RETREAT seismic data analysis: from records to 3D velocity model

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Introduction

The Apennines represent one of the most accessible convergent mountain belts with horizontal contraction and extension occurring simultaneously. The RETREAT project (Margheriti et al., 2006) was developed to study the tectonic processes acting in Northern Apennines and one of the tasks was a passive seismological experiment active from October 2003 until September 2006. About forty temporary broadband stations were deployed and their continuous recordings together with the recordings from several permanent seismic stations of Italian National Network were archived in the IRIS data centre.

This study presents the analysis of seismic records from the RETREAT project using a sequence of seismological methodologies to obtain shear-wave velocity models of the area in twenty-six contiguous cells, 0.5°x0.5° large. The used methodologies are: relocation of local events; frequency-time analysis to obtain group velocities; tree-station method to measure phase velocities; 2D surface-wave tomography; and optimised non-linear inversion. The study area is shown in Fig. 1a.

Data.

The equipment of RETREAT seismic stations consists of STS2 or CMG40 seismometers and Reftec 130 or Vistec digitisers (Margheriti et al., 2006). The stations operated for various periods of time. The events were selected by ISC (2010), following several criteria: the best azimuthal coverage of the studied area; the station-epicenter distance less than 1000 km (for 95% of the data); the deep events are not considered.

Group-velocity measurements.

The frequency-time analysis, FTAN (Levshin et al., 1989) was applied to measure group velocity of Rayleigh and Love wave fundamental modes. The method presents the 1D seismic records in 2D domain (group velocity-period), utilizing multiple narrow-band Gaussian filters. Generally, the maximum of the amplitudes of the 2D signal corresponds to the surface wave dispersion curve of the fundamental mode (Rayleigh waves on vertical and radial components and Love waves on transverse component). The tool is indispensable in complex structures, as Apennines, when several maximums appear and the amplitudes of the fundamental modes are not dominant. The identification of fundamental modes and the relevant maximum in the FTAN diagram is facilitated by the visualization of waveform records from RETREAT stations in order of the event-to-station azimuth. The measured dispersions at all stations for each event are compared and a value is excluded if it differs more than 20% of average value at specific period.

Additionally to our measurements, some regional measurements available in the literature were considered (Pontevivo and Panza, 2001; Raykova and Nikolova, 2007). The assembled data set of measurements ensures relatively good coverage of the study region in the period range from 3 s to 60 s.

Errors in group-velocity measurements.

The errors in group velocity measurements were evaluate in three different ways: as difference in the measured values along similar wave paths in period range 7-60 s; as difference in the measured values in period range 3-10 s multi-locations of local events; published error values for periods 35-150 s (Brandmayr et al., 2010). The errors at each period in the range 3 – 60 s were calculated as the average between the different values.

Different origin locations for the same event were used in group velocity determination and error computation at the shortest periods (3s – 10 s). Fifteen events in the North Apennines were re-located, merging the data from RETREAT and Italian National Network stations. The used location program hypo2000 (Klein, 2002) determines the earthquake location and magnitude by first-arrival P and S travel times and preliminary defined velocity model. Three different locations (models by Zollo et al, 1995; Chiarabba and Amato, 1996; Stich and Morelli, 2007), obtained by hypo2000, and four additional locations from seismic centers (two from ISC, 2010; INGV, 2010; CSEM, 2010) were used in the dispersion measurements. The average standard deviation errors were calculated for periods from 3 s to 10 s.

Phase velocity measurements.

Nine stations from the RETREAT array, with the same equipment (the Czech mobile station), were used for phase velocity measurements since they covered the largest area. The distance between stations ranges from 33 to 240 km, allowing phase velocity measurement for periods 10 – 40 s. Seven regional events were selected and the vertical components of the records were used only. The phase velocity and the direction of the propagation (true azimuth) were calculated, evaluating 81 possible triangular configurations (3S) between the 9 stations (Knopoff et al., 1966) and considering only 3S groups with theoretical direction of wave front propagation differs not more than 30° from at least one of the legs of the group (Knopoff et al., 1966, 1967).

Phase velocity c(T) and true azimuth of propagation θ(T) (T=1/ω) at different periods (T=10, 15, 20, 25, 30, 35 and 40 s) were obtained for each event and each considered 3S group, following Menke and Levin (2002). The values of c and θ are proportional to differential phase $\Delta\varphi_{ij}(\omega)$, that is derived by four approaches: (I) Fourier transform of the "raw" seismograms (applying instrument response, detrend, band-pass filtering 8 – 46 s, Fourier transform and phase unwrap); (II) correlation of the "raw" seismogram (applying instrument response, detrend, band-pass filtering 8 – 46 s, correlation, Fourier transform and phase unwrap); (III) Fourier transform of the "cleaned" Rayleigh wave seismogram (applying instrument response, detrend, FTAN, Fourier transform and phase unwrap); and (IV) correlation of the "cleaned" Rayleigh wave seismogram (applying instrument response, detrend, FTAN, correlation, Fourier transform and phase unwrap). The phase velocity c and true azimuth θ for each event and 3S group is the average of the values, estimated by each approach with relevant r.m.s. errors. Both the values were considered if the error of c is less than 0.5 km/s and the error of θ is less than five times the average difference in the theoretical azimuth of the three stations.

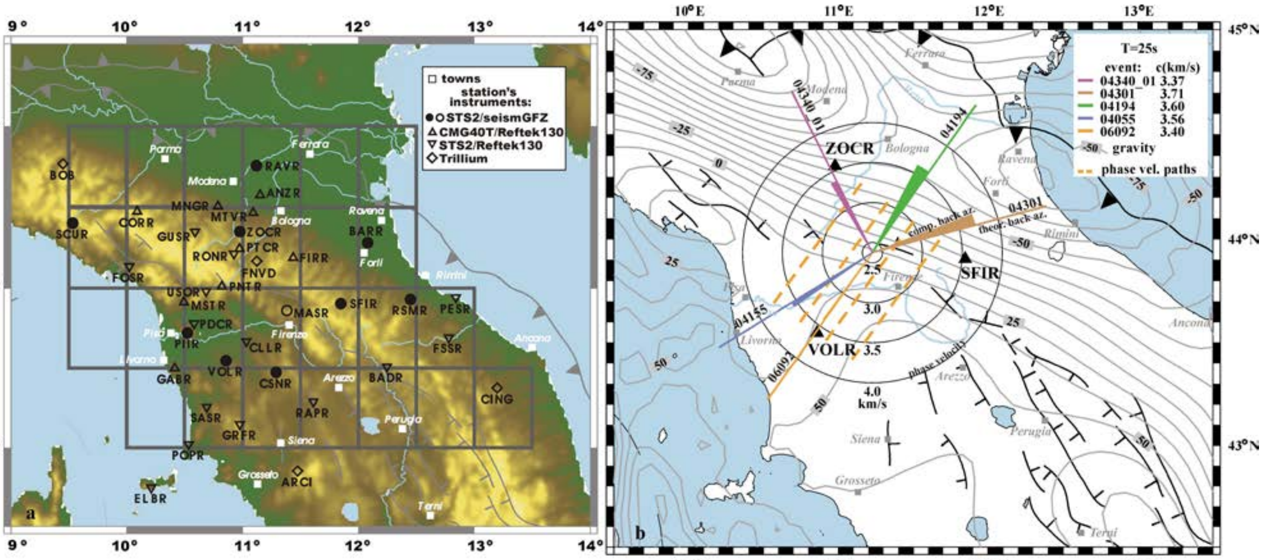

Fig. 1. North Apennines region (a) and phase velocity measurements (b). See the text for details.

Although 3S groups are the same for each event, significant differences were obtained in the values of the phase velocity. Knopoff et al. (1966) associated these variations with structural differences along the wave paths, crossing the same area from different directions. Such variations are in the crust's thickness, correlated with Bouguer anomalies by Ewing and Press (1959). Fig. 1b summarizes the results for phase velocity estimations at 25 s for the group VOLR-ZOCR-SFIR. The segments represent the deviation of the true azimuth of propagation from the theoretical one; the radius of the each segment is proportional to the phase velocity. The distribution of Bouguer anomaly (Sandowall and Smith, 2009) is plotted as solid grey isolines. The lowest phase velocity at 25 s was measured for event 04340_01, where the Bouguer anomaly along the wave-path varies from -50 mGal to 40 mGa. The Bouguer anomaly along the wave-path of event

05293 is almost constant and relevant value of phase velocity has the highest value at this period. The c measurements for every period, event, and 3S group were assigned to four "wave paths" with true back azimuth (dashed grey lines for event 06092 in Fig. 1b). These four "wave paths" cover the surface of relevant 3S group and their length is equal to the longest tripartite lag projection on the true wave-propagation direction.

2-D tomography

The distribution of measured group and phase velocities was obtained by 2D tomography technique (Yanovskaya and Ditmar, 1990). The method is based on the Backus–Gilbert method, velocities (group or phase) along each wave path at specific period are converted to travel-times and their residual is defined assuming the average travel-time as a starting value. The solution is found minimizing the time residual on a predetermined grid. The size of the area and the grid does not influence the final solution since every residual is distributed along whole wave path. The obtained distributions mimic the horizontal (at a specific period) and vertical (at a specific grid knot) variations in the Earth's structure.

The size of the tomographic grid in present study is 0.5°×0.5° and the considered periods are 3, 5, 7, 10, 15, 20, 25, 30, 35, 40, 50, and 60 s for group velocity of Rayleigh and Love waves and 10, 15, 20, 30, and 40 s for phase velocity of Rayleigh waves. The tomography area included all RETREAT stations.

The tomography maps were compared with the recent publications of cross-correlated ambient seismic noise tomography in Italian region for Rayleigh waves with periods 8-36 s. The results, presented in this study, are rather similar with results in Li et al. (2010), and the main differences with the results of Verbeke et al. (2012) are obtained for shortest periods. All tomographic maps evidenced the low-velocity uppermost mantle of Adriatic plate and high-velocity Tyrrhenian uppermost mantle.

Local dispersion curves

Local dispersion curves at each grid knot were assembled from the tomographic maps and the cellular dispersion curves were calculated as the average of the local curves at the four grid points in the corners of 26 cells, sized 0.5º by 0.5º. The penetration depth of the data was increased, considering the published group and phase velocity tomographic data in Brandmayr et al. (2010), measured on a grid 1º by 1º for Rayleigh waves. The assembled three dispersion curves (group velocity of Rayleigh waves with periods from 3 s to 150 s; group velocity of Love waves with periods from 3 s to 50 s; and phase velocity of Rayleigh waves with periods from 10 s to 150 s) for each of the 26 cells span over a varying period range according to the available data, ensuring the vertical resolution down to depths of 300-350 km.

Inversion

The obtained cellular dispersion data were inverted by the optimised non-linear inversion (ONLI) method (Raykova, 2014), based on Monte-Carlo search. The Earth's structure was modelled as 16 horizontal homogeneous layers down to the depth of about 600 km. The uppermost layer has fixed a priori characteristics, defined by published information by each cell, that define also the average topography. The following eight layers were parameterised for each cell as follow: Vs and thickness h are variable; V_P is estimated using the values of V_S and Poisson ratio; density is estimated by Nife&Drake relation and some additional considerations. The tenth layer has fixed V_P, V_S, and density, while h varies so that the whole stack of 10 layers has a total depth of 350 km. The remaining 6 layers, with constant properties common to all cells, were fixed from the global model ak135 (Kennett et al., 1995). The independent geophysical information is used to define several properties of each cell during inversion: the average cellular topography or bathymetry, rounded to 0.1 km; the Poisson ratio of 0.273, (Piana Agostinetti and Amato, 2009); Moho boundary depth rage (Tesauro et al., 2008); the properties of the first layer for each cell. Optimised inversion was run several times and the representative solution was selected as the one that has the average deviation from the data.

Conclusion

Velocity structure in 26 adjacent cells, sized 0.5°x0.5°, was obtained by complex processing of records from seismic network RETREAT, employed in Northern Apennines. The Moho boundary depth in north, north-eastern and eastern cells is significantly greater than the Moho depth in south-western cells, where shallow, hot mantle is retrieved.

Резюме

Анализ на сеизмични данни от мрежата RETREAT: от записите до тримерната скоростна структура

Ренета Б. Райкова

Поредица от методи са използвани за анализиране на цифровите записи от сеизмичната мрежа RETREAT, разположена в Северните Апенини (Италия), за периода 2003-2006. Няколко локални земетресения са преопределени използвайки процедурата hypo2000. FTAN е използвана за измерване на груповата скорост на вълните на Рейли и Лъв. Фазовата скорост на вълните на Рейли от няколко събития е измерена посредством разработена за целта процедура. Дисперсионните измержания са регионализирани посредством томография за клерки с размер 0.5°x0.5°. Скоростната структра на 26 граничещи клетки до дълбочина 350 км е намерена, прилагайки процедурата за оптимизирана нелинейна инверсия ONLI.

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