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Understanding Extension within a Convergent Orogen: Lithospheric Structure of the Pannonian Basin

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Summary

SEIS-UK provided a loan of 51 broadband seismic systems (5 x CMG3T and 46 x CMG6TD) for periods of between 14 and 24 months, for deployment in an array that extended more than 500 km across Austria, Hungary and Serbia, from September 2005 until August 2007. These systems recorded continuously (in most cases for a period of 16 months at 100 samples per second), with relatively minor data losses due to equipment problems. The dataset thus collected has been archived with IRIS (Incorporated Research Institutions for Seismology) and has been the central element of a major NERC-funded research project based at the University of Leeds: "Understanding Extension within a Convergent Orogen: Lithospheric Structure of the Pannonian Basin" (NE/C004574/1). Records of teleseisms have been processed to deliver *P*-wave and *S*-wave velocity models for the upper mantle beneath the Pannonian Basin. Receiver functions have also been calculated to reveal the structure of the upper mantle discontinuities, and fast anisotropy directions obtained from SKS wave arrivals to reveal the signature of lithospheric deformation. Further processing for surface wave tomography using ambient noise correlation techniques is in progress and was presented at Fall AGU 2010. A PhD by Ben Dando, based mainly on the teleseismic tomography, has recently been successfully examined (Jan. 2011). The results show clearly (and unexpectedly) a seismically fast structure reaching underneath the Pannonian Basin, extending out eastward from the present-day eastern Alps, and extending down into the Mantle Transition zone (between 410 and 660 km depth) where it has spread out to cover an area at least as big as the Pannonian Basin. This fast material is interpreted as the signature of mantle downwelling associated with Miocene extension of the Pannonian Basin lithosphere. Another important result from our seismic experiment is that the seismic discontinuity at 660 km depth is depressed by as much as 40 km under a large part of the Pannonian Basin. Such a widespread depression of the 660 km seismic discontinuity has not previously been seen beneath a major sedimentary basin, but the observation is fully consistent with the presence of the fast material revealed by the teleseismic tomography.

Background

Extension and heating of the mantle lithosphere beneath the Pannonian Basin has been attributed to the roll-back and subduction of an oceanic micro-plate that is now entirely subducted beneath the East Carpathians (Horvath, 1993; Wortel and Spakman, 2000). Previous tomographic images of the crust and upper mantle beneath the Pannonian and surrounding regions (Wortel and Spakman, 2000; Piromallo and Morelli, 2003) showed widespread fast material in the mantle transition zone (between 410 and 660 km) beneath the Pannonian Basin, with thinned lithosphere and slow uppermost mantle velocities. It had been suggested that these features could also have been created by gravitational instability of the continental lithosphere rather than a detaching slab (Houseman and Gemmer, 2007). The seismological part of the Carpathian Basins Project (CBP) aimed to determine upper mantle velocity structure in order to provide constraints on these competing models for the formation of the Pannonian Basin. We deployed two temporary networks of SEIS-UK broadband seismometers; a regional array deployed from Sept. 2005 until Aug. 2007, consisted of 10 CMG-3T 120s sensors (including 5 owned by the University of Leeds), and a high resolution network of 46 CMG-6TD 30s sensors deployed along 3 profiles, approximately 500 km long, running NW-SE through Austria, western Hungary and northern Serbia, operated from May 2006 until Aug. 2007 (Fig. 1). To date we have published or presented P- and S-wave tomography (Dando et al., 2010), mantle transition zone receiver functions (Hetenyi et al, 2009), and a study of local seismicity in eastern Austria (Hausmann et al., 2010). Studies of SKS anisotropy (Stuart et al., 2007) and ambient noise tomography (Ren et al., 2010), have been presented at conferences, and further publications on these topics are planned, along with a project summary / interpretation paper. Also under the CBP project, geodynamic modelling studies of the tectonic processes important in the evolution of the basin have been published (Houseman and Gemmer, 2007; Lorinczi and Houseman, 2009, 2010).

Survey Procedure

Installation for both networks was similar at each site; a pit up to 1 m deep was lined with a plastic container. A compacted layer of sand and a concrete tile was placed at the bottom as a stable base. A typical 6TD site is shown in Figure 2. Most sensors recorded at 100 sps. Service runs to download the data took place every 4 months. As much of the region of interest was on a sedimentary basin, the

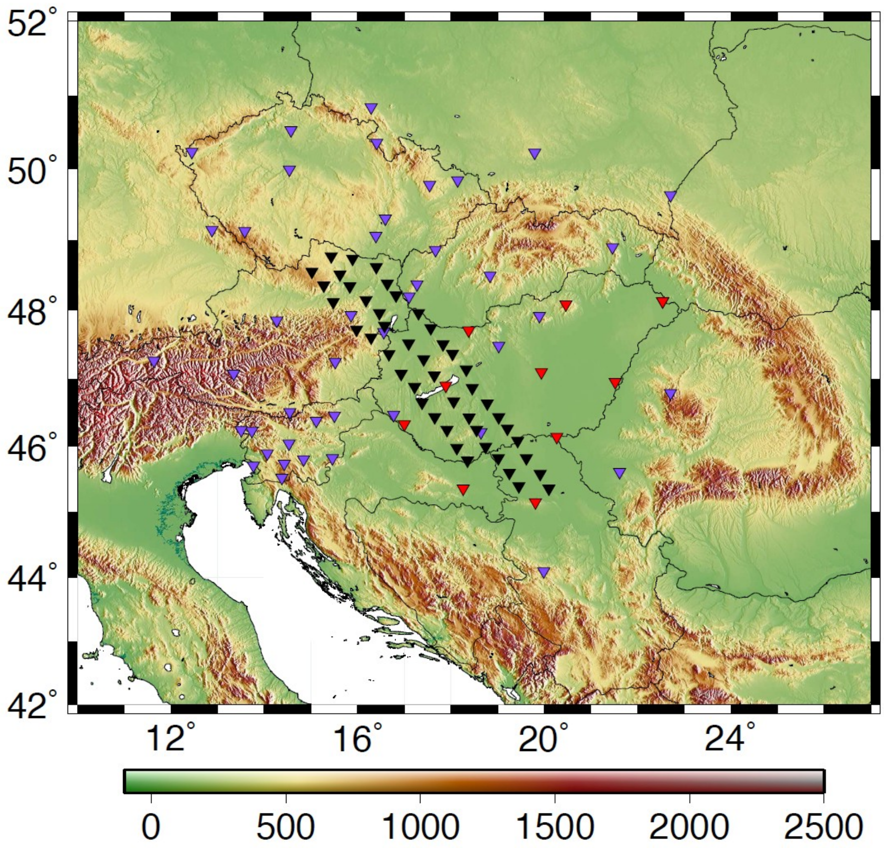

Fig 1. Distribution of broadband stations used in this study. Black triangles are the Carpathian Basins Project (CBP) CMG6TD (30s period) instruments, red triangles the CBP 100s period instruments and purple triangles are the permanent broadband seismological stations used in this study.

majority of sensors were not installed on bedrock. Figure 2 also shows power spectral density plots for typical 6TD stations, compared with standard low and high noise models. Successful field operations were facilitated by excellent collaboration established with the Technical University of Vienna, The Eötvös Loránd Geophysical Institute of Budapest and the Seismological Survey of Serbia in Belgrade.

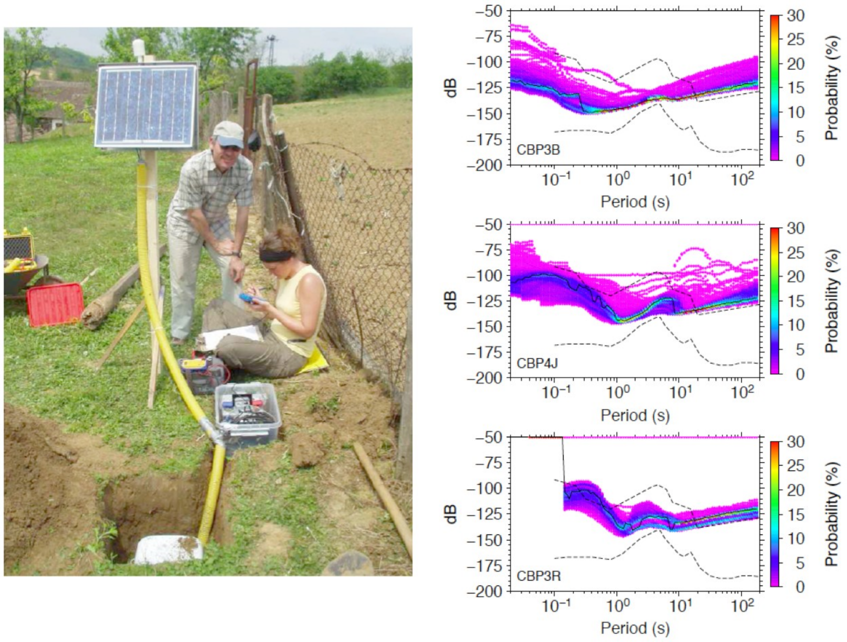

Fig 2. Left: Typical 6TD site configuration: a mounted solar panel and GPS antenna, connected to a battery, solar regulator and breakout box in a plastic box. The seismometer in the foreground is covered with a plastic container and buried. Right: Power spectral density plots of the vertical components over a seismically quiet period. The stations show typical ambient noise at 3 points on the middle line of the CMG6 array, from north-west (CBP3B) to south-east (CBP3R). The dashed lines show the high and low noise model of Peterson (1993). The modal value is shown as a solid black line.

Data Quality

From the 745 teleseismic earthquakes published in the ISC catalogue between 11/04/2006 and 22/08/2007 with M_w > 5.5 (Fig. 3) 225 events were used for P-wave tomography (15853 arrival times) and 124 for the S-wave study (8016 arrival times) – see Fig. 3. The relative arrival times were picked using the multi-channel cross-correlation (MCCC) method of VanDecar & Crosson (1990). Figure 3 shows an example of P-wave arrivals aligned on the MCCC picks.

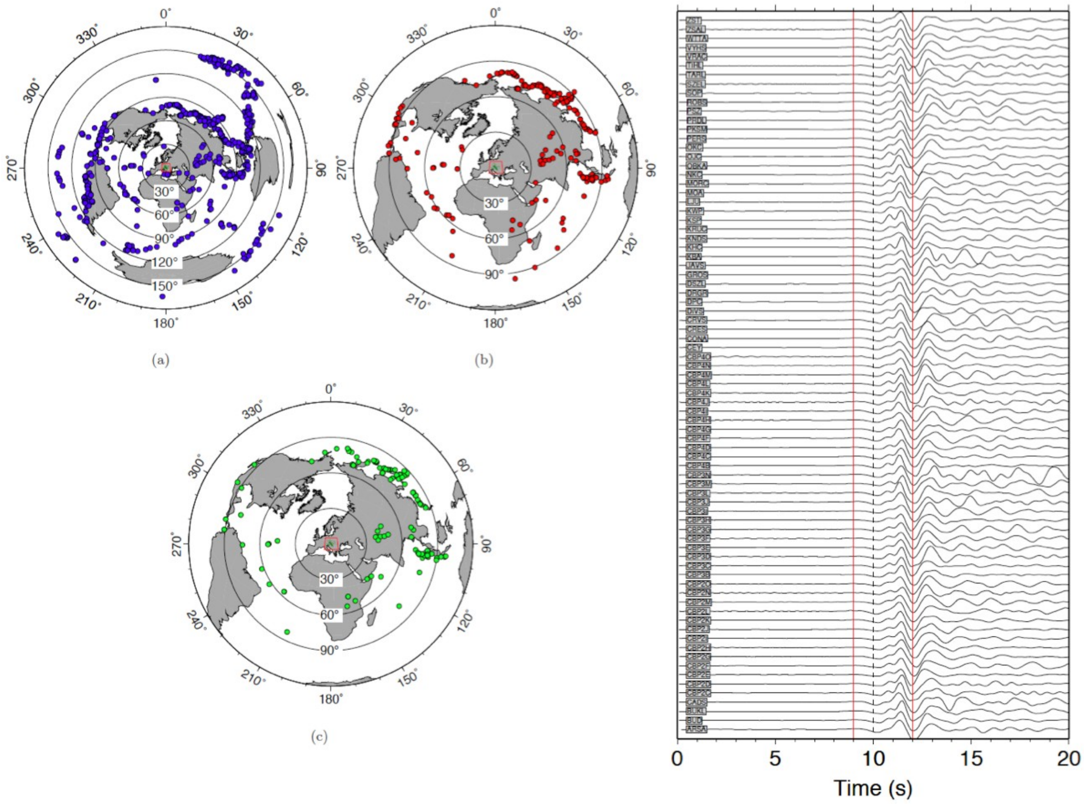

Fig 3. Left: Azimuthal projection of events recorded from 11/04/2006 to 22/08/2007 with magnitude Mw ≥ 5.5. Hypocentral information is from the Bulletin of the International Seismological Centre. a) all seismicity - 745 events; b) events used for the P-wave tomography - 225 events; c) events used for the S-wave tomography - 124 events. The stations are located in the centre of each plot. Right: Example of the MCCC for a P-wave arrival from a Mw 6.0 earthquake, at 10:53.11 on 22/06/2006 at 45.4◦N, 149.3◦E, with a depth of 9.5 km. The plot shows the traces aligned around the MCCC derived pick at 10 seconds. The 3 second window around the pick is shown in red.

The 6TD systems which provided most of the CBP dataset are simple and cost-effective to deploy and maintain, and provided good quality data for the tomography. For the purposes of SKS and receiver function analyses, however, these systems were relatively noisy in the Pannonian environment and had some minor reliability problems related to the firewire download capability. The 3TD systems provided good quality data at the longer periods, and in general were more reliable.

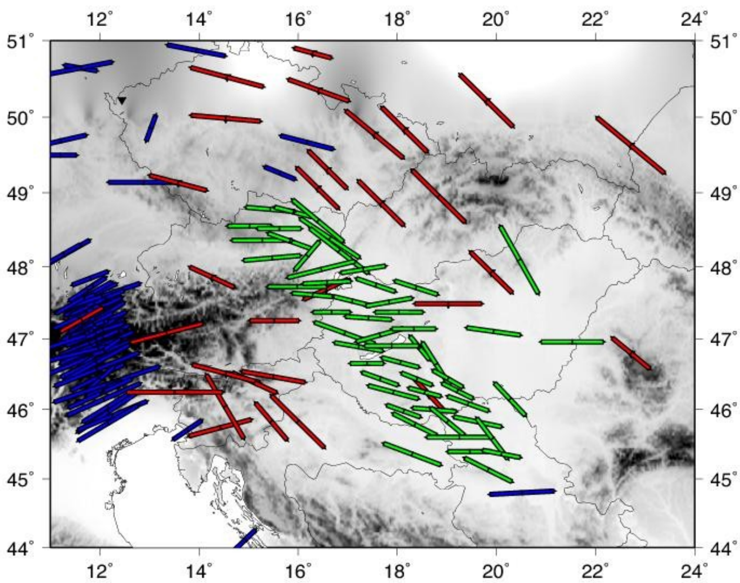

Fig 4. Lithospheric anisotropy as indicated by SKS fast polarization directions. For scale, length of the arrow is proportional to delay time between fast and slow polarization and the blue arrow on the lower right represents a delay time of 1.3 seconds.

Processing and modelling

We used the SKS analysis technique of Silver and Chan (1991) to determine fast polarization direction of lithospheric anisotropy (Fig. 4). We used the tomographic technique of VanDecar et al (1995) to invert the relative travel time residuals in to velocity anomaly images (Fig. 5). In addition to inverting for slowness (the inverse of velocity), the inversion also simultaneously solves for an arrival-time correction associated with each source and receiver. Source terms account for hypocentral error, as well as ray-path distortions caused by velocity heterogeneities external to the grid. The station terms take into account travel-time anomalies directly beneath each receiver: a lack of crossing rays at shallow depths prevents resolution of vertical structure in the crust and uppermost mantle. The robustness of the tomographic model was tested with different regularization and depth parameterization, and resolution was tested using synthetic model datasets (Dando et al., 2011).

Interpretation to date

At 75 km depth (Fig. 5a) four localised slow anomalies within the Pannonian basin are imaged: i) on the northern edge of the Pannonian Basin (48º N, 19.5º E), a low velocity region (-1.66%) overlies the Neogene Central Slovakian volcanics (Kovács et al., 2007); this anomaly appears to be terminated in the south at the mid-Hungarian shear zone; ii) in the eastern Pannonian basin (47.2º N, 21.8º E), a low velocity anomaly (-0.82%) appears directly beneath the Derecske sub-basin; iii) in the south of the Pannonian basin, close to the Hungarian-Serbian border (46.2º N, 20.0º E) a low velocity anomaly appears directly beneath the deepest and most rapidly subsiding Miocene NW-SE sub-basins of the Pannonian - the Békés and Makó basins. This region also has anomalously high heat flow: up to 130 mW m^{-2}, relative to the regional average of 90 mW m^{-2} (Tari et al., 1999); iv) in the west of the Pannonian basin a similar low velocity anomaly (-1.05%) is imaged close to the Hungarian-Croatian border (46.6º N, 17.7º E), beneath the Drava depression.

The lithosphere-asthenosphere boundary (LAB) is estimated to be between 45 and 60 km deep (Tari et al., 1999) within the Pannonian Basin, so the 75km depth slice is just below the LAB. The slow anomalies are likely to represent warmer asthenospheric upwellings associated with basin depocentre development (Corver et al., 2009). At 200 km depth (Fig. 5b), these slow anomalies have merged and decreased in amplitude to produce a sub-circular low velocity feature, underlying the surface expression of the Pannonian basin.

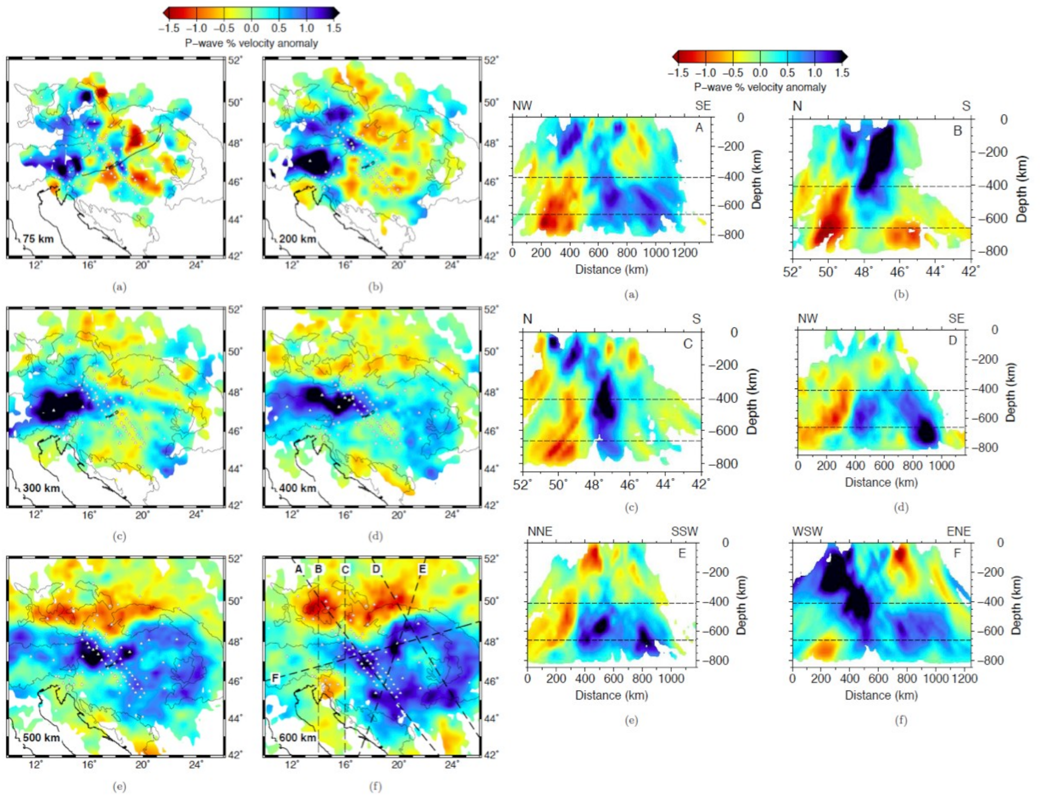

Fig 5. Left: Depth slices through the P-wave tomographic model. The locations of stations are shown as triangles. Right: Vertical sections through the P-wave tomographic model. Locations of vertical sections are shown in the 600 km depth slice.

At 75 km depth, high velocity (1.8%) features are imaged beneath the Eastern Alps and are presumably related to the continental convergence and downwelling of colder lithospheric material in the Alpine collision zone. High velocities also extend south into the Dinarides and north into the Bohemian Massif. At 200 and 300 km depth, the images are dominated by the fast anomaly beneath the eastern Alps. This high velocity feature has been previously imaged by Lippitsch et al. (2003), who interpreted it in terms of north-east dipping subduction of the Adriatic plate to depths of ~250 km. The fast anomaly is observed to continue into the Pannonian Basin region at 300 km depth and into the mantle transition zone (MTZ). Fig. 5, right c), provides a north-south cross-section at 16º E, through the extended Alpine-Pannonian anomaly, showing a vertical fast structure (interpreted as mantle downwelling) extending into the MTZ. In Fig. 5, right f), continuity with the eastern Alps structure is shown; the anomaly extends laterally beneath the Pannonian basin with increasing depth, but with decreased amplitude.

Within the MTZ, particularly in the 600 km depth slice (Fig. 5), the fastest anomalies approximately follow the outline of the Carpathian mountains enclosing slower material beneath the eastern Pannonian basin (47º N, 21.5º E), within a doughnut shaped structure. In vertical cross-section, (Fig. 5, right d & e), these peak anomalies could be interpreted as separate downwellings which have accumulated in the MTZ. However, the circular shape and continuous nature of the fast anomaly at 600 km suggests that the structures may have spread out laterally from a central location. Interpretation of the apparently slow material within the MTZ 'doughnut' must take into account the topography on the 660 km velocity discontinuity. Hetényi et al. (2009) showed that this surface is depressed by up to 40 km beneath the centre of the basin.

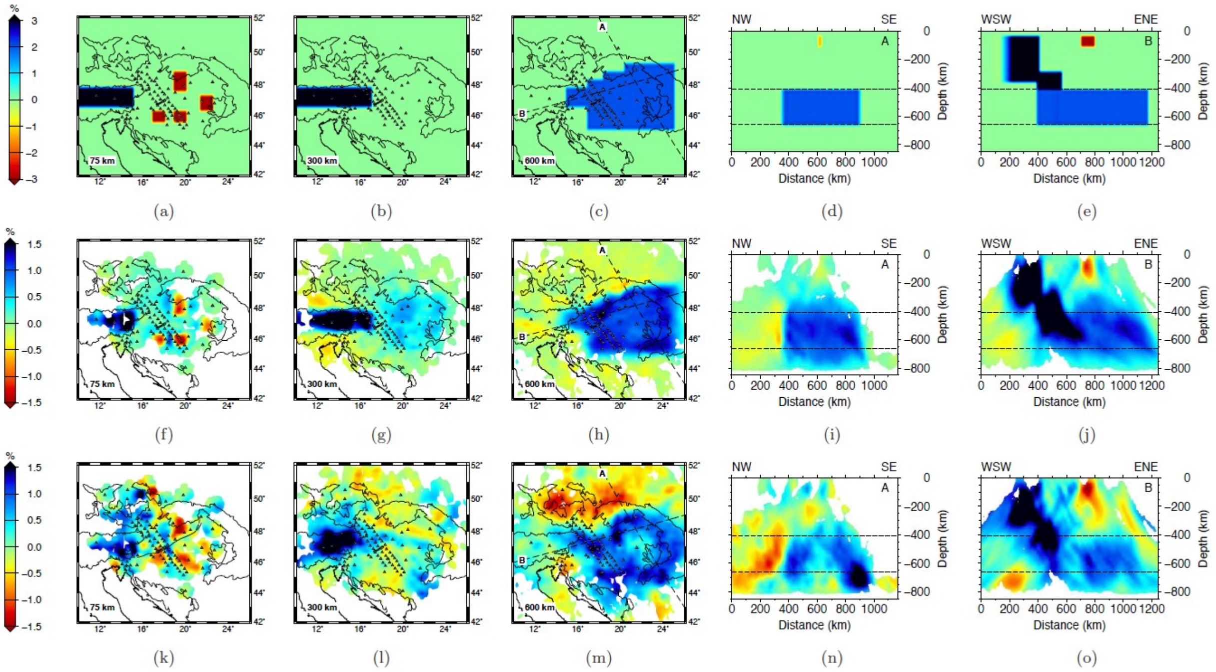

Fig. 6. Top (a-e): Synthetic model of a simplified structure inspired by the results of the data inversion. Middle (f-j): Recovered structure after the inversion of the synthetic travel-times from the above model. Bottom (k-o): corresponding sections from the preferred solution model. Locations of the cross-sections are shown in the 600 km depth slice.

Synthetic modelling showed that the observations of relatively low velocity surrounded by a relatively high-velocity annular structure could be produced by the effect of an over-deepened '660 km' discontinuity on the inversion results (Dando et al., 2011). Figure 6 shows the results of inverting synthetic travel times computed by ray tracing through a simplified structure representing our interpretation.

Conclusions and recommendations

This SEIS-UK loan enabled the collection of a major regional seismology dataset, now archived at IRIS. Fifty six temporary stations were operated safely and continuously for an average period of ~16 months. The body wave tomography has been successfully completed, along with the deep receiver function study. Other elements of the data analysis are continuing, with studies based on ambient noise correlation, surface wave analysis and lithospheric anisotropy from SKS. The Carpathian Basins Project has re-invigorated debate about the geological processes that caused the formation of the Pannonian

Basin in Central Europe. The high-resolution tomographic images of the upper mantle beneath the Basin have revealed a fast structure crossing the middle of the basin below 300 km depth. We interpret this structure as the remnant of mantle downwelling that pre-dates the extension of the basin, but reveals the location of a surface convergent zone active in the Miocene and probably similar to and continuous with the present Eastern Alps. Our data have also revealed that the 660 km seismic discontinuity is depressed by up to 40 km beneath the Pannonian Basin, consistent with the concept of a large volume of cold, dense mantle introduced into the transition zone by this mantle downwelling. The CBP dataset will also make an important contribution to a later NERC funded project focussed on the South Carpathian mountain range.

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Other conference presentations describing the results of the CBP project have been made at 2008, 2009, 2010 European Geoscience Union meetings in Vienna, and 2007, 2008, 2009 American Geophysical Union Fall meetings in San Francisco, as well as other small meetings such as: the Alpine-Pannonian-Carpathian workshop held in Hungary in 2007 (convened by the PIs), and invited presentations at the annual meeting of the Austrian Geological Society in 2008, and an LAB workshop held in Dublin 2009.