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Modelling seismic wavefield across the southern Tyrrhenian Sea

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Summary. — The Italian peninsula and the Tyrrhenian Sea are the ideal regions to explore the potential of wavefield modelling in a mixed continental-oceanic crust through finite-difference based simulations. In these structural settings, we show that such modelling can discriminate reverberating crustal waves created between layers from the average stochastic properties of the crust. This framework provides a novel forward model to image oceanic basins in 3D while constraining Moho depths.

1. – Introduction

From global to local scales, seismic velocity and attenuation are the main imaging attributes to interpret the Earth deeper and shallower structures using from exploration to passive seismic data [1]. However, strong lateral and depth variations of the medium properties (*e.g.*, discontinuities between layers) dramatically affect the response of seismic wavefields in terms of arrivals and amplitude. These variations are especially relevant across oceanic basins with mixed continental-oceanic crust and including magmatic systems. Besides, high-scattering and high-absorption media produce stochastic signatures that are hard to separate from complex coherent reverberations due to shallow Moho. This discrimination is fundamental for improving full-waveform imaging across oceanic basins at regional and global scales.

A low-frequency wavefield is controlled primarily by large-scale velocity discontinuities when their dimension becomes comparable with the seismic wavelength, λ. At the regional scale, the effect of crustal thickness variation [2] and loss of energy due to leakage into the mantle [3] are thus primary factors to model seismic energies and wavefields at frequencies below 1 Hz [2]. Radiative-transfer (RT) based forward modelling is efficient in discriminating the role played by waves reverberation due to deterministic structures from scattering and absorption due to small-scale heterogeneities in different geological settings [2, 4, 5].

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Przybilla *et al.* [6] showed how to describe envelopes with both RT and wave equation modelling. Such a combined approach describes the regional seismic wavefield under oceanic basins, constraining geological interpretations. Coda-attenuation imaging provides the RT-based modelling across Italy and the Tyrrhenian basin [5]. This region is suitable to investigate the effects of large-scale structures on the deterministic propagation via wave equation modelling. This region is characterized by relevant crustal thickness variations due to a mixed oceanic and continental crust. Full-waveform-based forward and inverse methods offer the potential to account for the full physics of 3D wave propagation [7] and thus constrain the crustal structure underneath oceans.

We describe the simulation tool employed for the wave equation modelling, including its set-up. The aim is to discriminate the deterministic propagation effects due to sharp velocity discontinuity such as Moho interfaces. In the process, we explore the sensitivity and resolution potential of the full wavefield to crustal variations.

2. – Methods and data

The parallelized Open-source Seismic Wave Propagation Code (OpenSWPC) [8] solves the equations of motion (velocity-stress formulation) in 2D and 3D heterogeneous viscoelastic media at local-to-regional scales using the finite difference (FD) method. It is tailored to work in high-attenuation lithospheric media as it includes the statistical fluctuations of the velocity field, which often dominate seismic wave propagation at crustal scale. The tool implements a frequency-independent attenuation model based on the generalized Zener body and a perfectly matched layer as absorbing boundary conditions.

The 3D FD simulation grid (node spacing ~ 0.5 km) covers the area of the southern Tyrrhenian basin and the Italian peninsula (fig. 1). The layered model includes the topography [9], sediments and different Moho models [10, 11]. Figure 2 shows the investigated crustal profile across the southern Tyrrhenian basin. We set velocities, intrinsic attenuation, velocity fluctuations ε and scale length a to the values obtained from previous radiative transfer simulations across the region [5], including appropriate values for air and sea water. The random velocity fluctuations are described by the root mean square of the velocity fluctuations (ε) and correlation lengths (a), and a Von Karman distribution function [2]. We implement the seismic source of the earthquake that occurred in Accumoli (Central Italy, 2016, Mw6.1) according to the moment tensor values given by Istituto Nazionale di Geofisica e Vulcanologia (INGV, Italy) and to Tinti *et al.* [12], who used the CIA (Central Italian Apennines) velocity model from Herrman *et al.* [13].

2˙1. *Moho models.* – The wave propagation and thus the shape of the waveforms are primarily governed by interfaces at depth. We carry out a sensitivity study of the entire seismogram relative to the variation of the Moho discontinuity by implementing different Moho models [10, 11]. Across the Tyrrhenian sea, the models show a thinner crust, where the Moho depth is about 10–12 km. However, our aim is to investigate the possible presence of continental crust and its signature on the seismogram. Between the Marsili and the Vavilov sub-basin, there should be a portion of continental crust (Issel bridge) [14]. We thus implement other crustal models by deepening the depth of the Moho of the EPcrust model across the southern basin (table I).

3. – Results and discussion

Regional seismic data test our model and act as markers for understanding the effect of the Tyrrhenian basin on full wavefields. For our preliminary sensitivity study, we simulate data for the seismic receivers across Southern Italy and Sicily (INGV seismic network,

Table I. – *Implemented crustal models across the Tyrrhenian basin.*

	Depth	
	Pinch	Continental crust
Moho	Manu-marfo *et al.* (2019)	
MohoEP	Molinari *et al.* (2011)	
MohoEP18	18 km	EPcrust
MohoEP20	20 km	>25 km

`http://cnt.rm.ingv.it/`) and for the four Moho models shown in table I. Figure 1 (left panel) shows the comparison between the recording and the synthetic data for a seismic station in Sicily, which is located along the north-south profile AA′ in fig. 1 (right panel), crossing the hypothesised region of continental crust. The seismogram time window from the event origin up to 200 s can discriminate the effects of the crustal variations on the arrival and the amplitude of crustal phases, *i.e.*, reverberating and converted phases or surface waves (Lg or Rg regional phases). We observe a variation in the amplitudes and arrival times of the crustal waves by varying the thickness of the oceanic crust, which turns out to be the primary factor affecting the crustal propagation. We evaluate the fit between the synthetic seismograms and recordings for all the stations in terms of the correlation coefficients for the time window 0–200 s. In fig. 1 (right panel), we map the correlation (> 0) in the space using a regionalisation approach. The coefficients of the ray paths crossing each cell are averaged. We show that a deeper (18 km) oceanic Moho better reproduces the arrival of the crustal waves revealing the actual presence of a thicker crust between the two sub-basins.

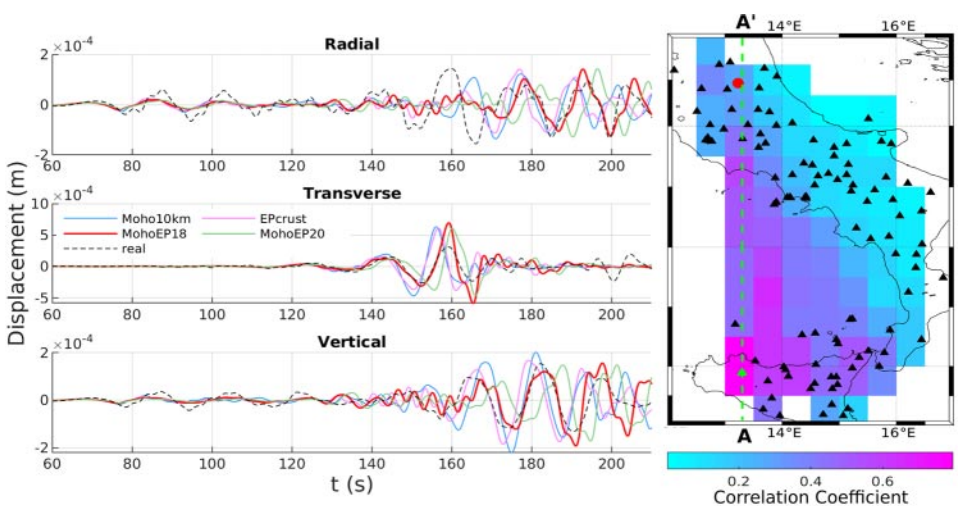

Fig. 1. – Left panel: three-components seismogram of the seismic wavefield generated by the Accumuli event (42.7°, 13.23°) and recorded at a seismic station located in Sicily (37.89°, 13.30°, green triangle in the right panel), in the frequency band 0.05–0.33 Hz. The dashed black is the recorded event. Color lines (see legend) are the results of our simulations by varying crustal structure (table I). Right panel: map of correlation between recorded and synthetic vertical seismograms in the time window 0–200 s for the MohoEP18 model (table I).

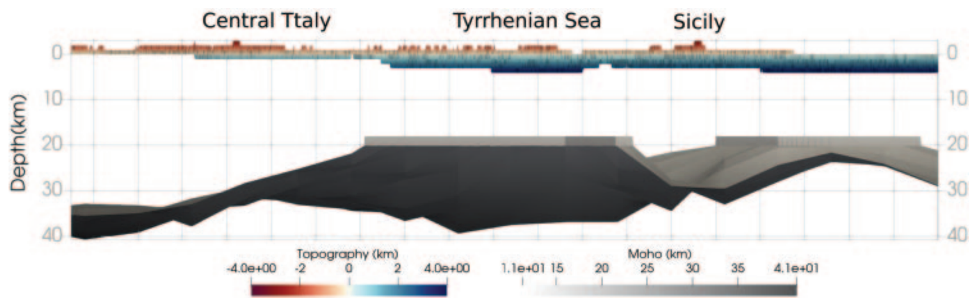

Fig. 2. – The section AA′ (fig. 1) shows the crustal thickness profile taken from the 3D MohoEP18 model across the Southern Tyrrhenian basin.

4. – Conclusion and outlooks

Full-waveform modelling allows investigating the physical processes affecting wave propagation. The wavefield in our frequency range changes depending on small- to large-scale structures and intrinsic properties of the medium, which are difficult to discriminate from the primary crust-mantle discontinuity. We explore the sensitivity of the 3-components seismograms to the Moho depth and the potential of using full-waveform information to map it. We compare and explore the effects of different crustal models (fig. 1) showing the effects of Moho depth variation on the arrival and amplitude of crustal phases. This sensitivity makes our framework an ideal forward model of seismic wavefields recorded across the oceanic crust for future full-waveform inversions and imaging of crustal discontinuities, like Moho depths.

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