was financially supported by the Belgian PRODEX program managed by the European Space Agency in collaboration with the Belgian Federal Science Policy Office, contract number PEA4000140326 Planet Interior of the European Space Agency.

This project was provided with computing HPC and storage resources by Grand Équipement National de Calcul Intensif (GENCI) at Institut du Développement et des Ressources en Informatique Scientifique (IDRIS) thanks to grants AD010413017R3 and AD010413017R4 on the supercomputer Jean Zay CSL partition. Numerical computations were partly performed on the S-CAPAD/DANTE platform, IPGP, France.

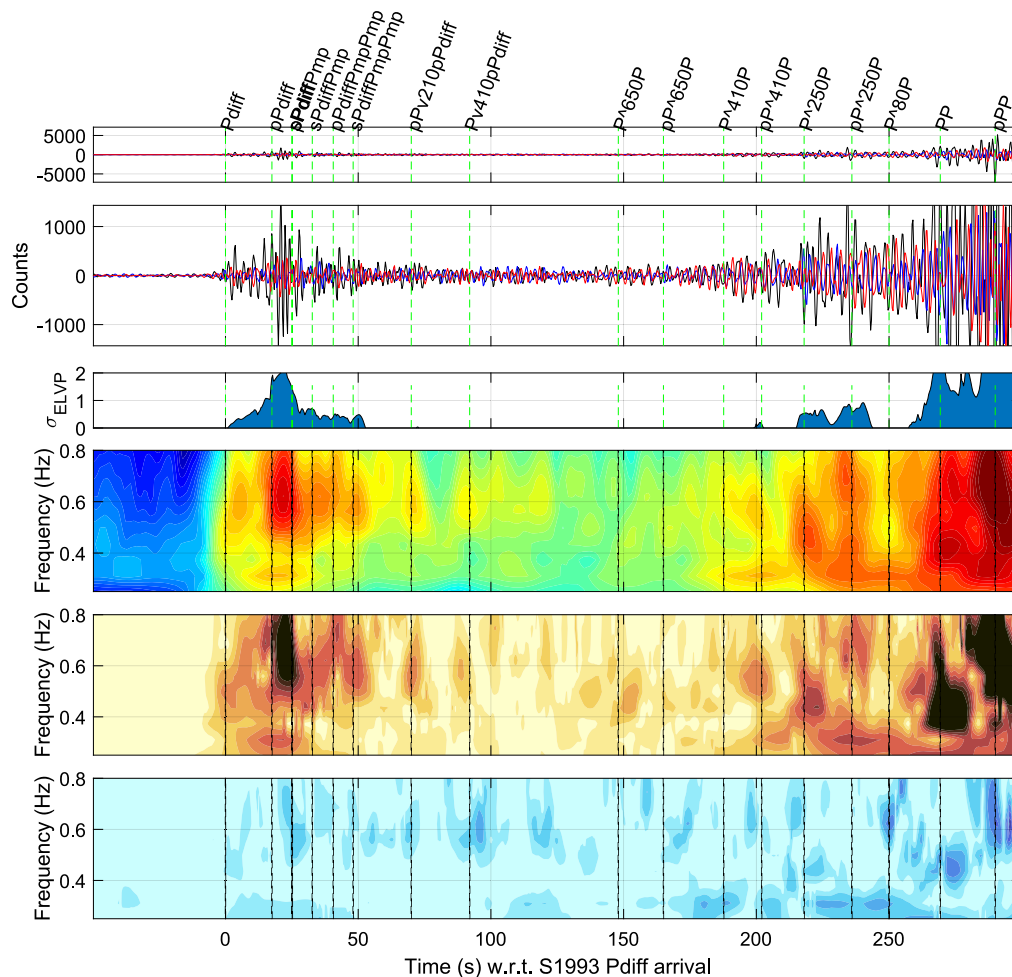


Fig. A.1. Frequency dependent polarization analysis (FDPA) analysis of the 1993-08-08, M_w 7.5, South of the Mariana Islands earthquake (Earth event 2 in Russell et al., 2026). Data were retrieved for station BFO, part of the GR network. Seismogram, spectrogram and FDPA analysis are made using the same approach as Fig. 1(b–f). Predictions for seismic arrivals are made using TauP (Crotwell et al., 1999), using realistic crustal and mantle 1D structures.

Appendix

See Fig. A.1.

Data availability

Terrestrial data were accessed from the National Science Foundation's National Geophysical Facility data archive operated by EarthScope Consortium (NSF award 2435260). These data were collected by the German Regional Seismic Network (GR; station BFO; Federal Institute for Geosciences and Natural Resources, 1976). InSight seismic data can be accessed via the NASA Planetary Data System or the National Geophysical Facility data archive where they have the network code XB (InSight Mars SEIS Data Service, 2019).

References

- Acuña, M.H., Connerney, J.P., Wasilewski, P., Lin, R.P., Anderson, K.A., Carlson, C.W., McFadden, J., Curtis, D.W., Mitchell, D., Reme, H., Mazelle, C., Sauvaud, J.A., d'Uston, C., Cros, A., Medale, J.L., Bauer, S.J., Cloutier, P., Mayhew, M., M. Winterhalter, D., Ness, N.F., 1998. Magnetic field and plasma observations at Mars: Initial results of the Mars global surveyor mission. *Science* 279, 1676–1680.
- Arkani-Hamed, J., 2009. Did tidal deformation power the core dynamo of Mars? *Icarus* 201 (1), 31–43.
- Ballmer, M.D., Lourenço, D.L., Hirose, K., Caracas, R., Nomura, R., 2017. Reconciling magma-ocean crystallization models with the present-day structure of the earth's mantle. *Geochem Geophys Geosyst* 18 (7), 2785–2806.
- Baratoux, D., Fall, M., Meslin, P.Y., Jessell, M.W., Vanderhaeghe, O., Moyen, J.F., Ndiaye, P.M., Boamah, K., Baratoux, L., André-Mayer, A.S., 2021. The impact of measurement scale on the univariate statistics of K, Th, and U in the Earth crust. *Earth Space Sci.* 8 (9), 1–16.
- Baratoux, D., Samuel, H., Michaut, C., Toplis, M.J., Monnereau, M., Wiczeorek, M., Garcia, R., Kurita, K., 2014. Petrological constraints on the density of the Martian crust. *J. Geophys. Res.: Planets* 119 (7), 1707–1727.
- Bonnet-Gibet, V., Dubuffet, F., Michaut, C., Bodin, T., Wiczeorek, M., 2025. Martian highlands differentiation concomitant to dichotomy formation. *J. Geophys. Res.: Planets* 130 (3), e2024JE008486.
- Bonnet-Gibet, V., Michaut, C., Wiczeorek, M., Lognonné, P., 2022. A positive feedback between crustal thickness and melt extraction for the origin of the Martian dichotomy. *J. Geophys. Res.: Planets* 127 (12), 1–28.
- Boukaré, C.-E., Badro, J., Samuel, H., 2025. Solidification of Earth's mantle led inevitably to a basal magma ocean. *Nature* 640, 114–119.
- Breuer, D., Spohn, T., 2003. Early plate tectonics versus single-plate tectonics on Mars: Evidence from magnetic field history and crust evolution. *J. Geophys. Res.: Planets* 108 (7), 1–8.
- Breuer, D., Spohn, T., 2006. Viscosity of the Martian mantle and its initial temperature: Constraints from crust formation history and the evolution of the magnetic field. *Planet. Space Sci.* 54 (2), 153–169.
- Broquet, A., Plesa, A., Klemann, V., Root, B.C., Genova, A., Wiczeorek, M.A., Knapmeyer, M., Breuer, D., 2025. Glacial isostatic adjustment reveals Mars's interior viscosity structure. *Nature* 639, 109–113.
- Broquet, A., Wiczeorek, M.A., Fa, W., 2020. Flexure of the lithosphere beneath the north polar cap of Mars: Implications for ice composition and heat flow. *Geophys. Res. Lett.* 47 (5), 1–8.
- Buffett, B.A., 2002. Estimates of heat flow in the deep mantle based on the power requirements for the geodynamo. *Geophys. Res. Lett.* 29 (12), 7–1–7–4.
- Cébron, D., Hollerbach, R., 2014. Tidally driven dynamos in a rotating sphere. *Astrophys. J. Lett.* 789 (1).

- Ceylan, S., Clinton, J.F., Giardini, D., Böse, M., Charalambous, C., van Driel, M., Horleston, A., Kawamura, T., Khan, A., Orhand-Mainsant, G., Scholz, J.R., Stähler, S.C., Euchner, F., Banerdt, W.B., Lognonné, P., Banfield, D., Beucier, E., Garcia, R.F., Kedar, S., Panning, M.P., Pike, W.T., Smrekar, S.E., Spiga, A., Dahmen, N.L., Hurst, K., Stott, A.E., Lorenz, R.D., Schimmel, M., Stutzmann, E., ten Pierick, J., Conejero, V., Pardo, C., Perrin, C., 2021. Companion guide to the marsquake catalog from InSight, sols 0-478: Data content and non-seismic events. *Phys. Earth Planet. Inter.* 310, 106597.
- Charalambous, C., Pike, W.T., Kim, D., Samuel, H., Fernando, B., Bill, C., Lognonné, P., Banerdt, W.B., 2025. Seismic evidence for a highly heterogeneous martian mantle. *Science* 389 (6763), 899–903.
- Cheng, K.W., Ballmer, M.D., Tackley, P.J., Khan, A., 2025. The impact of a long lived basal magma ocean on the thermochemical evolution of Mars. *J. Geophys. Res.: Planets* 130 (11), e2025JE009213.
- Christensen, U.R., 2010. Dynamo scaling laws and applications to the planets. *Space Sci. Rev.* 152 (1–4), 565–590.
- Clinton, J.F., Ceylan, S., van Driel, M., Giardini, D., Stähler, S.C., Böse, M., Charalambous, C., Dahmen, N.L., Horleston, A., Kawamura, T., Khan, A., Orhand-Mainsant, G., Scholz, J.R., Euchner, F., Banerdt, W.B., Lognonné, P., Banfield, D., Beucier, E., Garcia, R.F., Kedar, S., Panning, M.P., Perrin, C., Pike, W.T., Smrekar, S.E., Spiga, A., Stott, A.E., 2021. The marsquake catalogue from InSight, sols 0-478. *Phys. Earth Planet. Inter.* 310, 106595.
- Crotwell, H.P., Owens, T.J., Ritsema, J., 1999. The taup toolkit: Flexible seismic travel-time and ray-path utilities. *Seismol. Res. Lett.* 70 (2), 154–160.
- Deng, S., Levander, A., 2023. Seismic autocorrelation analysis of deep Mars. *Geophys. Res. Lett.* 50 (24), e2023GL105046.
- DeSilva, S., Cormier, V.F., Zheng, Y., 2018. Inner core boundary topography explored with reflected and diffracted P waves. *Phys. Earth Planet. Inter.* 276, 202–214.
- van Driel, J., Vočadlo, L., Brodholt, J., 2025. Thermodynamics of Fe-S-O-C-H liquids: Implications for the Martian core. *Earth Planet. Sci. Lett.* 668, 119540.
- Drilleau, M., Beucier, E., Lognonné, P., Panning, M., Knapmeyer-Endrun, B., Banerdt, W.B., Beghein, C., Ceylan, S., van Driel, M., Joshi, R., Kawamura, T., Khan, A., Menina, S., Rivoldini, A., Samuel, H., Stähler, S., Xu, H., Bonnin, M., Clinton, J., Giardini, D., Kenda, B., Lekic, V., Mocquet, A., Murdoch, N., Schimmel, M., Smrekar, S., Stutzmann, E., Tauzin, B., Tharimena, S., 2020. MSS/1: single-station and single-event marsquake inversion. *Earth Space Sci.* 7 (12), e2020EA001118.
- Drilleau, M., Samuel, H., Garcia, R.F., Rivoldini, A., Perrin, C., Michaut, C., Wiczorek, M., Tauzin, B., Connolly, J.A.D., Meyer, P., Lognonné, P., Banerdt, W.B., 2022. Marsquake locations and 1-D seismic models for Mars from InSight data. *J. Geophys. Res.: Planets* 127 (9), e2021JE007067.
- Drilleau, M., Samuel, H., Garcia, R.F., Rivoldini, A., Perrin, C., Wiczorek, M., Lognonné, P., Banerdt, W.B., 2024. Constraints on lateral variations of martian crustal thickness from seismological and gravity field measurements. *Geophys. Res. Lett.* 51 (4), e2023GL105701.
- Drilleau, M., Samuel, H., Rivoldini, A., Panning, M., Lognonné, P., 2021. Bayesian inversion of the martian structure using geodynamic constraints. *Geophys. J. Int.* 226 (3), 1615–1644.
- Duran, C., Khan, A., Ceylan, S., Charalambous, C., Kim, D., Drilleau, M., Samuel, H., Giardini, D., 2022. Observation of a core-diffracted p-wave from a farside impact with implications for the lower-mantle structure of Mars. *Geophys. Res. Lett.* 49 (21), e2022GL100887.
- Emmerich, H., 1993. Theoretical study on the influence of CMB topography on the core reflection ScS. *Phys. Earth Planet. Inter.* 80 (3–4), 125–134.
- Federal Institute for Geosciences and Natural Resources, 1976. German Regional Seismic Network (GRSN). <http://dx.doi.org/10.25928/mbx6-hr74>.
- Gastine, T., Wicht, J., Aubert, J., 2016. Scaling regimes in spherical shell rotating convection. *J. Fluid Mech.* 808, 690–732.
- Greeley, R., Schneid, B.D., 1991. Magma generation on Mars: amounts, rates, and comparisons with Earth, Moon, and Venus. *Science* 254 (5034), 996–998.
- Grott, M., Breuer, D., 2008. The evolution of the martian elastic lithosphere and implications for crustal and mantle rheology. *Icarus* 193 (2), 503–515.
- Grott, M., Breuer, D., 2010. On the spatial variability of the martian elastic lithosphere thickness: evidence for mantle plumes? *J. Geophys. Res.* 115 (E3), 116–163.
- Gubbins, D., 1977. Energetics of the Earth's core. *J. Geophys. Res.* 453–464.
- Hahn, B.C., McLennan, S.M., Klein, E.C., 2011. Martian surface heat production and crustal heat flow from Mars odyssey Gamma-ray spectrometry. *Geophys. Res. Lett.* 38 (14), 1–5.
- Horleston, A.C., Clinton, J.F., Ceylan, S., Giardini, D., Charalambous, C., Irving, J.C.E., Lognonné, P., Stähler, S.C., Zenhäusern, G., Dahmen, N.L., Duran, C., Kawamura, T., Khan, A., Kim, D., Plasman, M., Euchner, F., Beghein, C., Beucier, E., Huang, Q., Knapmeyer, M., Knapmeyer-Endrun, B., Lekic, V., Li, J., Perrin, C., Schimmel, M., Schmerr, N.C., Stott, A.E., Stutzmann, E., Teanby, N.A., Xu, Z., Panning, M., Banerdt, W.B., 2022. The far side of Mars: Two distant marsquakes detected by InSight. *Seism. Rec.* 2 (2), 88–99.
- Hsieh, W.P., Deschamps, F., Okuchi, T., Lin, J.F., 2018. Effects of iron on the lattice thermal conductivity of Earth's deep mantle and implications for mantle dynamics. *Proc. Natl. Acad. Sci. USA* 115 (16), 4099–4104.
- Huang, Q., Schmerr, N.C., King, S.D., Kim, D., Rivoldini, A., Plesa, A.-C., Samuel, H., Maguire, R.R., Karakostas, F., Lekic, V., Charalambous, C., Collinet, M., Myhill, R., Antonangeli, D., Drilleau, M., Bystricky, M., Bollinger, C., Michaut, C., Gudkova, T., Irving, J.C.E., Horleston, A., Fernando, B., Leng, K., Nissen-Meyer, T., Bejina, F., Bozdag, E., Beghein, C., Waszek, N.C., Scholz, J.-R., Davis, P.M., Lognonné, P., Pinot, B., Widmer-Schmidrig, R., Panning, M.P., Smrekar, S.E., Spohn, T., Pike, W.T., Giardini, D., Banerdt, W.B., 2022. Seismic detection of a deep mantle discontinuity within Mars by InSight. *Proc. Nat. Acad. Sci.* 119 (42), e2204474119.
- InSight Mars SEIS Data Service, 2019. SEIS raw data, InSight Mission. IPGP, JPL, CNES, ETHZ, ICL, MPS, ISAE-Supaero, LPG, MFSC. <http://dx.doi.org/10.18715/SEIS.INSIGHT.XB.2016>.
- Irving, J.C.E., Lekic, V., Duran, C., Drilleau, M., Kim, D., Rivoldini, A., Khan, A., Samuel, H., Antonangeli, D., Banerdt, W.B., Beghein, C., Bozdag, E., Ceylan, S., Clinton, J., Garcia, R., Giardini, D., Horleston, A., Huang, Q., Hurst, K.J., Kawamura, T., King, S., Knapmeyer, M., Li, J., Lognonné, P., Maguire, R., Panning, M.P., Plesa, A., Schimmel, M., Schmerr, N.C., Stähler, S., Stutzmann, E., Xu, Z., 2023. First observations of core-transiting seismic phases on Mars. *Proc. Nat. Acad. Sci.* 120 (18), e2217090120. <http://dx.doi.org/10.1073/pnas.2217090120>.
- Johnson, C.L., Mittelholz, A., Langlais, B., Russell, C.T., Ansan, V., Banfield, D., Chi, P.J., Fillingim, M.O., Forget, F., Haviland, H.F., Golombek, M., Joy, S., Lognonné, P., Liu, X., Michaut, C., Pan, L., Quantin-Nataf, C., Spiga, A., Stanley, S., Thorne, S.N., Wiczorek, M.A., Yu, Y., Smrekar, S.E., Banerdt, W.B., 2020. Crustal and time-varying magnetic fields at the InSight landing site on Mars. *Nat. Geosci.* 13 (3), 199–204.
- Karakostas, F., Schmerr, N., Maguire, R., Huang, Q., Kim, D., Lekic, V., Margerin, L., Nunn, C., Menina, S., Kawamura, T., Lognonné, P., Giardini, D., Banerdt, B., 2021. Scattering attenuation of the Martian interior through coda-wave analysis. *Bull. Seismol. Soc. Am.* 111 (6), 3035–3054.
- Kerswell, R.R., 2002. Elliptical instability. *Annu. Rev. Fluid Mech.* 34 (1), 83–113.
- Khan, A., Ceylan, S., van Driel, M., Giardini, D., Lognonné, P., Samuel, H., Schmerr, N.C., Stähler, S.C., Duran, A.C., Huang, Q., Kim, D., Broquet, A., Charalambous, C., Clinton, J.F., Davis, P.M., Drilleau, M., Karakostas, F., Lekic, V., McLennan, S.M., Maguire, R.R., Michaut, C., Panning, M.P., Pike, W.T., Pinot, B., Plasman, M., Scholz, J.-R., Widmer-Schmidrig, R., Spohn, T., Smrekar, S.E., Banerdt, W.B., 2021. Upper mantle structure of Mars from InSight seismic data. *Science* 373 (6553), 434–438.
- Khan, A., Huang, D., Durán, C., Sossi, P.A., Giardini, D., Murakami, M., 2023. Evidence for a liquid silicate layer atop the Martian core. *Nature* 622 (7984), 718–723.
- Khan, A., Sossi, P., Liebske, C., Rivoldini, A., Giardini, D., 2022. Geophysical and cosmochemical evidence for a volatile-rich Mars. *Earth Planet. Sci. Lett.* 578, 117330.
- Kim, D., Davis, P., Lekic, V., Maguire, R., Compaire, N., Schimmel, M., Stutzmann, E., Irving, J.C.E., Lognonné, P., Scholz, J.-R., Clinton, J., Zenhäusern, G., Dahmen, N., Deng, S., Levander, A., Panning, M.P., Garcia, R.F., Giardini, D., Hurst, K., Knapmeyer-Endrun, B., Nimmo, F., Pike, W.T., Pou, L., Schmerr, N., Stähler, S.C., Tauzin, B., Widmer-Schmidrig, R., Banerdt, W.B., 2021. Potential pitfalls in the analysis and structural interpretation of seismic data from the Mars InSight mission. *Bull. Seismol. Soc. Am.* 111 (6), 2982–3002.
- Kite, E.S., 2019. Geologic constraints on early Mars climate. *Space Sci. Rev.* 215 (1).
- Knapmeyer-Endrun, B., Panning, M.P., Bissig, F., Joshi, R., Khan, A., Kim, D., Lekic, V., Tauzin, B., Tharimena, S., Plasman, M., Compaire, N., Garcia, R.F., Margerin, L., Schimmel, M., Éléonore Stutzmann, N., Bozdag, E., Plesa, A.-C., Wiczorek, M.A., Broquet, A., Antonangeli, D., McLennan, S.M., Samuel, H., Michaut, C., Pan, L., Smrekar, S.E., Johnson, C.L., Brinkman, N., Mittelholz, A., Rivoldini, A., Davis, P.M., Lognonné, P., Pinot, B., Scholz, J.-R., Stähler, S., Knapmeyer, M., van Driel, M., Giardini, D., Banerdt, W.B., 2021. Thickness and structure of the martian crust from InSight seismic data. *Science* 373 (6553), 438–443.
- Koelemeijer, P., 2021. Toward Consistent Seismological Models of the Core-Mantle Boundary Landscape. *American Geophysical Union (AGU)*, pp. 229–255, chapter 9.
- Labrosse, S., 2003. Thermal and magnetic evolution of the Earth's core. *Phys. Earth Planet. Inter.* 140 (1–3), 127–143.
- Landeau, M., Fournier, A., Nataf, H.-C., Cébron, D., Schaeffer, N., 2022. Sustaining Earth's magnetic dynamo. *Nat Rev Earth Env.* 3, 255–269.
- Lodders, K., Fegley, B., 1997. An oxygen isotope model for the composition of Mars. *Icarus* 126 (2), 373–394.
- Lognonné, P., Banerdt, W.B., Pike, W.T., Giardini, D., Christensen, U., Garcia, R.F., Kawamura, T., Kedar, S., Knapmeyer-Endrun, B., Margerin, L., Nimmo, F., Panning, M., Tauzin, B., Scholz, J.-R., Antonangeli, D., Barkaoui, S., Beucier, E., Bissig, F., Brinkman, N., Calvet, M., Ceylan, S., Charalambous, C., Davis, P., van Driel, M., Drilleau, M., Fayon, L., Joshi, R., Kenda, B., Khan, A., Knapmeyer, M., Lekic, V., McClean, J., Mimoun, D., Murdoch, N., Pan, L., Perrin, C., Pinot, B., Pou, L., Menina, S., Rodriguez, S., Schmelzbach, C., Schmerr, N., Sollberger, D., Spiga, A., Stähler, S., Stott, A., Stutzmann, E., Tharimena, S., Widmer-Schmidrig, R., Andersson, F., Ansan, V., Beghein, C., Böse, M., Bozdag, E., Clinton, J., Daubar, I., Delage, P., Fuji, N., Golombek, M., Grott, M., Horleston, A., Hurst, K., Irving, J.C.E., Jacob, A., Knollenberg, J., Krasner, S., Krause, C., Lorenz, R., Michaut, C., Myhill, R., Nissen-Meyer, T., ten Pierick, J., Plesa, A.-C., Quantin-Nataf, C., Robertson, J., Rochas, L., Schimmel, M., Smrekar, S., Spohn, T., Teanby, N., Tromp, J., Vallade, J., Verdier, N., Vrettos, C., Weber, R., Banfield, D., Barrett, E.,

- Bierwirth, M., Calcutt, S., Compaire, N., Johnson, C.L., Mance, D., Euchner, F., Kerjean, L., Mainsant, G., Mocquet, A., Rodriguez Manfredi, J.A., Pont, G., Laudet, P., Nebut, T., de Raucourt, S., Robert, O., Russell, C.T., Sylvestre-Baron, A., Tillier, S., Warren, T., Wiecezorek, M., Yana, C., Zweifel, P., 2020. Constraints on the shallow elastic and anelastic structure of Mars from InSight seismic data. *Nat. Geosci.* 13 (3), 213–220.
- Maurice, M., Tosi, N., Samuel, H., Plesa, A.-C., Hüttig, C., Breuer, D., 2017. Onset of solid-state mantle convection and mixing during magma ocean solidification. *J. Geophys. Res.: Planets* 122 (1–2), 577–598. <http://dx.doi.org/10.1002/2016JE005250>.
- Menina, S., Margerin, L., Kawamura, T., Heller, G., Drilleau, M., Xu, Z., Calvet, M., Garcia, R., Knapmeyer-Endrun, B., Carrasco, S., et al., 2023. Stratification of heterogeneity in the lithosphere of Mars from envelope modeling of event S1222a and near impacts: Interpretation and implications for very-high-frequency events. *Geophys. Res. Lett.* 50 (7), e2023GL103202.
- Mittelholz, A., Johnson, C.L., Feinberg, J.M., Langlais, B., Phillips, R.J., 2020. Timing of the martian dynamo: New constraints for a core field 4.5 and 3.7 Ga ago. *Sci. Adv.* 6 (18), 1–7.
- Monteux, J., Jellinek, A.M., Johnson, C.L., 2011. Why might planets and moons have early dynamos? *Earth Planet. Sci. Lett.* 310 (3–4), 349–359.
- Morgan, J.W., Anders, E., 1979. Chemical composition of Mars. *Geochim. Cosmochim. Acta* 43 (10), 1601–1610.
- Morschhauser, A., Grott, M., Breuer, D., 2011. Crustal recycling, mantle dehydration, and the thermal evolution of Mars. *Icarus* 212 (2), 541–558.
- Nimmo, F., Stevenson, D.J., 2000. Influence of early plate tectonics on the thermal evolution and magnetic field of Mars. *J. Geophys. Res.: Planets* 105 (E5), 11969–11979.
- Nimmo, F., Tanaka, K., 2005. Early crustal evolution of Mars. *Annu. Rev. Earth Planet. Sci.* 33 (1), 133–161.
- Nissen-Meyer, T., van Driel, M., Stähler, S.C., Hosseini, K., Hempel, S., Auer, L., Colombi, A., Fournier, A., 2014. AxiSEM: broadband 3-D seismic wavefields in axisymmetric media. *Solid Earth* 5 (1), 425–445.
- Plesa, A.C., Grott, M., Tosi, N., Breuer, D., Spohn, T., Wiecezorek, M.A., 2016. How large are present-day heat flux variations across the surface of Mars? *J. Geophys. Res.: Planets* 121 (12), 2386–2403.
- Plesa, A.C., Padovan, S., Tosi, N., Breuer, D., Grott, M., Wiecezorek, M.A., Spohn, T., Smrekar, S.E., Banerdt, W.B., 2018. The thermal state and interior structure of Mars. *Geophys. Res. Lett.* 45 (22), 12, 198–112, 209.
- Posiolova, L.V., Lognonné, P., Banerdt, W.B., Clinton, J., Collins, G.S., Kawamura, T., Ceylan, S., Daubar, L.J., Fernando, B., Froment, M., Giardini, D., Malin, M.C., Miljković, K., Stähler, S.C., Xu, Z., Banks, M.E., Beucier, E., Cantor, B.A., Charalambous, C., Dahmen, N., Davis, P., Drilleau, M., Dundas, C.M., Durán, C., Euchner, F., Garcia, R.F., Golombek, M., Horleston, A., Keegan, C., Khan, A., Kim, D., Larmat, C., Lorenz, R., Margerin, L., Menina, S., Panning, M., Pardo, C., Perrin, C., Pike, W.T., Plasman, M., Rajšić, A., Rolland, L., Rougier, E., Speth, G., Spiga, A., Stott, A., Susko, D., Teanby, N.A., Valeh, A., Werynski, A., Wójcicka, N., Zenhäusern, G., 2022. Largest recent impact craters on Mars: Orbital imaging and surface seismic co-investigation. *Science* 378 (6618), 412–417.
- Pou, L., Nimmo, F., A. Rivoldini, A., Bagheri, A., Gray, T., Samuel, H., Lognonné, P., Plesa, A.-C., Gudkova, T., Giardini, D., 2022. Tidal constraints on the martian interior. *J. Geophys. Res.: Planets*.
- Romanowicz, B.A., Panning, M.P., Gung, Y., Capdeville, Y., 2008. On the computation of long period seismograms in a 3-D earth using normal mode based approximations. *Geophys. J. Int.* 175 (2), 520–536.
- Russell, S., Hannemann, K., Cottaar, S., Plesa, A.-C., Thomas, C., Breuer, D., 2026. An examination of the evidence for and feasibility of a molten silicate basal layer in Mars' mantle. *Icarus* 457, 117149. <http://dx.doi.org/10.1016/j.icarus.2026.117149>.
- 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. *J. Geophys. Res.: Planets* 126 (4), e2020JE006613. e2020JE006613 2020JE006613.
- Samuel, H., Drilleau, M., Rivoldini, A., Xu, Z., Huang, Q., Garcia, R.F., Lekić, V., Irving, J.C.E., Badro, J., Lognonné, P.H., Connolly, J.A., Kawamura, T., Gudkova, T., Banerdt, W.B., 2023a. Geophysical evidence for an enriched molten silicate layer above Mars's core. *Nature* 622 (7984), 712–717.
- Samuel, H., Drilleau, M., Rivoldini, A., Xu, Z., Huang, Q., Garcia, R.F., Lekić, V., Irving, J.C.E., Badro, J., Lognonné, P.H., Connolly, J.A., Kawamura, T., Gudkova, T., Banerdt, W.B., 2023b. Peer review file for: geophysical evidence for an enriched molten silicate layer above Mars's core. https://static-content.springer.com/esm/art/10.1038/s41586-023-06601-8/MediaObjects/41586_2023_6601_MOESM2_ESM.pdf.
- Samuel, H., Lognonné, P.H., Panning, M., Lainey, V., 2019. The rheology and thermal history of Mars revealed by the orbital evolution of Phobos. *Nature* 569, 523–527. <http://dx.doi.org/10.1038/s41586-019-1202-7>.
- Sanloup, C., Jambon, A., Gillet, P., 1999. A simple chondritic model of Mars. *Phys. Earth Planet. Inter.* 112 (1–2), 43–54.
- Sauret, A., Le Bars, M., Le Gal, P., 2014. Tide-driven shear instability in planetary liquid cores. *Geophys. Res. Lett.* 41 (17), 6078–6083.
- Scholz, J.R., Widmer-Schmidrig, R., Davis, P., Lognonné, P., Pinot, B., Garcia, R.F., Hurst, K., Pou, L., Nimmo, F., Barkaoui, S., deÁ Raucourt, S., Knapmeyer-Endrun, B., Knapmeyer, M., Orhand-Mainsant, G., Compaire, N., Cuvier, A., Beucier, É., Bonnin, M., Joshi, R., Sainton, G., Stutzmann, E., Schimmel, M., Horleston, A., Böse, M., Ceylan, S., Clinton, J., vanÁ Driel, M., Kawamura, T., Khan, A., Stähler, S.C., Giardini, D., Charalambous, C., Stott, A.E., Pike, W.T., Christensen, U.R., Banerdt, W.B., 2020. Detection, analysis, and removal of glitches from InSight's seismic data from Mars. *Earth Space Sci.* 7 (11), 1–25.
- Schumacher, S., Breuer, D., 2006. Influence of a variable thermal conductivity on the thermochemical evolution of Mars. *J. Geophys. Res.: Planets* 111 (9), E02006.
- Shen, Z., Ni, S., Wu, W., Sun, D., 2016. Short period ScP phase amplitude calculations for core-mantle boundary with intermediate scale topography. *Phys. Earth Planet. Inter.* 253, 64–73.
- Smrekar, S.E., Lognonné, P., Spohn, T., Banerdt, B., Breuer, D., Christensen, U., Dehant, V., Drilleau, M., Folkner, W., Fujii, N., Garcia, R., Giardini, D., Golombek, M., Grott, M., Gudkova, T., Johnson, C., Khan, A., Langlais, B., Mittelholz, A., Mocquet, A., Myhill, R., Panning, M., Perrin, C., Pike, T., Plesa, A.-C., Rivoldini, A., Samuel, H., van Hoolst, T., Verhoeven, O., Weber, R., Wiecezorek, M., 2019. Pre-mission InSights on the interior of Mars. *Space Sci. Rev.* 215, 3.
- Solomon, S.C., Aharonson, O., Aurnou, J.M., Banerdt, W.B., Carr, M.H., Dombard, A.J., Frey, H.V., Golombek, M.P., Ii, S.A.H., Iii, J.W.H., Jakosky, B.M., Johnson, C.L., McGovern, P.J., Neumann, G.A., Phillips, R.J., Smith, D.E., Zuber, M.T., 2005. New perspectives on ancient Mars. *Science* 307, 1214–1220.
- Spohn, T., 1991. Mantle differentiation and thermal evolution of Mars, Mercury, and Venus. *Icarus* 90 (2), 222–236.
- Stähler, S.C., Khan, A., Banerdt, W.B., Lognonné, P., Giardini, D., Ceylan, S., Drilleau, M., Duran, A.C., Garcia, R.F., Huang, Q., Kim, D., Lekić, V., Samuel, H., Schimmel, M., Schmerr, N., Sollberger, D., Stutzmann, É., Xu, Z., Antonangeli, D., Charalambous, C., Davis, P.M., Irving, J.C.E., Kawamura, T., Knapmeyer, M., Maguire, R., Marusiak, A.G., Panning, M.P., Perrin, C., Plesa, A.-C., Rivoldini, A., Schmelzbach, C., Zenhäusern, G., Beucier, É., Clinton, J., Dahmen, N., van Driel, M., Gudkova, T., Horleston, A., Pike, W.T., Plasman, M., Smrekar, S.E., 2021. Seismic detection of the martian core. *Science* 373 (6553), 443–448.
- Stähler, S.C., van Driel, M., Auer, L., Hosseini, K., Sigloch, K., Nissen-Meyer, T., 2016. MC kernel: broadband waveform sensitivity kernels for seismic tomography. In: EGU General Assembly Conference Abstracts, vol. 18, EGU2016–7020–2.
- Stevenson, D.J., Spohn, T., Schubert, G., 1983. Magnetism and thermal evolution of the terrestrial planets. *Icarus* 54 (3), 466–489.
- Stott, A.E., Garcia, R.F., Chédozeau, A., Spiga, A., Murdoch, N., Pinot, B., Mimoun, D., Charalambous, C., Horleston, A., King, S.D., Kawamura, T., Dahmen, N., Barkaoui, S., Lognonné, P., Banerdt, W.B., 2023. Machine learning and marsquakes: a tool to predict atmospheric-seismic noise for the NASA InSight mission. *Geophys. J. Int.* 233 (2), 978–998.
- Stott, A.E., Garcia, R.F., Murdoch, N., Mimoun, D., Drilleau, M., Newman, C., Spiga, A., Banfield, D., Lemmon, M., Navarro, S., Mora-Sotomayor, L., Charalambous, C., Pike, W.T., Lognonné, P., Banerdt, W.B., 2025. Windsightnet: the inter-annual variability of martian winds retrieved from InSight's seismic data with machine learning. *J. Geophys. Res.: Planets* 130 (2), e2024, e2024JE008695. e2024JE008695 2024JE008695.
- Taylor, G.J., 2013. The bulk composition of Mars. *Geochemistry* 73 (4), 401–420.
- Taylor, G.J., Stopar, J.D., Boynton, W.V., Karunatillake, S., Keller, J.M., Brückner, J., Wänke, H., Dreibus, G., Kerry, K.E., Reedy, R.C., Evans, L.G., Starr, R.D., Martel, L.M., Squyres, S.W., Gasnault, O., Maurice, S., D'Uston, C., Englert, P., Dohm, J.M., Baker, V.R., Hamara, D., Janes, D.M., Sprague, A.L., Kim, K.J., Drake, D.M., McLennan, S.M., Hahn, B.C., 2007. Variations in K/Th on Mars. *J. Geophysical Research: Planets* 112 (3).
- Thiriet, M., 2018. Effect of the north/south dichotomy on the thermal structure and evolution of Mars (Ph.D. thesis). Université Sorbonne Paris Cité École Doctorale STEP'UP – ED 560.
- Thiriet, M., Michaut, C., Breuer, D., Plesa, A.C., 2018. Hemispheric dichotomy in lithosphere thickness on Mars caused by differences in crustal structure and composition. *J. Geophys. Res.: Planets* 123 (4), 823–848.
- Treiman, A.H., Drake, M.J., Janssens, M.J., Wolf, R., Ebihara, M., 1986. Core formation in the Earth and Shergottite parent body (SPB): Chemical evidence from basalts. *Geochim. Cosmochim. Acta* 50 (6), 1071–1091.
- Wanke, H., Dreibus, G., 1994. Chemistry and accretion history of Mars. *Philos. Trans. R. Soc. Lond. Ser. A: Phys. Eng. Sci.* 349 (1690), 285–293.
- Wiecezorek, M.A., 2008. Constraints on the composition of the martian south polar cap from gravity and topography. *Icarus* 196 (2), 506–517.
- Wiecezorek, M.A., Broquet, A., McLennan, S.M., Rivoldini, A., Golombek, M., Antonangeli, D., Beghein, C., Giardini, D., Gudkova, T., Gyalay, S., Johnson, C.L., Joshi, R., Kim, D., King, S.D., Knapmeyer-Endrun, B., Lognonné, P., Michaut, C., Mittelholz, A., Nimmo, F., Ojha, L., Panning, M.P., Plesa, A.C., Sieglar, M., Smrekar, S.E., Spohn, T., Banerdt, W.B., 2022. InSight constraints on the global character of the Martian crust. *J. Geophys. Res.: Planets* 127 (5), 1–35.
- Wu, W., Ni, S., Shen, Z., 2014. Constraining the short scale core-mantle boundary topography beneath Kenai Peninsula (Alaska) with amplitudes of core-reflected PcP wave. *Phys. Earth Planet. Inter.* 236, 60–68.
- Yoshizaki, T., McDonough, W.F., 2020. The composition of Mars. *Geochim. Cosmochim. Acta* 273, 137–162.