Effects of 3D structure on Martian seismic waves

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The InSight (Interior exploration using Seismic Investigations, Geodesy and Heat Transport) lander provides the unique opportunity to explore the seismicity and the present-day seismic structure of Mars (Banerdt et al., 2020; Lognone et al., 2020; Giardini et al. 2020). Since the deployment of the seismometer SEIS, hundreds of seismic events have been recorded, and information about these events is available in the seismic catalogs produced by the Mars Quake Service (MQS) (Clinton et al., 2021; MQS Catalog V9).
Fig. 1: Computational framework used in this study to incorporate thermal models in numerical wave simulations: Spherical harmonic Vp, Vs, and density models based on thermal simulations (e.g., Plesa et al., 2021, top-left) are expanded on a spectral-element mesh (Ciardelli et al. 2022, bottom-left) at desired resolutions. Sample synthetic 3D and 1D seismograms at 0, 90, 180, and 270-degree azimuths and 29 and 74-degree epicentral distances computed for the thermal model Case65-TAY (Plesa et al. 2021) with crustal thickness model 3200_1_DWTh2Ref1 (Wieczorek & Zuber 2004) and its average, respectively, shown on the right. Topography, rotation, ellipticity, gravity, and PREM attenuation are all taken into account during simulations with the SPECFEM3D_GLOBE package (Komatitsch & Tromp 2002). The source is the moment tensor solution of event S0235b located at the InSight lander with a higher scalar moment. The seismograms are bandpass filtered between 10-100 s.

InSight’s seismic recordings have been used to constrain the thickness of the crust (Knapmeyer-Endrun et al., 2021), the upper mantle structure (Khan et al., 2021) and the size of the martian core (Stähler et al., 2021), which has recently been updated by Duran et al. (2022). The latest largest moment magnitude ~5 event provides an unprecedented opportunity to investigate the interior of Mars, and to constrain its seismic structure using both body and surface waves. Seismic wave speeds can present substantial variations in particular in the lithosphere where they follow the same pattern as the crustal thickness (Plesa et al., 2021). These variations can extend to 400 km or
deeper for models with a thick thermal lithosphere as suggested by the analysis of seismic events.

In this study, we investigate the 3D structural effects on the seismic body and surface waveforms, such as surface topography, crustal thickness variations, etc., and combine them with thermal evolution models using 3D seismic wave simulations (Fig. 1). We quantify the difference between 1D radially symmetric seismic models, radially symmetric models with 3D crustal thickness variations and topography, and full 3D seismic wavespeeds caused by the variations of crust-mantle interface and mantle thermal anomalies (i.e., mantle plumes) derived from thermal simulations. In our simulations, we include the latest crustal thickness models of Mars (Wieczorek et al., 2022) derived from gravity and topography data and constrained by seismic measurements from InSight.

In a first step, we use the radially symmetric structure constrained by the InSight data and similar to the study of Bozdag et al. (2017), and investigate the effect of surface topography, 3D crustal thickness variations, attenuation, and moment tensor solutions constrained by Insight data on body and surface waves. As expected, surface waveforms are most affected by the crustal dichotomy, which also highlights the importance of anelasticity in explaining multi-orbit Rayleigh and Love waves.

In a second step, we explore the effect of a 3D mantle derived from thermal evolution models on body and surface waves. We use seismic models that are representative of various thermal conditions obtained by 3D geodynamical models. Similar to Plesa et al. (2021), we use the present-day thermal state and associated temperature variations to calculate P and S wavespeeds that are then used to simulate the seismic wave propagation. We use the 3D global wave propagation solver SPEC-FEM3D_GLOBE package (Komatitsch & Tromp 2002) for numerical simulations, freely available from CIG (Computational Infrastructure for Geodynamics), and compare synthetics to the prominent marsquakes, including the latest largest moment magnitude ~5 event.

References
Knapmeyer-Endrun et al., 2021. Thickness and structure of the Martian crust from InSight seismic data, Science, 6553(373), 438-443, DOI: 10.1126/science.abf8966.
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