Lithospheric-asthenosphere system in the Balkan Peninsula region
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1. Abstract
Velocity structure of the lithospheric-asthenosphere system, to the depth of 350 km is obtained for the region of the Balkan Peninsula for the cells sized 1° x 1° by using 3D seismicity tomography. The models are obtained by the following sequence of methods and tools: surface-wave dispersion measurements and collection; 2D tomography of dispersion relations; non-linear inversion of cellular dispersion relations; computational optimization method to select a preferred model for each cell. The 3D velocity model, that satisfies Occam razor principle, is obtained as a juxtaposition of selected cellular models. The distribution of seismicity and other geophysical information was used as independent constraints for the definition of the crustal and lithospheric thickness. The obtained picture of the lithosphere-asthenosphere system for the Balkan Peninsula region confirms a strongly heterogeneous structure of the crust and mantle. The moment tensor inversion of few recent damaging earthquakes which occurred in the Balkan Peninsula region is performed through a powerful non-linear technique and obtained solutions are related to the different rheologic-mechanic properties of the Earth's structure.

2. Methodology
This study defines a 3D shear-wave velocity model for the depth range from 350 km in the region of the Balkan Peninsula by application of a new method and tools for analysis on 3D dispersion data. This method is based on the construction of a 1-D non-linear inversion of dispersion relations; local smoothing optimization; and justification of representative cellular models. The obtained area is divided for the region by Raykova and Panza (2006), Raykova and Nikolova (2007), Panza et al. (2007) and Bracca and Lalet (2010) are applied, revised and extends. This methodology is applied in a number of studies: Panza et al. (2003), Panza et al. (2006), Raykova and Nikolova (2007), Panza et al. (2007), Panza et al. (2008), Brandmair et al. (2010), Raykova & Panza (2011).

3. Frequency-time analysis (FTAN)
The main part of the collected data is composed by group-velocity measurements made by Pontevecchio and Panza (2001, 2006), Karaganis et al. (2002), Raykova et al. (2004), Raykova and Nikolova (2007) and El Gabry et al. (2013). The frequency-time analysis (FTAN), Levshin et al. (1985) was used to extract the fundamental mode of Rayleigh waves and to calculate relevant dispersion curve from each seismogram. Additionally, published group and phase velocity measurements were included to determine the density and penetration depth of the data. The resolution set for Rayleigh wave dispersions consists of more than 100 events, for each model the period range from about 5 to 68 and in more than 150 phase velocity measurements in the period range from 10 to 150 s.

4. 2D tomography
The two-dimensional tomography based on the Newmark-Logan method was used to determine the local values of the group and phase velocities for the period of periods, mapping the horizontal at a specific period and vertical (at a specific grid) velocities in the Earth's structure. The choice of the set of periods is based on the vertical ray-tracing, on the available data, as determined by the partial derivatives of dispersion values (group and phase velocities) with respect to the structural parameters (Panza, 1981, Urban et al., 1993). The lateral resolution of the tomographic maps is defined as the average size of the equivalent smoothing area and its elongation (Raykova, 1997) and hence it is not necessary to perform check board or similar tests (Flodger et al., 2013).

Local values of group and phase velocities were assembled for cells sized 1° x 1°. Group-velocity data from the global tomography study of Potevecchio and Levshin (1998) were used to extend the period range of group velocities from 80 to 150 s. The local dispersion curves constructed in such a way open over varying period range according to the availability of the data. Each local dispersion value is qualified by an error that is combination of measurement error and tomographic resolution.

5. Local dispersion curves
The non-linear “hedgehog” inversion of cellular dispersion curves was applied to obtain the shear-wave velocity models for cells sized 1° x 1°. The period range of dispersion data allows retrieving velocity structure reliably in the thickness of 10-15 km. A 3D cellular model of each cell was modeled as a stack of 10 homogeneous strata layers and some of the layers connected by a finite number of numerical parameters. A priori, independent information about the crustal properties at each defined cell was used in parameterization of layers to improve the resolving power of the tomographic data (Pontecorvo and Panza, 2006). Uppermost five layers have properties fixed (specific for each cell). The underlying five layers have variable s- and P-wave velocity, Vp, Vp/Vs and appropriate density. The uppermost layer thickness is variable and is set by the thickness of the whole stack of eleven layers that has a total thickness of 350 km. The bottom layer, below 250 km, consist of Porsession material (De et al., 1998), are common to all cells and are kept fixed during inversion. The thickness of the uppermost crustal layer and thickness step in the parameterized crustal layers were rounded to 0.5 km or 1 km (the only exception is the water layer rounded to 0.1 km, a precision consistent with bathymetry resolution).

6. Non-linear inversion
A non-linear inversion technique is required in order to construct a 3D model of the studied area and to define the geologic meaning of the resulting structures. An optimized non-linear inversion (Raykova, 2000, 2002) was used to define the representative model for each cell with a formalized criterion. This method decreases the mismatch between the calculated and observed set of the selected velocity value was weighted with the ratio between layer thickness and the total thickness of the structure. The optimization procedure for the inverse modeling was considered only the neighbors of the selected cell and fixing structural layer as the one, which minimizes the norm between such neighbors. The algorithm follows the principles of multi-cellular divergence in the models.

7. Local smoothing optimization (LSO)
A smoothing optimization is used with its own uncertainties to determine the representative model, is introduced by the introduction of a minimization. The LSO selects the cellular model, minimizing the norm between the neighbor cells (one side in common, as representative of the solution of the processed cell). Once a solution is chosen in the running cell, the search continues by applying the procedure to the neighboring cells, but not yet processed, with the smallest average deviation of the interpolated values. This mechanism is the progressive choice of the representative solution of the cells, until the whole investigation domain is explored.

The search starts from the cell with minimal average dispersion of the cellular models, where cellular solutions are the densest in the parameter space and therefore the potential system bias introduced by the choice is minimized. The LSO selects the cellular model, minimizing the norm between the neighbor cells (one side in common, as representative of the solution of the processed cell). Once a solution is chosen in the running cell, the search continues by applying the procedure to the neighboring cells, but not yet processed, with the smallest average deviation of the interpolated values. This mechanism is the progressive choice of the representative solution of the cells, until the whole investigation domain is explored.

Since the non-linear inversion and its smoothing optimization guarantees only the mathematical validity of the solution of the inverse problem, the optimization procedure may be repeated whenever necessary, including additional geophysical constraints, such as Moho boundary depth, seismic energy distribution, depth presence of magmatic, heat flow, etc.

8. Validation of representative cellular models

9. 3D velocity (Vs) model
In the Balkan Peninsula region 133 cells have been processed. The juxtaposition of the representative cellular models of each cell results in the 3D shear-wave velocity model for the study region. Each representative cellular solution gives the average of the vertical distributions in 10 km cells. The models are obtained by justifying the cellular model with the help of seismic data and other geophysical information, in general, equal in size to the resolution cell.

The results are summarized in right graph 7, 100% are in the range of every respective cells labeled Moho structure. The distribution of depth and velocity indicates that the crustal and lithospheric thickness of the Balkan Peninsula are the same. The velocity value defines the Moho depth very closely defined when in the top of crystalline layer Vp is in the lithosphere the lowest mantle velocity. The middle depth in km of the mantle layer with the lowest vs is defined. The thickness of the top part mantle and the thickness of the top part of the mantle layer with the lowest vs are determined by the result of the moment tensor inversion and the distribution of the hypocentral parameters which are crucial importance for the correctly location of the hypocentral depth and the epicenter. The obtained solutions are related to the different rheologic-mechanic properties of the Earth's structure.