The impact of density heterogeneities on seismic wave propagation

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1. Introduction & Motivation

- Lateral density variations are the source of mass transport in the Earth at all scales, acting as drivers of convective motion in the mantle
- Classic seismic observables and gravity provide only weak constraints with strong trade-offs and so the density structure of the Earth remains largely unknown

We propose to develop a seismic tomography technique that directly inverts for density, using complete seismograms rather than arrival times of certain waves only. The first task in this challenge is to systematically study the imprints of density on synthetic seismograms. To compute the full seismic wavefield in a 3D heterogeneous medium without making significant approximations, we use numerical wave propagation based on a spectral- element discretization of the seismic wave equation.

2. Why is it hard to see the impact of density on seismograms?

Backward scattering

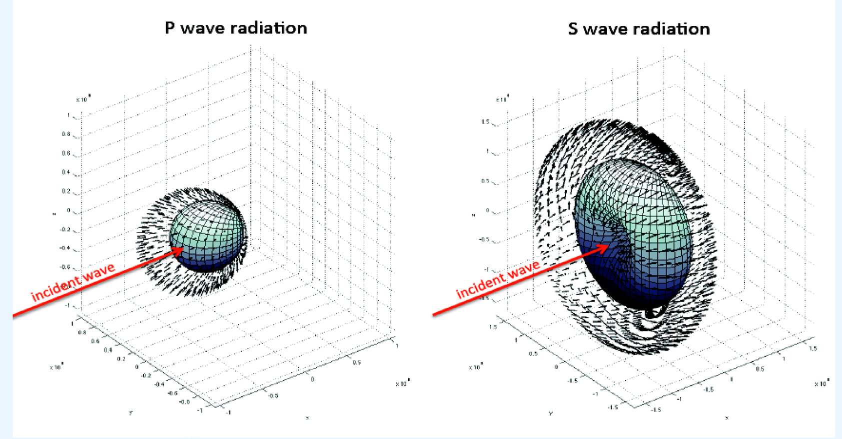


Fig.1:Radiation patterns for waves scattered on density heterogeneity, indicent P wave

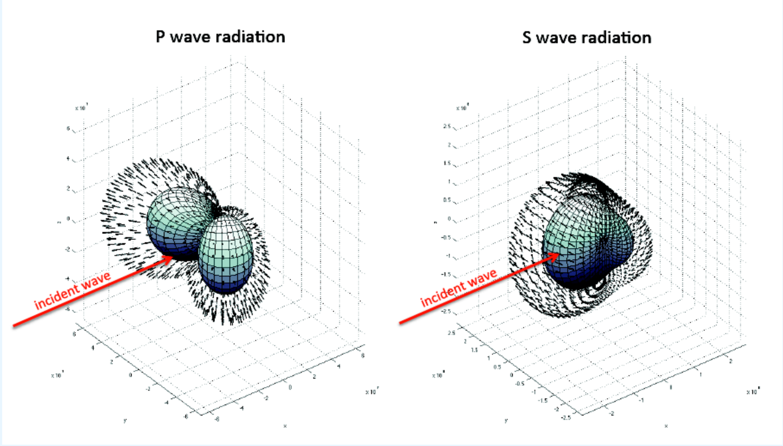


Fig.2: Radiation patterns for waves scattered on density heterogeneity, indicent SH wave

- Heterogeneities (density, velocity varations) in the medium in which seismic waves propagate act as sources.
- It is possible to calculate source radiation patterns for different types of scattered waves given certain heterogeneity and incident wave type (figures 1 and 2)

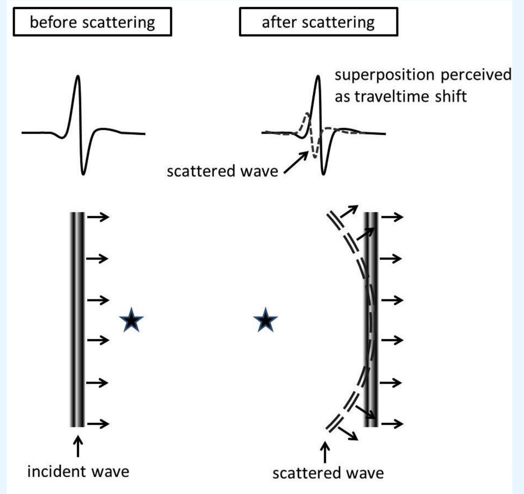


Fig.3: Forward scattering is directly visible in the waveform [1]

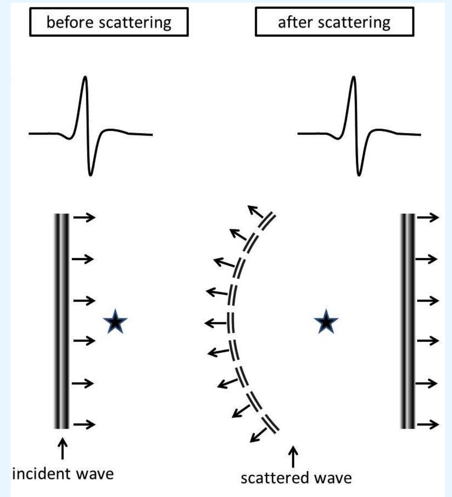


Fig.4: Backward scattering will not affect the waveform [1]

- For **velocity heterogeneities** the **scattered** wave propagates **forwards** and so the presence of the scatterer (heterogeneity) is directly visible in the waveform – the amplitude and traveltime of the direct P or S wave changes (figure 3)
- For **density heterogeneities** the waves are **scattered backwards** and the primary waveform remains unchanged (figure 4). The impact of density is visible in other parts of the seismogram, but not in the direct wave. Identifying those parts of the seismogram is our first goal

3. Numerical wave propagation

Mathematical background

We are simulating elastic wave propagation in heterogeneous media using spectral-elements in a spherical section. It solves the elastic wave equation

$$\rho(x)\,\frac{\partial^2}{\partial t^2}u(x,t) - \nabla\,\sigma(x,t) = f(x,t)$$

Where ρ denotes density, u – the displacement field, f – the external force density and σ – the stress tensor.

Model setup

Computational grid parameters:
- regional scale (example - the Anatolia region)
- 34° to 43° latitude, 23° to 43° longitude
- 471 km depth to the surface of the Earth
- divided into 50 subdomains, each of which is assigned to one compute core
- the total number of elements: 250'000

The hypocentre location is: latitude: 39.26°, longitude: 41.04°, depth: 5 km, the source mechanism is an explosion.

Velocity and density structure used in simulations

We superimposed 3D velocity (SH, SV, P) and 3D density heterogeneities onto a homogeneous model of the medium and performed the forward wave propagation simulation.

For comparison we used a medium model of the same 3D velocity heterogeneities, but 1D density structure. The two models are displayed in figures 5 and 6.

In the next section we compare seismograms computed for these models.

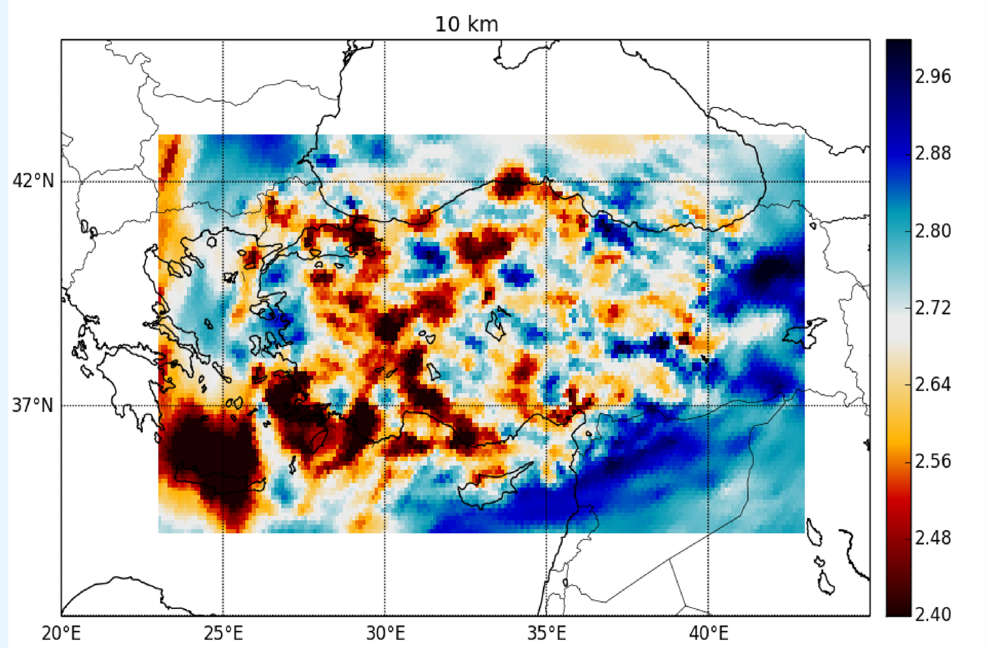


Fig. 5: 3D density structure. Density in colorbar, plotted at 10 km depth

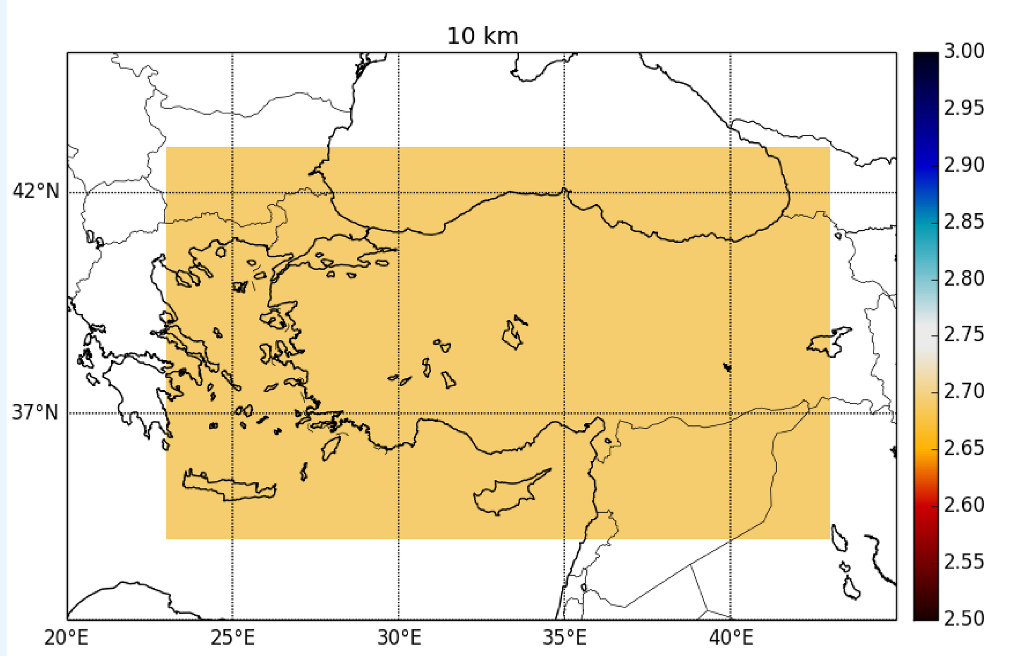
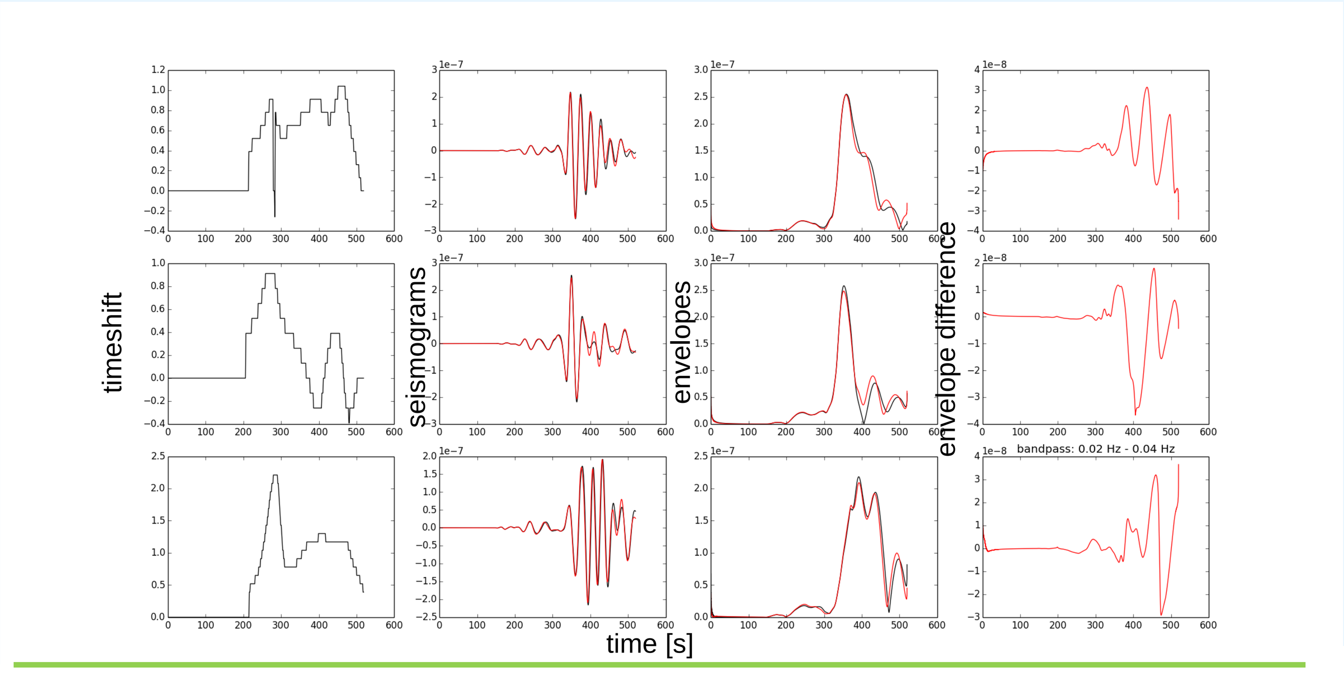
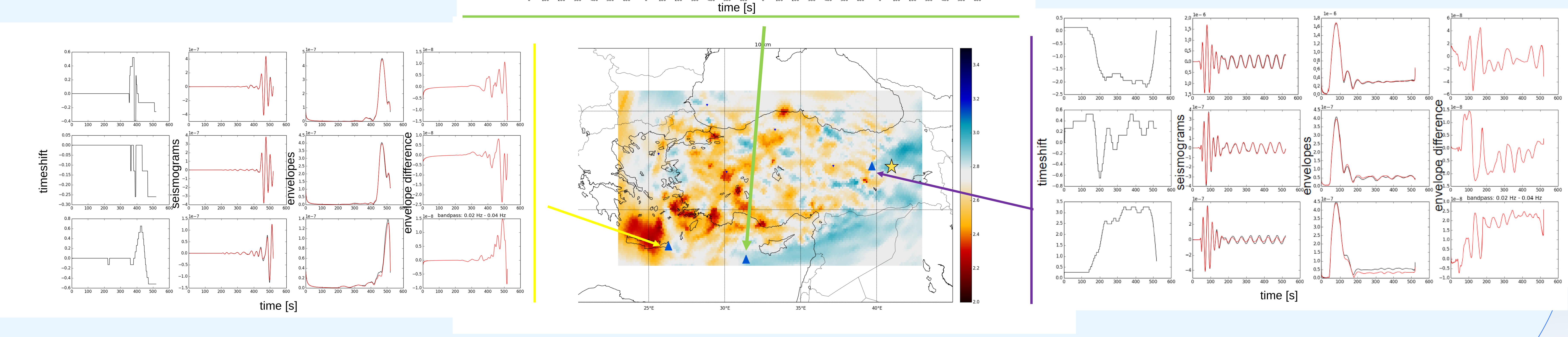


Fig.6: 1D density structure

4. Results

We compare seismograms from three chosen stations (depicted as blue triangles on the map). The star indicates the source location and in the background we present the 3D density structure used in simulations at 10 km depth (density in colorbar). We present the 0,02- 0,04 Hz band. The plot structure is as follows (from left to right): timeshifts for x, y, z components (up to 600 timesteps, computed by cross-correlation with a gaussian window), seismograms for x,y,z components (black – 3D density structure, red – 1D density structure), envelopes calculated by using analytical signals, envelope differences.





5. Conclusions

We observed time shifts of up to a couple of seconds, meaning that the impact of density on seismic wave propagation is measurable and big enough to pollute tomographies where 3D density structure is not accounted for.

Further work will include designing a numerical experiment of source-receiver configuration particularly sensitive to density.

6. References

[1] Trampert J., Fichtner A., 2013. Global imaging of the Earth's deep interior: seismic constraints on (an)isotropy, density and attenuation, in: Physics and chemistry of the deep Earth, edited by Karato S.-I., Wiley-Blackwell, p. 324-350.