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Travel Time Residuals at the Contact of the Dinarides and Pannonian Basin

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SUMMARY

Teleseismic earthquake records from a passive array of 15 short-period and 4 broad-band seismometers are used to estimate traveltime residual patterns at the contact of the Dinarides and Pannonian basin. Estimation of relative residuals is achieved with fast and powerful stacking procedure through iterative alignment of traces. Global ak135 propagation model is used for achieving initial alignment by selecting the time window around the desired phase. Final alignment is obtained by rapid convergence of introduced time-shifts between reference trace and traces from each station. Similar residual patterns are caused by events arriving from the same region, but patterns differ if the events originate from various locations. Stations situated in the south-western part of the array show positive residuals, and stations situated in the north-eastern part of the array show negative residuals. Stations that show positive residuals are situated on thick Dinaridic crust, which explains later arrivals. Early arrivals correspond to stations situated on much thinner Pannonian crust, hence the negative residuals. Residual pattern that occurs between these two distinctive groups is characterized by alternating negative and positive residuals. This feature corresponds to ophiolitic Transitional zone characterized by strong lateral heterogeneities in the lithosphere.

Introduction

Passive seismic experiment ALPASS-DIPS, that was carried out as a continuation of an active seismic project ALP2002, helped in revealing lithosphere structure in the wide area of NW Dinarides, transitional zone towards the Pannonian basin and the SW part of the Pannonian basin. For that purpose, an array of 15 temporary short-period seismic stations was placed in Croatia, data from which had later been used in a receiver functions analysis (Šumanovac *et al.*, 2010). Orientation of the array was nearly perpendicular to the Dinarides, main faults in the Adriatic region and the contact between the Dinarides and Pannonian basin. In the most recent work, data from these stations, along with the 4 broad-band stations that were situated in Hungary (Fig. 1a), have been used in estimating travel time residuals in order to discuss the velocity structure of the lithosphere under the array. An adaptive stacking technique (Rawlinson and Kennett, 2004) has been applied to seismic traces that have similar spatial characteristics (e.g. epicentral distance). Apart from determining travel times of body waves, the technique uses cross-correlation of teleseismic waveforms to achieve optimal alignment of traces. Travel time residuals that are produced with this technique point out lateral heterogeneities in lithosphere structure as variations in wave speed.

a) *b)*

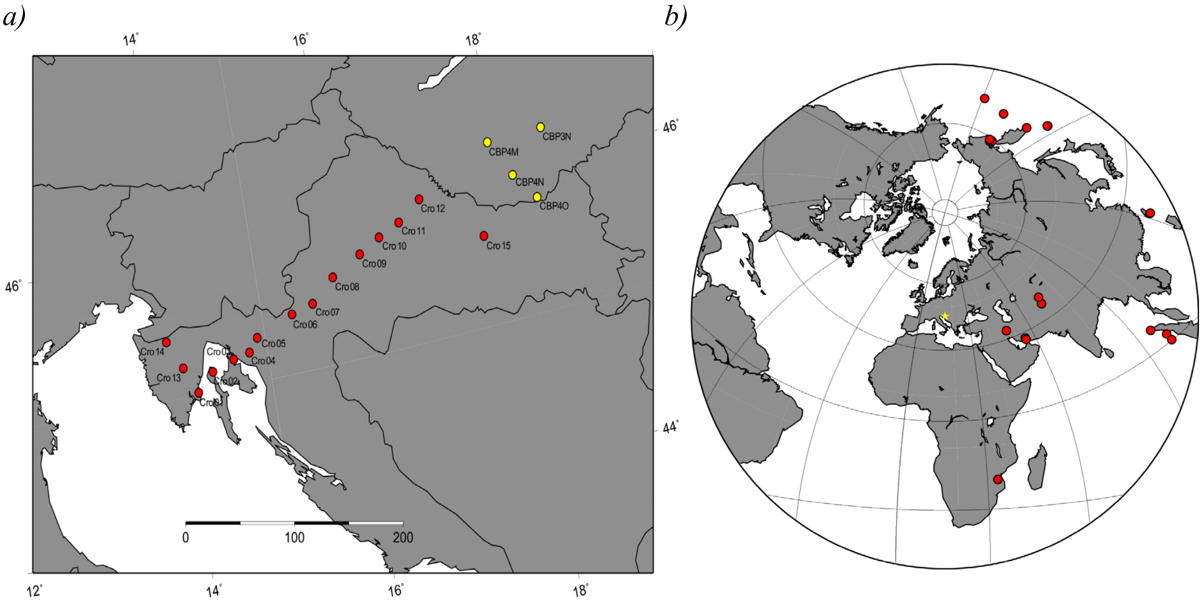

***Figure 1** a) Location of temporary seismic stations in Croatia and Hungary. Red dots denote short-period seismometers and yellow dots denote broad-band seismometers. b) Distribution of 19 teleseismic events used in travel time residuals estimation. Red dots denote observed events and yellow star denotes center of the array.*

Dataset

Teleseismic events were continuously recorded for the period of 18 months (November, 2005 – May, 2007) on three-component, short-period seismic sensors MARK L-4 1D with sampling interval of 0.02 and a resonance frequency of 2 Hz (Orešković *et al.* 2009). Dataset of more than 70 events that were used for receiver functions analysis had been reexamined and a subset of 19 teleseisms was considered for travel time residual estimates (Fig. 1b). Main criteria for creating a subset were the number of stations that recorded the event with good signal-to-noise ratio. All of the events were recorded on at least 10 stations that were placed in the Croatian part of the array. Data from Hungarian stations accounted only for 6 events, due to lack of data or too low signal-to-noise ratio. Epicentral distances for all of the events were between 30° and 90°, with magnitudes greater than 5.5. Spatial distribution of the events situated them mostly NE or SE of the array, that is approximately inline with the array, or perpendicular to the orientation of the array, respectively. Picking of the P-arrivals had been done previously during the receiver functions analysis. All traces have been low pass filtered at 0.5 Hz or 1 Hz in order to remove high-frequency noise.

Travel time residuals

Absolute travel time residuals represent the difference between the observed travel time (t^{obs}) and predicted travel time (t^{pred}). Prediction of arrivals is done using the specific propagation model, in this case the *ak135* model (Kennett *et al.* 1995). For minimizing the effect of imprecise determination of source location and/or origin time, mean residual is removed to produce relative residuals.

$$r_{ij} = t_{ij}^{obs} - t_{ij}^{pred} - \frac{1}{n_j} \sum_{i=1}^{n_j} \left(t_{ij}^{obs} - t_{ij}^{pred} \right) \qquad (1)$$

where n_j is the number of the observed events j at the *ith* station.

Estimation of residuals is achieved with adaptive stacking technique (Rawlinson and Kennett, 2004). The procedure starts with selecting a segment of each trace around the P arrival. Generally, any phase can be selected, because the propagation model can calculate predicted arrivals for each phase, however phases should be visually identified. Initial alignment of traces is accomplished by applying time-shifts derived from the propagation model, relative to some reference station. However, if the segments of each trace are cut around the predicted arrival time, then the time-shifts are not necessary and possible incorrect preliminary alignment is avoided. Preliminary alignment is followed by the calculations of linear and quadratic stack, which represent an estimate of the typical waveform across the array, and the spread in alignment between stations, respectively (Fig. 2). Final alignment is obtained with iterative procedure of direct search over time-shifts restricted to a specified interval (e.g. $-1<\tau<1$s), where waveforms that exhibit good fit get displaced by a multiple of specific wavelength. Therefore, the repetition of alignment procedure produces an improved estimate of the residuals from values predicted by the propagation model until the traces are aligned accurately.

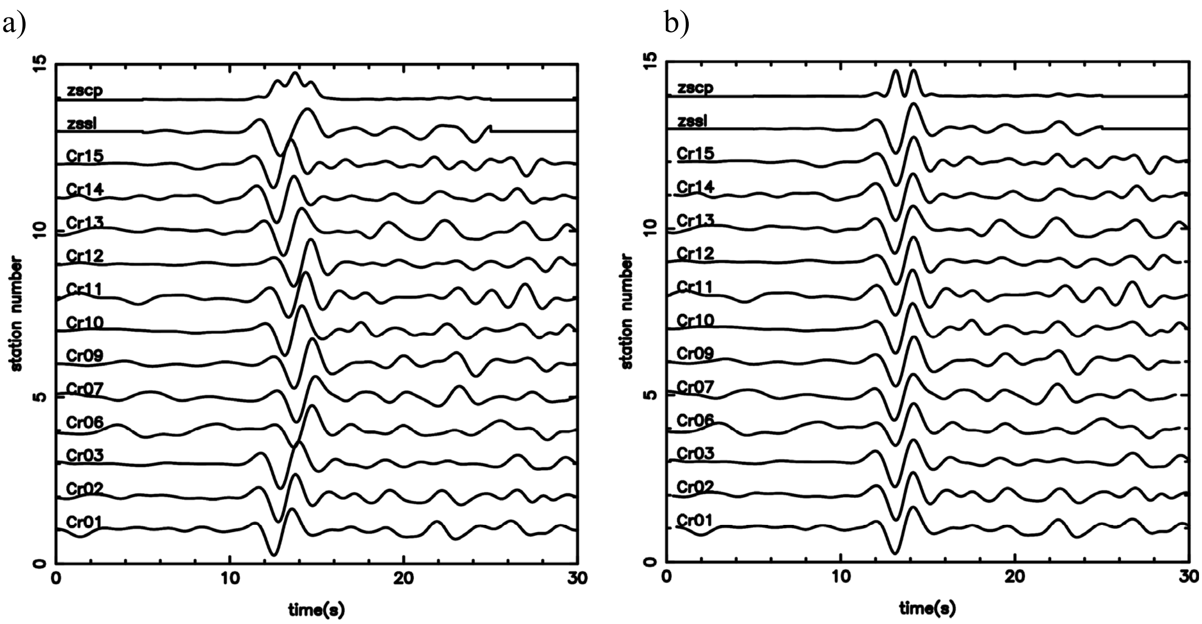

Figure 2 *Example of adaptive stacking using the event from Indonesia (located at 94.45°E, 5.58°S and 40 km depth): a) Initial alignment obtained using global ak135 model; b) final alignment achieved after five iterations. In both a) and b), the top two traces zscp and zssl represent quadratic and linear stack, respectively.*

Results

A total of 226 travel time residuals have been calculated from 19 events, accompanied by error estimates in order to weight the relative importance of each residual. Azimuthal distribution of travel time residuals shows a consistent pattern for different events that occur in the same region, however patterns from different regions do not share that characteristic. These patterns resulted from the superposition of the effect of wave velocity anomalies, which occur within the last few hundred kilometres of the ray paths. Ideally, anomalies are identical for waves arriving from the same incidence angle (Graeber *et al.* 2002).

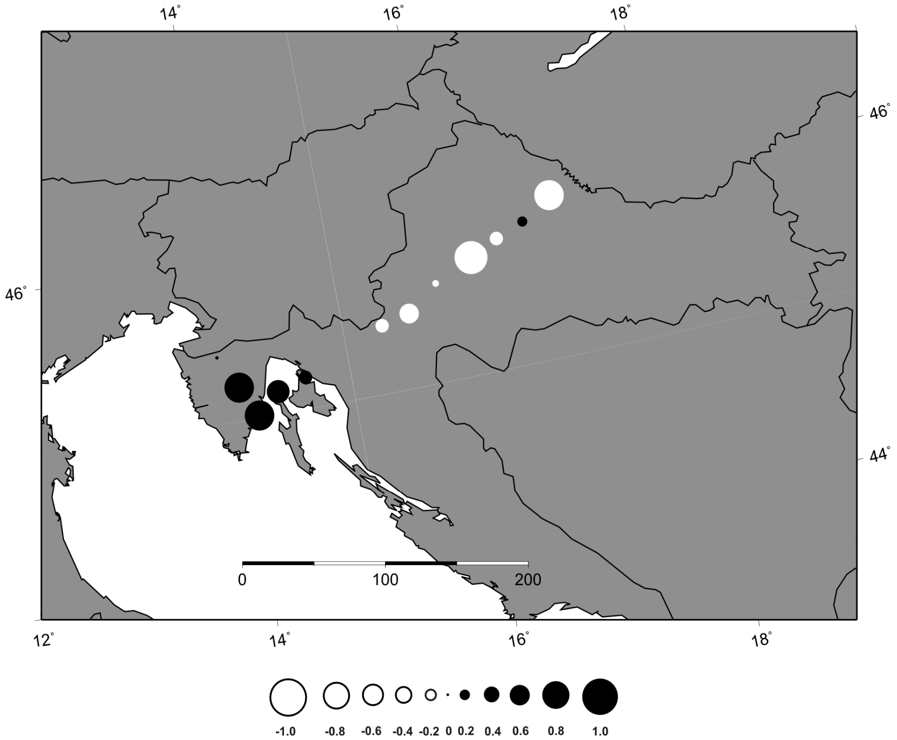

Figure 3 *Pattern of residuals (in seconds) for an event from Taiwan.*

There are two distinctive features which can be observed in residual patterns. Stations Cro-01 to Cro-04, together with stations Cro-13 and Cro-14 all have positive residuals suggesting later arrivals (Fig. 3), and stations situated in Hungary (CBP4M, CBP3N, CBP4N and CBP4O) including station Cro-12, have negative residuals suggesting early arrivals (Fig 4). Stations between these two groups (Cro-07 to Cro-11) show variations in residuals, being either positive or negative. Station Cro-15, which is somewhat outside of the array, shows positive residuals for each observed event. These features coincide well with mapped residuals in the Pannonian basin that were suggested by Wéber (2001) (Fig. 4). As the residuals have path-averaged nature, pattern tends to change according to event azimuth and distance, and therefore some stations show positive residuals for some of the events, and negative residuals for other events. This is mostly the case with stations situated in the Transitional zone between the Dinaridic and Pannonian part (Figures 3 and 4). Although crustal velocities cannot be defined separately from thickness, residuals tend to be most affected by variations in thickness. Early arrivals in the Hungarian part of the array correspond to the thin Pannonian crust, and late arrivals in the SE part correspond to the thick Dinaridic crust. Because of significant crustal velocity variations in this region, residuals cannot be directly transformed to Moho depth. However, Moho depth had already been well defined with other geophysical data (Šumanovac *et al.*, 2009).

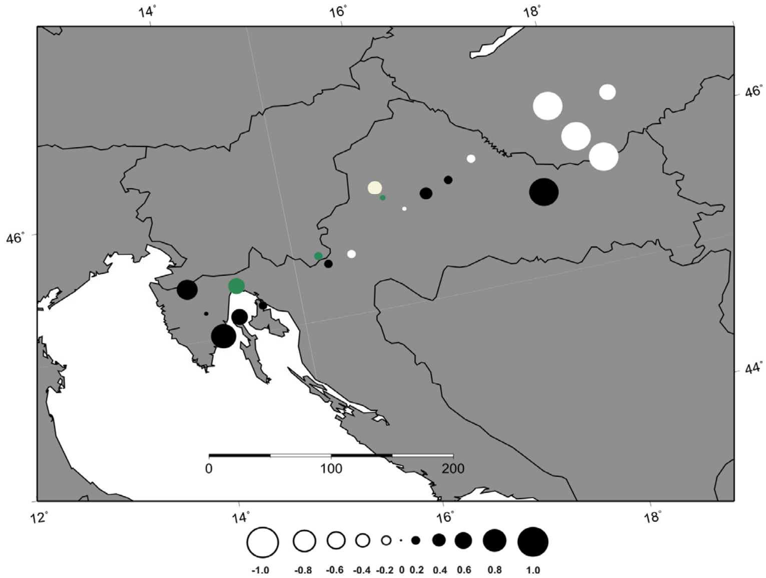

Figure 4 *Pattern of residuals (in seconds) for an event from Indonesia. Green circles represent positive residuals, and beige circle represents negative residual (from Wéber, 2001).*

Conclusions

Stations that are located in the SW part of the array, all have positive residuals which can be explained with the approximately 40 km thick Dinaridic crust under the array, and negative residuals at the stations situated in the Pannonian part of the array can in the same way be explained with much thinner Pannonian crust (approx. 25 km). Although the velocities in the Dinaridic crust are much higher than in the Pannonian crust, values of these residuals represent relative arrival times, therefore the perturbations in wave velocity should also be considered as relative rather than absolute. Station Cro-15 is clearly situated in the tectonic setting where positive residuals occur, therefore tectonic setting under the station should not be considered as a part of Tisia block, but as a part of ophiolitic Transitional zone (Šumanovac *et al.*, 2009). Residuals from other stations (Cro-07 – Cro-12) in the Transitional zone show that there are strong lateral heterogeneities in lithosphere under the array, which requires further analysis in the means of seismic tomography to reveal lithospheric structure in this area.

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