Geological Quarterly, 2009, 53 (1): 141–158

Seismic structure of the lithosphere between the East European Craton and the Carpathians from the net of CELEBRATION 2000 profiles in SE Poland

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Janik T., Grad M., Guterch A. and CELEBRATION 2000 Working Group (2009) — Seismic structure of the lithosphere between the East European Craton and the Carpathians from the net of CELEBRATION 2000 profiles in SE Poland. Geol. Quart., **53** (1): 141–158. Warszawa.

During the CELEBRATION 2000 experiment, the area of SE Poland was investigated by relatively dense system of deep seismic sounding profiles. Apart from five main profiles CEL01–CEL05, eight additional profiles were executed between the edge of the East European Craton and the Carphatians: CEL06, CEL11, CEL12, CEL13, CEL14, CEL21, CEL22 and CEL23. In this paper, we present results of modelling of refracted and reflected waves with use of a 2D ray tracing technique. All 13 profiles were jointly interpreted with verification of models at crossing points, and a quasi 3D model of the crust and upper mantle was developed. The obtained P-wave velocity models of the crust and uppermost mantle are very complex and show a differentiation of the seismic structure for tectonic units in SE Poland. The depth of the Moho discontinuity in the investigated area changes from about 30 to about 52 km. As a summary of all seismic models, the Moho depth map for SE Poland is presented, as well as a map of the extent of the most characteristic crustal elements in the area: a high velocity body in the upper crust, division into two- and three-layer consolidated crust, ranges of very deep layers with low velocities in the upper and middle crust, approximate ranges of detected velocity anisotropy in the upper/middle crust, ranges of the high-velocity lower crust and high-velocity uppermost mantle. Both maps are compared with the main structural elements from tectonic map. This could form the base for a new geotectonic interpretation of this complex area.

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Key words: lithospheric structure, East European Craton, Trans-European Suture Zone, Carpathians, deep seismic soundings, Moho map.

INTRODUCTION

Central European Lithospheric Experiment Based on Refraction — CELEBRATION 2000 project was an international large-scale deep seismic sounding experiment. It targeted the structure and evolution of the complex collage of major tectonic features in the Trans-European Suture Zone (TESZ) (Fig. 1), as well as the southwestern portion of the East European Craton (EEC — southern Baltica), the Carpathian Mountains, the Pannonian Basin, the Bohemian Massif and Eastern Alps (Guterch *et al*., 2000, 2001, 2003). The results of 2D seismic modelling for the main profiles have been published in a number of papers (Janik *et al*., 2005; Malinowski *et al*., 2005; Hrubcová *et al*., 2005; Grad *et al*., 2006, 2007; Środa *et al*., 2006; Guterch *et al*., 2007). It should be noted that the experiment was 3D in nature, meaning that, to the extent possible, all shots were designed to be recorded by all in-line and off-line recorders. Thus, the ultimate goal was a consistent 3D interpretation of all existing data in the vast area covered by the experiment (Malinowski *et al*., 2008).

In this study, we present part of results from the CELEBRATION 2000 experiment focused on the area of SE Poland, which is a collision zone between the East European Craton (EEC), Palaeozoic Platform and Carpathian Mountains. The relatively dense net of seismic profiles covering this area consists of five main profiles (CEL01–CEL05), and eight additional profiles (CEL06, CEL11, CEL12, CEL13, CEL14, CEL21, CEL22 and CEL23) (Fig. 1). The profiles cross all the above mentioned tectonic units; the EEC and TESZ with: the Kuiavian Unit, the Radom–Łysogóry Unit, the Małopolska Unit (or terrane) and the Upper Silesia Unit (USU), in the northern and central parts. The main tectonic lineaments here are the Grójec Fault (GF), Kazimierz–Ujazdów Fault (KUF), Kraków–Lubliniec Fault Zone (KLF), and the Holy Cross

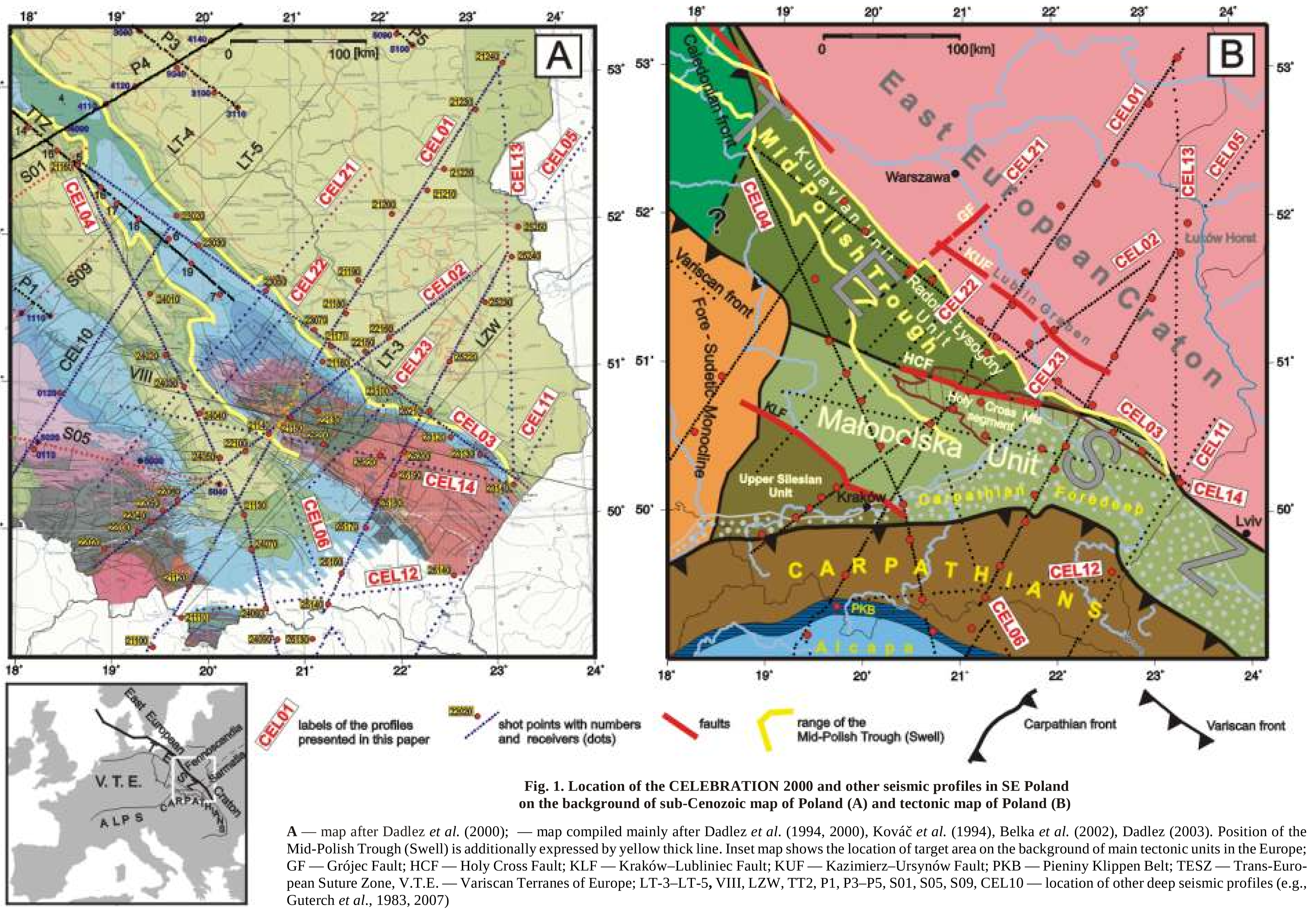

Fig. 1. Location of the CELEBRATION 2000 and other seismic profiles in SE Poland on the background of sub-Cenozoic map of Poland (A) and tectonic map of Poland (B)

A — map after Dadlez *et al.* (2000); — map compiled mainly after Dadlez *et al.* (1994, 2000), Kováč *et al.* (1994), Belka *et al.* (2002), Dadlez (2003). Position of the Mid-Polish Trough (Swell) is additionally expressed by yellow thick line. Inset map shows the location of target area on the background of main tectonic units in the Europe; GF — Grójec Fault; HCF — Holy Cross Fault; KLF — Kraków–Lubliniec Fault; KUF — Kazimierz–Ursynów Fault; PKB — Pieniny Klippen Belt; TESZ — Trans-European Suture Zone, V.T.E. — Variscan Terranes of Europe; LT-3–LT-5, VIII, LZW, TT2, P1, P3–P5, S01, S05, S09, CEL10 — location of other deep seismic profiles (e.g., Guterch *et al*., 1983, 2007)

Mountains Fault (HCF). The southern part is covered by the Carpathian orogen and its foredeep. The Pieniny Klippen Belt (PKB) separates the Outer and Inner Carpathians. Locations of some important tectonic elements are displayed in Figure 1B (e.g., Variscan and Caledonian fronts), however, these are still a matter of controversy and dispute between different authors (*cf.* Birkenmajer, 1976; Książkiewicz, 1977; Franke, 1990; Pożaryski, 1990; Dadlez *et al.*, 1994; Kováč *et al.*, 1994; Pharaoh *et al.*, 1997; Berthelsen, 1998; Belka *et al.*, 2002; Antonowicz *et al*., 2003; Narkiewicz, 2007).

THE DATA AND FORWARD RAY TRACING MODELLING

During the CELEBRATION 2000 experiment we collected data along 31 main and additional profiles. Many of them were located in SE Poland. Results of 2D modelling and tectonic interpretation along main profiles have already been published (CEL02 — Malinowski *et al.*, 2005; TTZ-CEL03 — Janik *et al*., 2005; CEL05 — Grad *et al*., 2006; CEL01 and CEL04 — Środa *et al*., 2006), as well as the results relating to seismic anisotropy in the upper/middle crust (Środa, 2006) and 3D first arrival tomography (Malinowski *et al*., 2008). Still, there remains a huge data set of high quality recordings on all additional profiles. The data set for this paper consists of five main profiles, CEL01–CEL05, and eight additional profiles executed in SE Poland: CEL06, CEL11, CEL12, CEL13, CEL14, CEL21, CEL22 and CEL23. They are quite long, of *ca*. 300 km length (profiles CEL13, CEL21, CEL23, CEL14 and CEL06 — extended into Slovakia and Hungary), or even longer, e.g. the 430 km profile CEL11. Other profiles are shorter: CEL12 and CEL22 are of *ca*. 210 and 90 km, respectively. Usually there were only a few shot points at additional profiles (Fig. 1), and spacing between recordings was about twice that along the main profiles. So, although the quality of records along additional profiles is high (see examples in Fig. 2), they have a lower rank comparing to main profiles. On the other hand, they are very important because they fill the gap between the main profiles, and in effect they have a substantial influence on the final image of the seismic structure of the area of SE Poland.

A correlation and picking of seismic phases was undertaken using the *ZPLOT* package (Zelt, 1994). For modelling of refracted and reflected waves, we used a 2D ray tracing technique. The modelling of travel times, rays and synthetic seismograms was done using the *SEIS83* package (Červený and Pšenčík, 1983), supported by *MODEL* and *XRAYS* (Komminaho, 1998). The initial models of the sedimentary cover and shallow basement for most individual profiles (CEL01–CEL05, CEL11 and CEL12) were constrained using borehole information and earlier geophysical studies, including high-resolution seismic reflection surveys (unpublished data). This information provides a much more detailed model of the uppermost 5–10 km of sediments than can be obtained from the refraction profiles alone. The initial models of the shallow structure were only slightly adjusted (in the sense of seismic velocity and depth of boundaries) during the ray tracing procedure. The overall velocity models for all the profiles were successively modified by a trial-and-error procedure, and travel times were recalculated many times until the agreement was obtained between observed and model-derived P-wave travel times. The final lithospheric models derived for the structure along all profiles are shown in Figures 3–5 (vertical exaggeration is 2.4:1 for the models, and about 20:1 for topography). All 13 profiles were jointly interpreted with verification of the models at crossing points. If necessary, models for the main profiles were re-interpreted to fit better in crossing points, however, these changes were not significant. The accuracy of first arrivals picking is about 0.05 s and for reflected phases (latter arrivals) about 0.1 s. Typical misfits for the observed and calculated P-wave travel times were of the order of 0.1–0.2 s (Figs. 6–8). Finally, in addition to kinematic modelling, synthetic seismograms were calculated to control velocity gradients within the layers and the velocity contrast at the seismic boundaries. The final synthetic seismograms show good qualitative agreement with the relative amplitudes of observed refracted and reflected P-waves (see, for example, SP23140 from profile CEL13 in Fig. 6).

The seismic data used for modelling along the main profiles were of good quality, with a dense system of sources and receivers. In modelling, clear first arrivals and later refracted/reflected phases were used. With the data of such a quality, the velocity and depth uncertainties of models derived by 2D forward modelling are on the order of ±0.1 km/s and ±1 km, where the crustal structure is relatively simple, and ±0.2 km/s and ±2 km for complicated structure, respectively (e.g., Janik *et al*., 2002; Grad *et al*., 2003, 2008). For the additional profiles, uncertainties could be slightly larger. For example, profile CEL22 has one shot point only with recordings up to 100 km. Formally, it should be modelled as 1D, but because we have information from the crossing point with profile CEL03, we modelled it as a 2D structure. The horizontal resolution in the ray tracing technique is about 20 km, or better for well documented data, depending from shots and stations spacing.

MODELS OF THE CRUSTAL AND UPPERMOST MANTLE STRUCTURE

The collection of seismic models of CELEBRATION 2000 project in SE Poland is shown in Figures 3–5. The models show large variations in the internal structure of the crust and the Moho topography within a relatively small area varies over the wide depth interval of 30–52 km. In general, profiles connected with the Carpathians are presented in Figures 3 and 4. Four profiles: CEL01, CEL04, CEL05 and CEL11/CEL13, cross nearly perpendicular to the collision zone in the Carpathians, through the TESZ to the EEC. Models for the CEL01 and CEL05 profiles are limited to study area. Two profiles, CEL11 and CEL13, united into one transect are *ca*. 700 km long. CEL06 runs parallel to CEL04, and CEL12 runs approximately along the Carpathian axis (W–E in this area). Other profiles presented in Figure 5 are located in the TESZ and the marginal zone of the EEC. Profiles CEL02, CEL21, CEL22, CEL23 and CEL11 run approximately in the SW–NE direction, nearly perpendicular to the edge of the EEC; profiles CEL03 and CEL14 are nearly

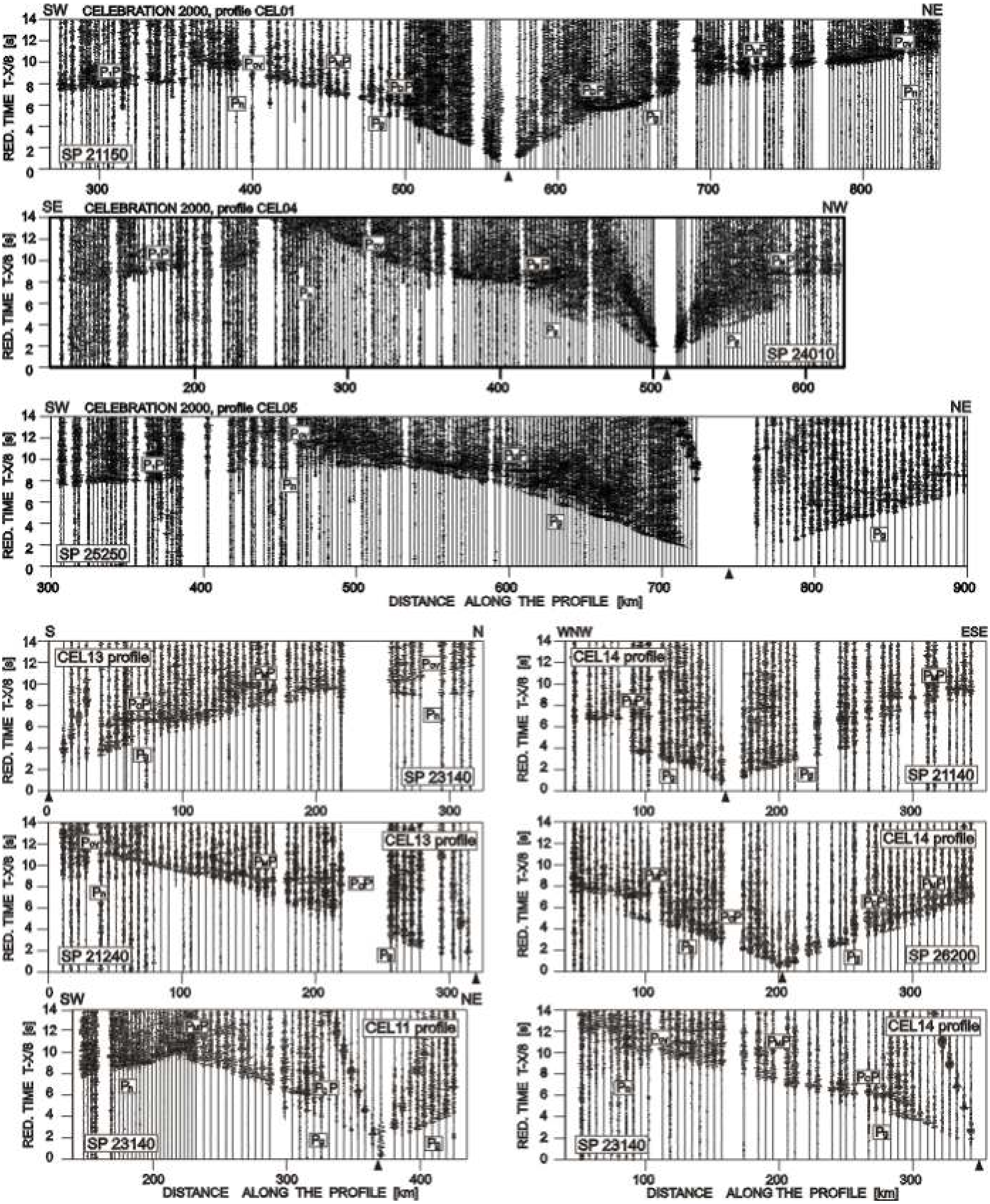

Fig. 2. Examples of seismic sections from experiment CELEBRATION 2000 recorded in SE Poland

The trace-normalized, vertical-component seismic record sections for P-waves along one of the main profile CEL05 are compared with record sections from profiles CEL01, CEL04, CEL05, CEL11, CEL13 and CEL14. Black triangles are shot locations. Band-pass filtration 2–15 Hz. The reduction velocity is 6 km/s. Abbreviations: Pg — seismic refracted waves from the upper and middle crystalline crust, Pov — overcritical crustal reflections, PcP — reflections from the middle crust discontinuities, PMP — reflected waves from the Moho boundary, Pn — refractions from the sub-Moho uppermost mantle, P_1P — P-wave phases from the upper mantle

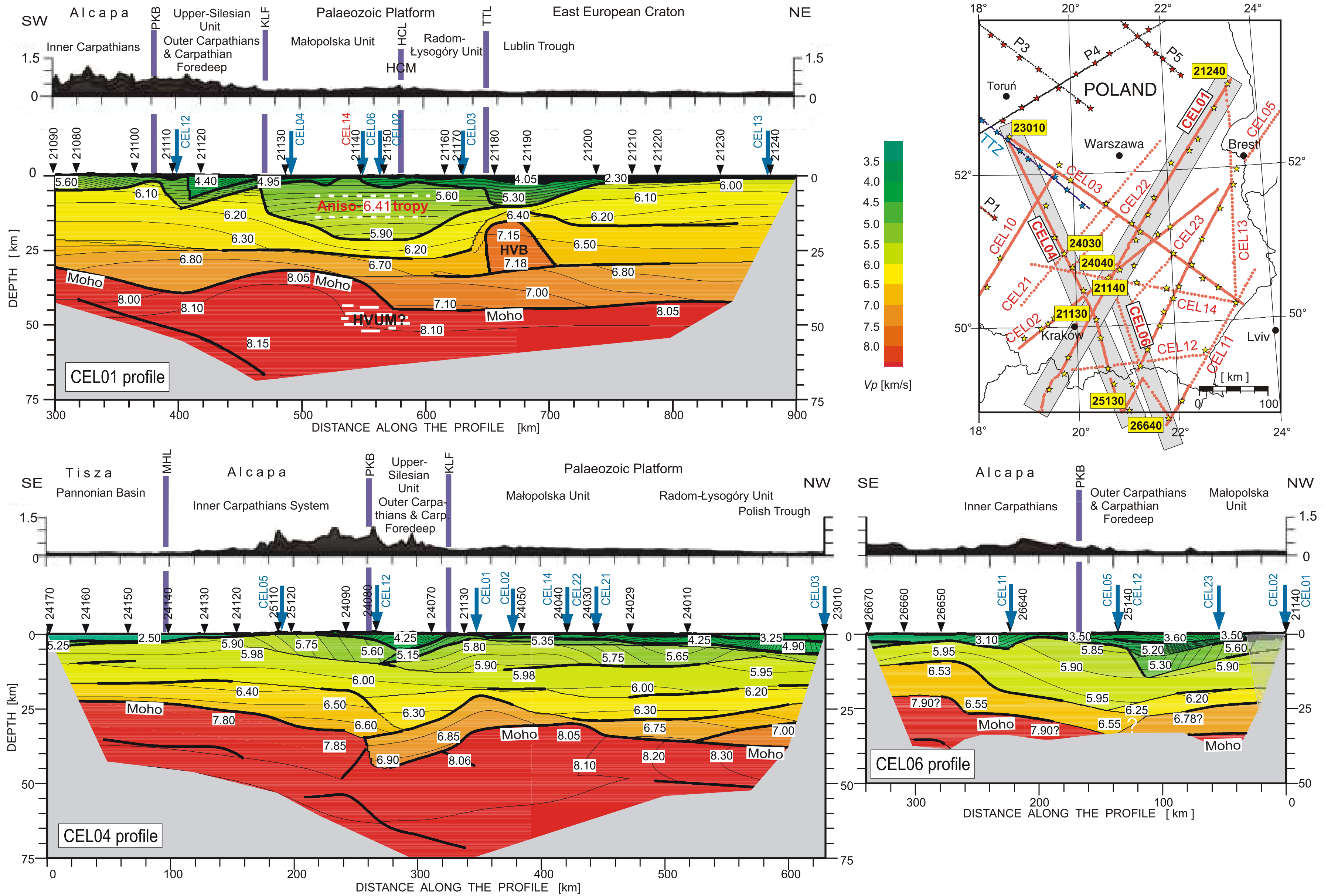

Fig. 3. 2D crustal and uppermost mantle models from CELEBRATION 2000

Two-dimensional models of seismic P-wave velocity in the crust and uppermost mantle derived by forward ray tracing modelling using the *SEIS83* package (Červený and Pšenčík, 1983) along the CELEBRATION 2000 profiles CEL01, CEL04 and CEL06 in SE Poland (highlighted in grey location). Those parts of the boundaries that have been constrained by reflected and/or refracted arrivals are marked by thick lines. Thin lines represent velocity isolines with values in km/s shown in white boxes. Position of large-scale crustal blocks is indicated. Black triangles show positions of shot points. Blue arrows show crossings with other profiles. Areas overlapped by transparent gray colour represent parts of profiles with not consistent system of measurements and lower accuracy. Two white dashed lines on CEL01 profile show area of detected anisotropy on crossing with CEL14 profile. Vertical exaggeration is 2.4:1 for the models, and about 20:1 for topography. TTL — Teisseyre-Tornquist Line, MHL — Mid-Hungarian Line; for geological abbreviations see Figure 1

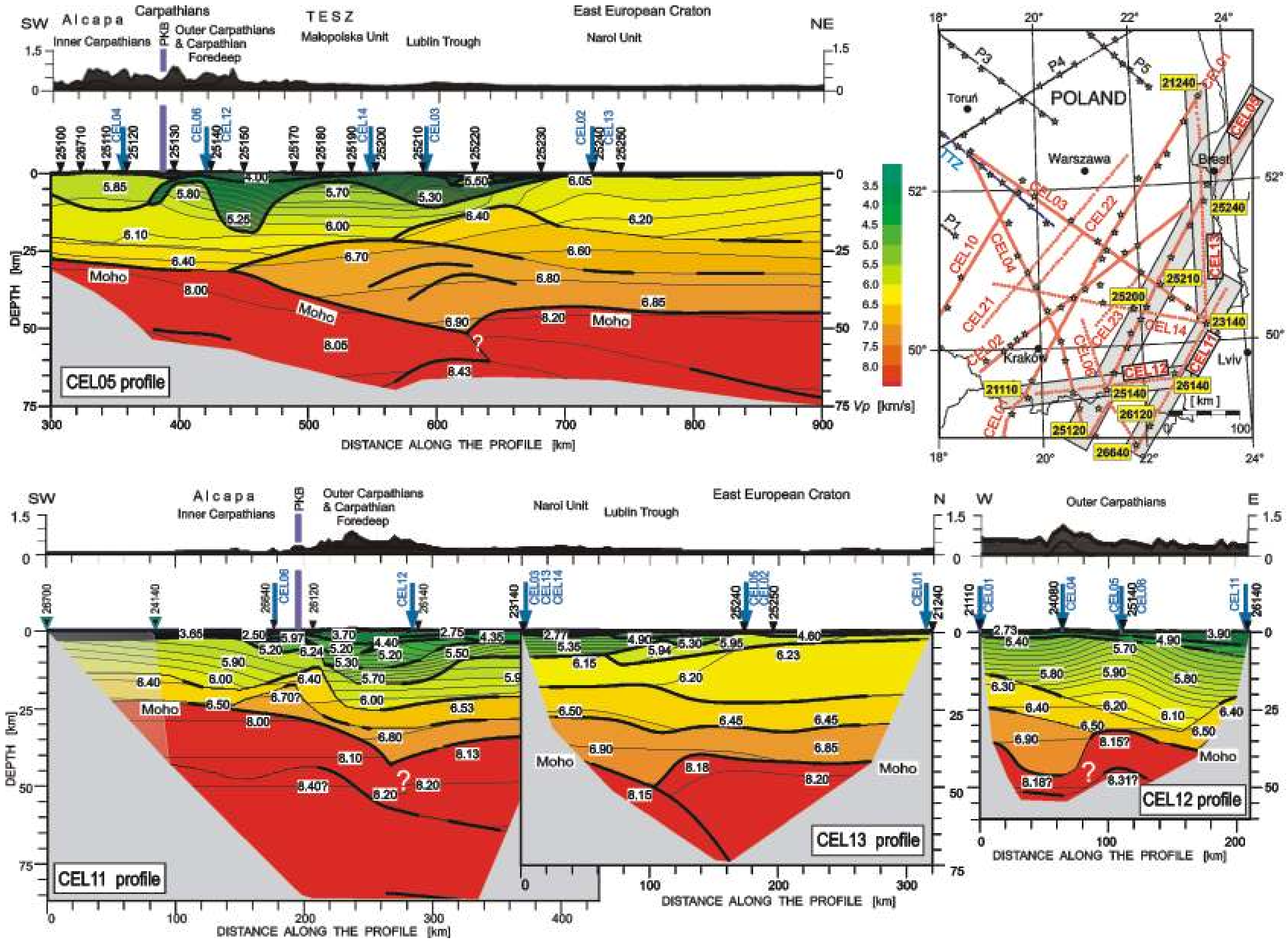

Fig. 4. 2D crustal and uppermost mantle models from CELEBRATION 2000
Two-dimensional seismic models along the CELEBRATION 2000 profiles CEL05, CEL12 and transect CEL11/CEL13; other explanations as in Figure 3

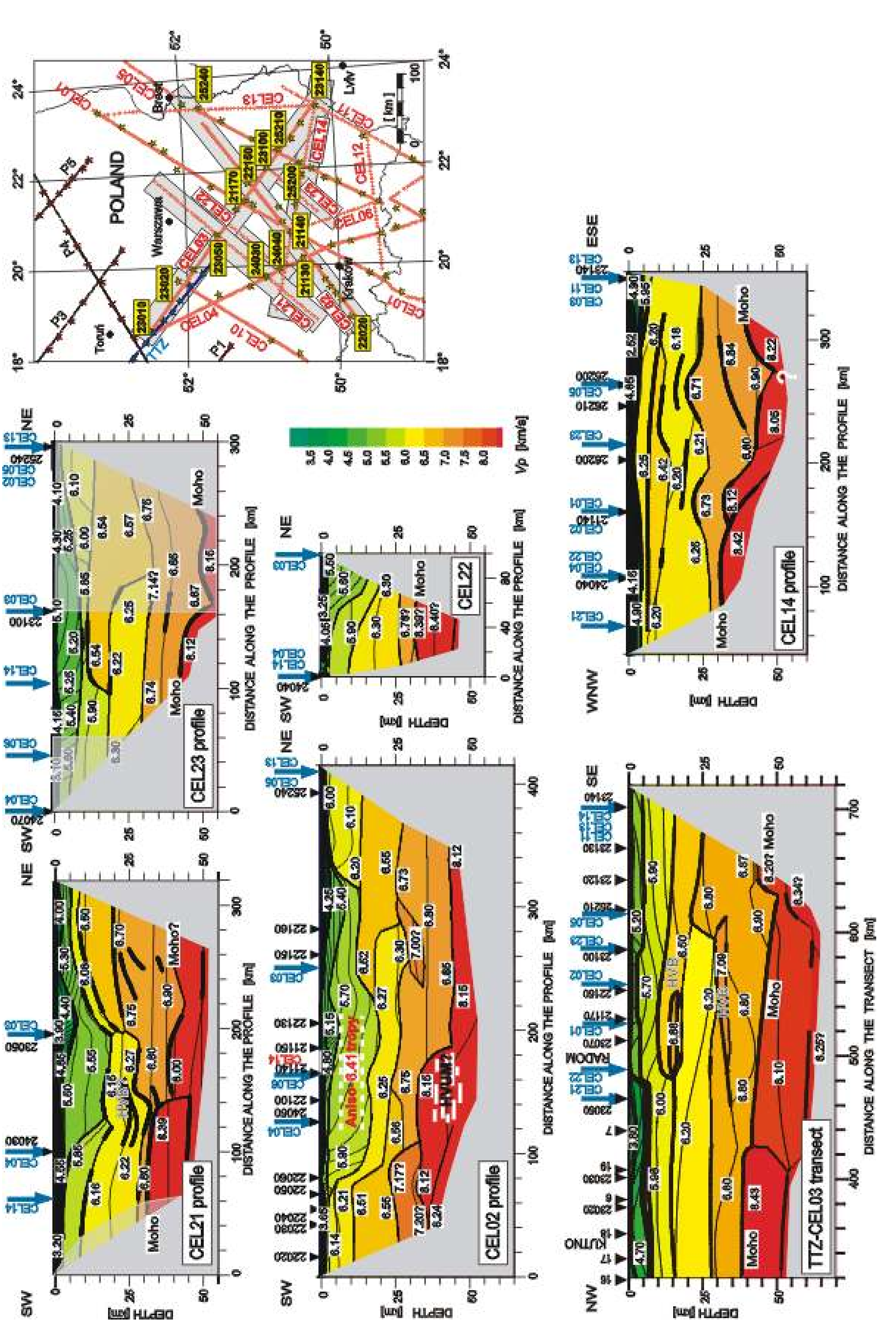

Fig. 5. 2D crustal and uppermost mantle models from CELEBRATION 2000
Two-dimensional seismic models along the CELEBRATION 2000 profiles CEL02, CEL14, CEL21, CEL22, CEL23 and transect TTZ-CEL03; other explanations as in Figure 3

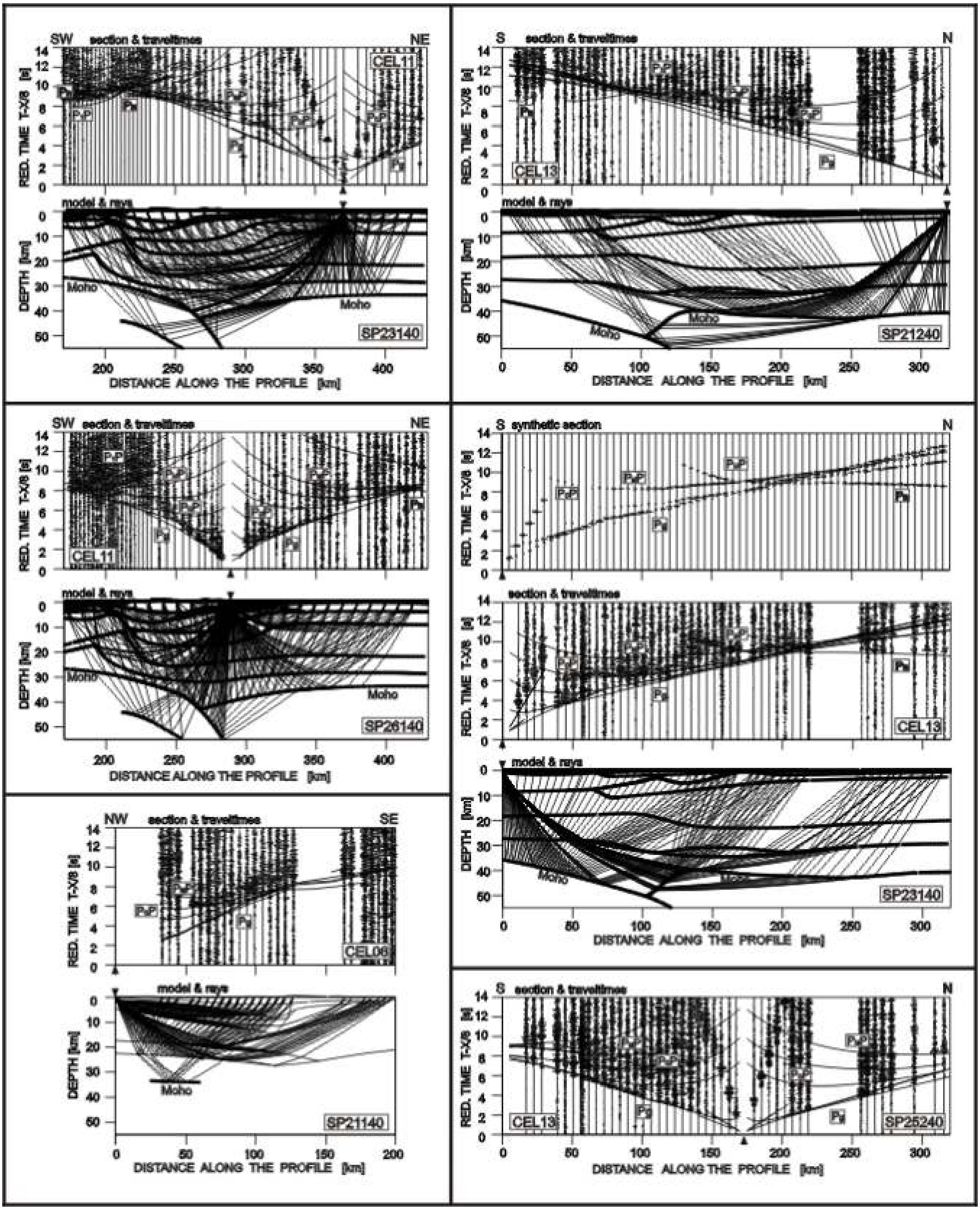

Fig. 6. Examples of seismic modelling along CELEBRATION 2000 profiles CEL11, CEL13 and CEL06

Seismic record sections of P-waves (amplitude-normalized vertical component) with theoretical travel times, synthetic seismograms and selected ray diagrams calculating using the *SEIS83* ray tracing package (Červený and Pšenčík, 1983); band-pass filtration 2–15 Hz; reduction velocity 8.0 km/s; all examples were calculated for the models presented in Figures 3–5; abbreviations of seismic phases as in Figure 2

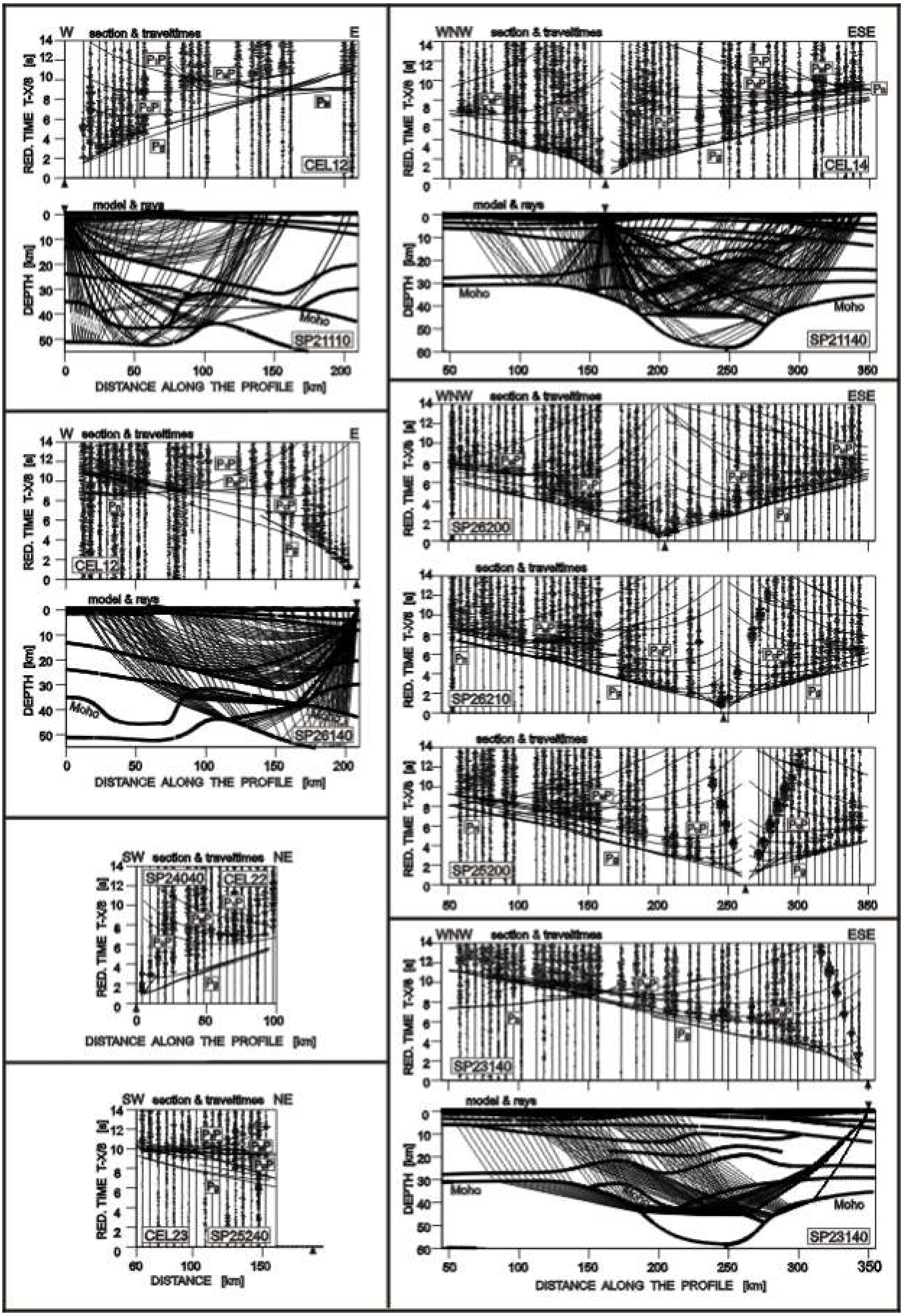

Fig. 7. Examples of seismic modelling along CELEBRATION 2000 profile CEL12, CEL14, CEL22 and CEL23

Abbreviations of seismic phases and other explanations as in Figures 2 and 6

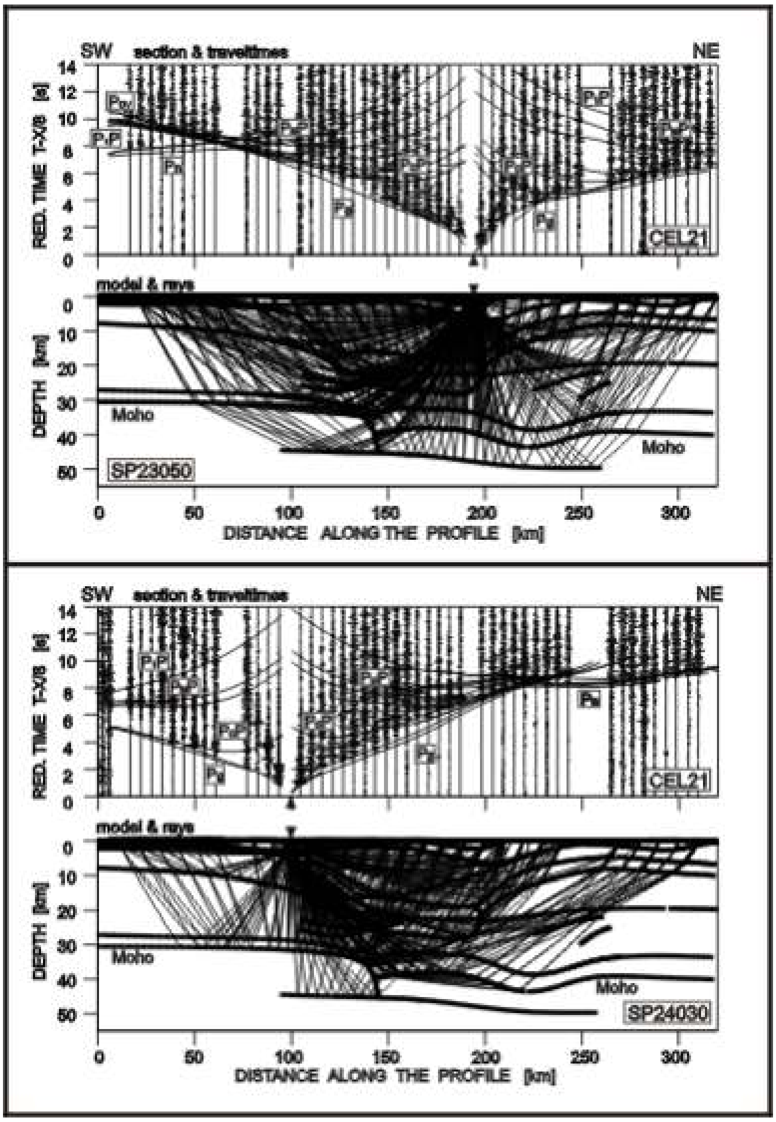

Fig. 8. Examples of seismic modelling along CELEBRATION 2000 profiles CEL21

Abbreviations of seismic phases and other explanations as in Figures 2 and 6

parallel to the EEC edge, in NW–SE and WNW–ESE directions, respectively (Fig. 1). Examples of modelling are shown in Figures 6–8.

The study revealed pronounced lateral variations in *Vp* velocity values in the crust and variations of the Moho depth (Figs. 3–5), which can be associated with the tectonic units crossed by profiles. In the southwestern part of the four Carpathians profiles (Alcapa, Tisza), the crust consists of only two layers, the upper and lower crust, both with velocities $Vp \leq$ 6.4 km/s. In the northern part of the profiles (EEC), the crust has one extra, *ca*. 12 km thick, layer at the bottom with $Vp =$ 6.7–7.0 km/s. Other characteristic features of the EEC is a relatively thin sedimentary cover with velocities $Vp =$ 2.3–4.6 km/s. The crystalline basement with velocities $Vp \geq$ 6.0 km/s was found here at depths of 1–5 km in the northern part of study area and at depths of 7–10 km in the area of the Lublin Trough. The exception is the CEL04 profile which ends in the Polish Trough.

The area between the Carpathians and EEC is the most tectonically complex area — the TESZ. Along all profiles perpendicular to the EEC edge (Figs. 3–5) we observe 10–20 km thick uppermost crust with relatively low velocity ($Vp \leq 6.0$ km/s) associated with the Polish trough and the Carpathian Foredeep. However, beneath the CEL14 profile, which crosses the same area in a WNW–ESE direction, nearly parallel to the edge, we observe much higher velocities, reaching 6.4 km/s. This phenomenon is explained by anisotropy, and was documented by Środa (2006) — see the text below. In the upper crust, numerous high velocity bodies (HVB, $Vp \geq 6.9$ km/s) were detected beneath the investigated area (profiles CEL01, CEL02, CEL03 — see Figs. 3 and 5 respectively). In some cases they correspond to “floating reflectors” (profiles CEL05 and CEL14). For most profiles, relatively very low velocities, $Vp =$ 6.2–6.3 km/s, for middle crust, at depths of 20–30 km were detected. For the TESZ in SE Poland, we observe the lower crustal layer with $Vp =$ 6.7–7.0 km/s, similar to the EEC. Slightly higher velocities Vp ~7.2 km/s were found in the lower crust in southwestern part of the CEL02 profile (Upper Silesian Unit).

In a relatively small area of SE Poland, we observe strong variations in the Moho depth and in the crustal and sub-Moho velocities. The thickness of the crust varies from 32–34 km beneath profiles CEL02, CEL04 and CEL14 in their western parts, to 40–52 km beneath eastern parts of profiles CEL01, CEL02, CEL03, CEL05 and CEL13. In the Carpathians, the Moho is at 40–42 km depth, except for their central part (profiles CEL04, CEL05 and CEL06) where it is 32–34 km only. An abrupt Moho rise was detected along profile CEL12, from depths of 44 km in the W to 32 km in the S (Fig. 4). Sub-Moho velocities have on average, values of 8.1 km/s in the NW and 8.2 km/s in the SE part of the study area. Much higher velocities, of *ca*. 8.4 km/s, were found beneath profiles CEL03, CEL14 and CEL21. This high-velocity upper mantle (HVUM) beneath the Moho was found earlier on the TTZ-CEL03 profile (Janik *et al*., 2005). A number of reflectors in the upper mantle were introduced at depths of ~57 km, 65–68 km and ~75 km in order to fit reflections P_1P (Figs. 6–8). However, the velocities beneath these reflectors are not well constrained, because, we usually do not observe refracted waves from these interfaces.

The joint interpretation of the net of profiles in the investigated area provides new data which has an influence on the images of the previously published models for main profiles. Small changes in the boundaries and velocities of the lower crust and upper mantle were implemented in the central parts of the CEL02 (Fig. 5) and CEL05 models (Fig. 4) — compare with Malinowski *et al*., (2005) and Grad *et al*., (2006). For models along CEL01 and CEL02, we attempted to verify the possibility of existence of the HVUM at crossings with profile

CEL14 (see Figs. 3 and 5). Comparison of calculated and experimental travel times shows that, from the CEL01 and CEL02 data, we can neither confirm nor exclude the existence of the HVUM.

SEISMIC CHARACTERISTICS OF THE CRUST AND UPPERMOST MANTLE IN SE POLAND

Deep seismic investigations carried out on the CELEBRATION 2000 profiles in SE Poland detected complex crustal structure in the contact zone between the Palaeozoic Platform, Carpathians and the EEC. Models presented in Figures 3–5 were the basis for constraining of the Moho depth map (Fig. 9A) and a map showing the extent of the most characteristic structural elements of investigated area (Fig. 9B). For the area of SE Poland, the presented Moho map contains more detail compared to the map on the continental scale (Grad *et al.*, 2009). Representative velocity models for the Carpathians, Upper Silesian Unit (Variscides), TESZ, the edge of the EEC and the EEC, are collated on Figure 10.

Moho depth. The depth of the Moho discontinuity in the investigated area varies from about 30 km to about 52 km. The northern part of the investigated area, associated with the EEC, is documented by parts of the CEL03, CEL01, CEL05, CEL13 and CEL21 profiles. Here Moho boundary is more or less stable, with depths of 42–46 km. The deepest Moho (*ca.* 52 km) was detected below the edge of the EEC (in the area crossed by the CEL03, CEL05, CEL14 profiles) with an extension to NE (CEL13 profile). Tectonically, this is the edge of the craton, at the SE termination of the Lublin Trough. Resolving its tectonic background, we kept in mind that this area coincides with termination of the suture between Fennoscandia and Sarmatia, the two main terranes that collided to form western Baltica in the Palaeoproterozoic (Bogdanova *et al.*, 1996, 2005, 2006; see inset of Fig. 1).

In the area SW of the craton edge, the Moho is 32–38 km deep, with two local maxima, slightly deeper than 42 and 44 km, divided by a local minimum, at *ca*. 32 km depth. This is an area at the intersection of CEL05, CEL04 and CEL12, in the Outer Carpathians. The western maximum is documented by the intersection of CEL04 and CEL12, and the eastern one by CEL11. The uplift up to 32–36 km between them is documented by profiles CEL05 and CEL12. Another local minimum, with *ca*. 32 km depth was detected below the boundary between the Małopolska and Upper Silesia units (in the area crossed by CEL02, CEL01, CEL21 and CEL14). A third local minimum in the Moho boundary (*ca*. 36 km) was detected in the SE part of area (crossing of CEL03, CEL11, CEL13 and CEL14) which coincides with the Narol Unit, postulated by Janik *et al.* (2005).

High velocity upper mantle. The HVUM (with velocity *Vp* ~8.4 km/s), detected below the P4, P1 and TTZ profiles (Janik *et al.*, 2005) extends SE, to the intersection of profiles CEL01, CEL02 and CEL14, and the intersection of CEL04 and CEL02. It is partly overlapped by a sub-Moho layer with velocity *Vp* ~8.1 km/s. The dome shape of the top of the HVUM was obtained by fitting the calculated traveltimes for the south-westward observed branches of PmP and Pn waves with the very high apparent velocity from CEL21 and CEL14 (Fig. 5). Hence, the velocities of the HVUM are not as well documented in this region, as in the central part of the body. Combining this information with the Moho map (Fig. 9A), we see that HVUM rises from a depth of 38 to 32 km. The HVUM in the Palaeozoic platform appears to be typical for nearby Caledonian terranes and the northernmost parts of nearby Variscan terranes (Guterch *et al.*, 1986, 1994; Jensen *et al.*, 1999).

Lower crust. In SE Poland we can distinguish two domains a the basis of velocities in the lower crust. The line running approximately along the Polish–Slovak border (Fig. 9B) divides areas of the lower crust with *Vp* = 6.7–7.0 km/s (to the north) and *Vp* < 6.6 km/s (to the south). It could be interpreted as the maximum range of the Baltica lower crust to the south (Grad *et al.*, 2002; Guterch and Grad, 2006). Relatively high velocity (*Vp* ~7.2? km/s) was found in the lower crust in the Upper Silesian Unit but it should be noted that this value was determined from dynamic properties (amplitude and frequency) of reflected waves only, and its accuracy is not as high as for velocities documented by refracted waves.

Upper/middle crust. Very low velocities in the upper/middle crust (*Vp* = 6.2–6.3 km/s at depths up to 20–30 km), were detected below the Radom–Łysogóry and Małopolska units, generally in the area which continues to the CEL05 profile line. This complex has the same properties as the layer detected in the Polish trough in previous investigations in NW and Central Poland, Pomeranian and Kuiavian units (Guterch *et al.*, 1994; Grad *et al.*, 1999, 2003; Jensen *et al.*, 1999; Janik *et al.*, 2005). In the marginal area of the EEC we observe an uplift of the middle crust with velocity *Vp* = 6.4–6.6 km/s to the depths of 15–10 km, which is much shallower in comparison with the continuation of this layer to the north and south-east (Fig. 9B). In the area along CEL03, between CEL01 and CEL05, this layer overlaps the previous one with lower velocities (*Vp* = 6.2–6.3 km/s).

Anisotropy. An analysis of data from profiles located around the CEL14 profile revealed azimuthal variation of the *Vp* velocity in the upper/middle crust (depth 8–17 km). This is explained by upper/middle crustal seismic anisotropy and was analysed by anisotropic delay-time inversion method (Środa *et al.*, 2006). The result, indicating 8–12% anisotropy (*Vp* = 5.6–6.4 km/s) fits with the geology of the area, where tightly folded metapelitic rocks are abundant (Środa, 2006). The fast velocity axis direction (115°, WNW–ESE) coincides well with the strike/hinge directions of folds axes and other deformational structures which crop out in the region. The large time delays in the upper/middle crust are caused by a significant thickening of the Mesozoic/Cenozoic and partially also the Palaeozoic cover towards the EEC margin (Środa, 2006). This was documented also by Środa *et al.* (2006), while the increase in delays in the south results from the thickening of the low-velocity sediments of the Outer Carpathians and the Carpathian Foredeep. Beneath the Małopolska Unit, the delays are minimal and are in general lower than beneath the Lublin Trough. This suggests that the Neoproterozoic basement occurs here at shallower depths than in the latter unit. The area of detected anisotropy is somewhat extended in our investigation (Fig. 9B) using differentiation of velocities beneath 2D pro-

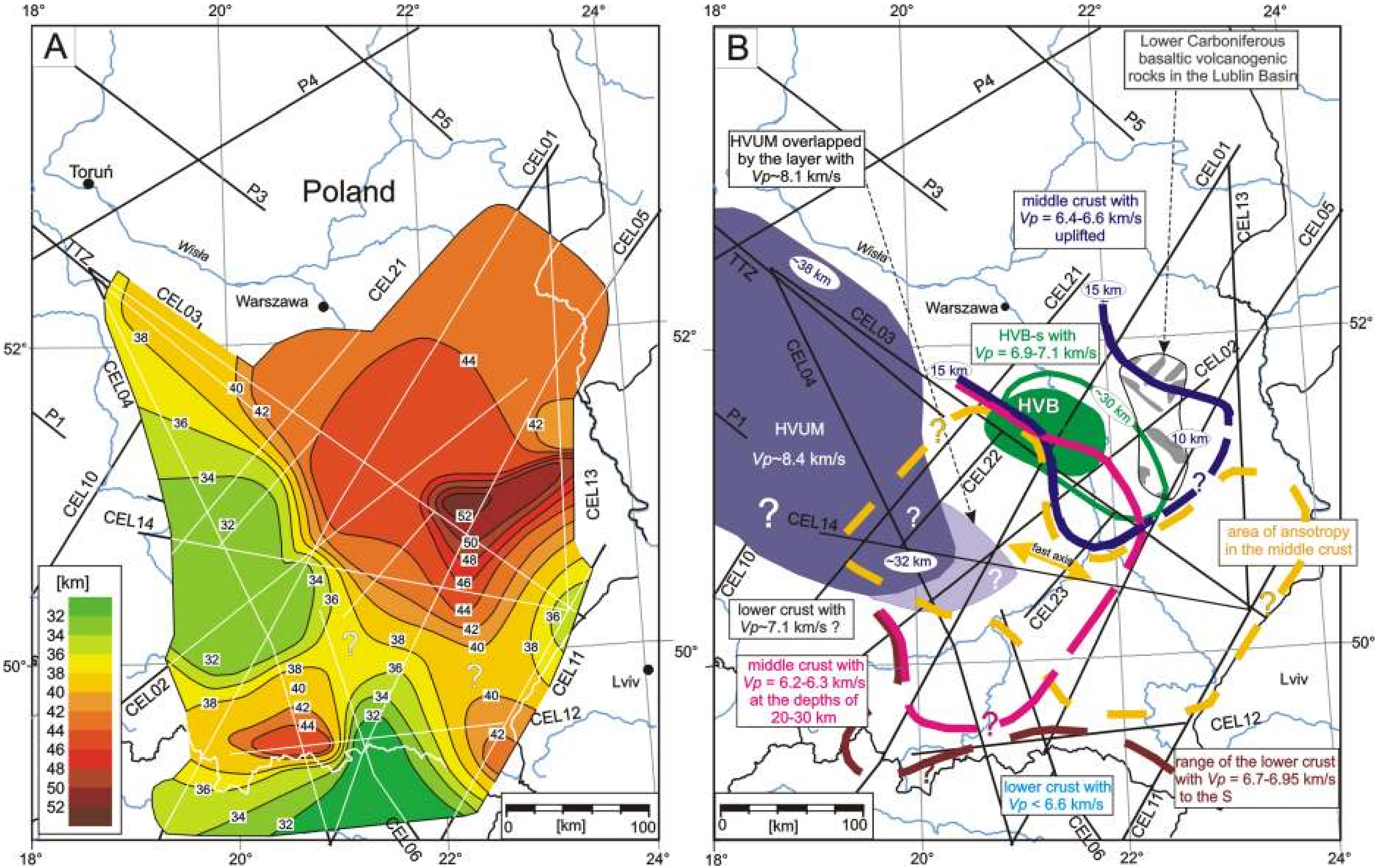

Fig. 9. Summary of results of CELEBRATION 2000 profiles in SE Poland: Moho depth map (A) and characteristic elements of the crustal structure (B)

A — white/black lines show location of the seismic profiles on the basis of which the map was constructed; B — abbreviations: violet — range of sub-Moho rocks with velocities ~8.4 km/s (HVUM), light violet — same layer as above but overlapped by sub-Moho rocks with velocities ~8.1 km/s; brown dashed line — approximately boundary between two- and three- layer types of the crust, range of the lower crust with Vp = 6.7–7.0 km/s to the south; light blue — approximate range of very low velocity middle crust (Vp = 6.2–6.3 km/s) at depth of 20–30 km; yellow — approximate range of area of anisotropy in the upper crust; green — range of detected high velocity bodies with Vp = 6.9–7.1 km/s (HVB) at depths of *ca.* 15 and 30 km; dark blue — range of uplifted middle crust with Vp = 6.4–6.6 km/s; area with grey stains — area of detected Lower Carboniferous basaltic volcanogenic rocks in the Lublin Basin/Trough, after Żelichowski and Kozłowski (1983); yellow arrow show the fast velocity axis direction for anisotropy detected by Środa (2006)

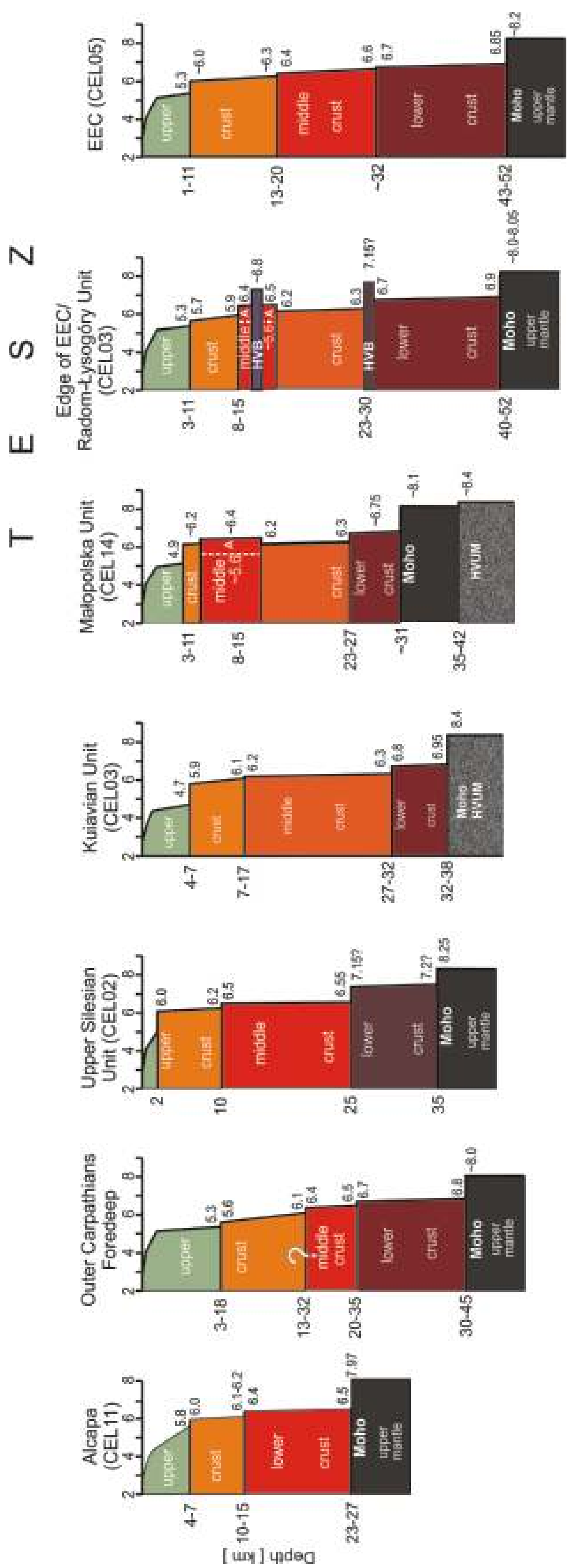

Fig. 10. Representative crustal velocity models for SE Poland

files. The range of the anisotropic area is marked in our Figure 9B by an yellow dashed line because it is really difficult to distinguish precisely from our data, particularly if anisotropy is lower than 8%.

High velocity bodies in the upper/middle crust. In the transition between the Kuiavian and Radom–Łysogóry units, a series of high velocity bodies (HVB; *Vp* = 6.9–7.2 km/s) were detected at depths of 15–30 km below the edge of the EEC (Fig. 9B). The extent of the high velocity body and deep Moho interpolated from the CEL01, CEL02 and CEL03 profiles is presented in Figure 9B. These were earlier interpreted also from seismic and gravity data by Grabowska and Perchuć (1985) and Grabowska and Bojdys (2001). This area partly overlaps the Lower Carboniferous volcanogenic rocks found in the Lublin Trough (Basin) (Żelichowski and Kozłowski, 1983).

Unit division. At the boundary between the Radom–Łysogóry Unit and the Narol Unit postulated by Janik *et al.* (2005), the Moho discontinuity rises from depth of 52 to 43 km. It is controversial whether this boundary is the edge of the EEC or is connected with the prolongation of the Holy Cross Fault which separates the Łysogóry region from the Kielce region in the HCM (Dadlez, 2001). The crustal structure of this unit is also similar to that of the EEC, except for the velocities in the lower crystalline crust, which do not exceed 7 km/s. The nature of the mantle contact between Radom–Łysogóry and Narol units is uncertain because this area lies near the end of the profile CEL03, in a zone of limited observations.

The main elements of the investigated area displayed on the tectonic map (Fig. 2B) can be compared with the map of Moho boundary (Fig. 9A) and location of characteristic elements differentiating the structure of the crust and upper mantle (Fig. 9B), on Figures 11A, B, respectively. At the first view, it is rather difficult to find any relationship between them. The shape of Variscan front seems to be parallel to north-east and east edges of the HVUM, also displaced *ca*.100 km from this line, but to the west.

METODOLOGICAL DISCUSSION OF THE "OLD" AND "NEW" RESULTS

The area of SE Poland was investigated using deep seismic sounding 20–30 years ago along profiles VIII, LT-3, LT-4, LT-5 and LZW (Guterch *et al*., 1983, 1986; Perchuć, 1984). These profiles called "old" are shown in Figure 1A by thin black lines. Seismic measurements along "old" profiles were acquired by the "continuous" profiling method. The distances between the shot points were 45–90 km. The recording was carried out in the distance interval from 50–90 km to 200–280 km from each shot point using multi-channel seismic instruments. The distances between the channels were 100 or 200 m, which permits the exact phase correlation between receiver spacing smaller than half a wavelength (e.g., for *Vp* = 6 km/s and frequency 10 Hz the length of the seismic P-wave is 600 m). Identification and correlation of seismic phases was done by a manual process using composite seismogram copies. The travel times of waves from individual shot points were

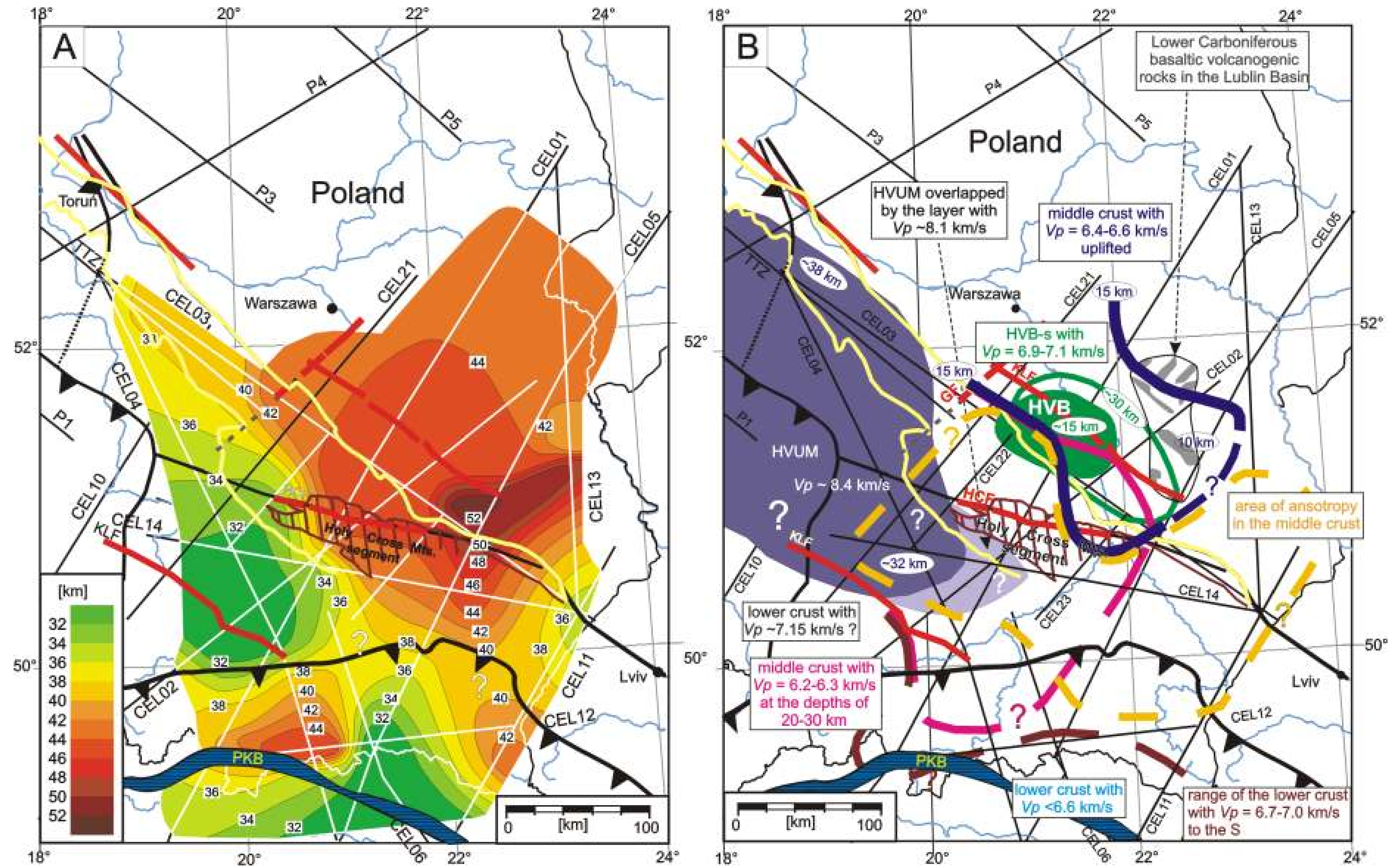

Fig. 11. Summary of results of CELEBRATION 2000 profiles in SE Poland with main tectonic features of the area: Moho depth map (A) and characteristic elements of the crustal structure (B)

Comparison of main tectonic lines and faults displayed in Figure 1 with the Moho map and location of characteristic elements differentiating structure of the crust and upper mantle in SE Poland from Figure 9 drawn on the scale 1:100 000, with the time scale of 2 cm for 1 s. Correlated phases build a system of refracted and reflected travel times used in the determination of seismic velocities and boundary depths in the crust and uppermost mantle. The dense recording system was an advantage of this technique, but a disadvantage was that records started at 50–90 km from the shot, and, as a result, information about the uppermost 10–15 km of the structure was missing.

In the multi-stage interpretation process of the "old" data, the boundary velocities were determined from apparent velocities of reverse travel times of refracted waves. In the interpretation of the reflected waves the method of effective parameters was used (e.g., Egorkin, 1966; Grad, 1983). The effective velocity V_{ef} was determined from the travel time $t(x)$ of reflected waves and has a form:

$$V_{ef}(x) = \left[x / p(x)t(x)\right]^{1/2}$$

where: x is the offset, $p = dt/dx$ is the ray parameter.

The effective depth of the reflector, h_{ef} , was determined from the formula:

$$h_{ef}(x/2) = 1/2\left(V_{ef}^2 t^2 - x^2\right)^{1/2}$$

Under the DSS conditions, the value of the effective velocity may exceed the value of the mean velocity by 10–15%. The effective depth h_{ef} determined from the reflected wave travel time is also greater than the true depth H of the reflecting boundary. The difference increases with increasing distance from the source, and under the DSS conditions it may exceed 20–30% (Grad, 1983).

Another important source of errors was poor knowledge of the upper crustal structure. Recordings along "old" profiles were made starting from a distance of 50–90 km from the shot point and depth and velocities for the uppermost crustal structure were taken from shallower refraction investigations (Skorupa, 1974). According to these investigations, the consolidated basement at about 10 km depth was characterized by a velocity of about 6.1 km/s. The "new" investigations showed that this basement has a velocity about 5.8 km/s only, and velocities lower than 6.1 km/s are observed down to 18–20 km depth (Janik *et al*., 2005; Malinowski *et al*., 2005; Grad *et al.*, 2006; Środa *et al*., 2006). So, velocities (V_{ef}) in the "old" interpretations were significantly overestimated (by about 0.2–0.3 km/s) as well as effective depths of Moho (by few km). This was confirmed when profiles LT-2, LT-4 and LT-5 were reinterpreted using modern ray tracing techniques (Grad *et al*., 2005). In the light of this reinterpretation and the new results from LT-7, TTZ, P2 and P4, the deep trough structure in the TESZ in Central Poland is not observed, and the Moho depth reaches 35–45 km only (Guterch *et al*., 1994; Grad *et al*., 1999, 2003; Janik *et al*., 2002, 2005).

As a result of the "old" interpretation, a few crustal blocks were distinguished in SE Poland corresponding to the East European Craton (EEC), Teisseyre-Tornquist Zone (TTZ), Holy Cross Mts. Unit, Palaeozoic Platform (PP), Małopolska Unit and Carpathians (Guterch *et al*., 1986). The thickness of the Earth's crust within the PP was determined to be 35–38 km and about 45 km beneath the EEC. The thickness in the 100 km wide TTZ was 50–60 km. The "new" 2D models of the crust from the CELEBRATION 2000 profiles show some differences compared to the "old" cross-sections obtained 20–30 years ago (compare Fig. 9A and Guterch *et al.*, 1986). The biggest difference relates to the TTZ (part of TESZ) structure, while for the EEC and the Variscan crust, the velocity models are almost the same. In the "old" models the depth of the Moho boundary in the TTZ is significantly deeper than in the "new" models. As mentioned above, this results from overestimated effective velocities for the upper crust and the use of the effective parameters technique.

SUMMARY

In this paper, we present the results of seismic modelling of refracted and reflected waves using the 2D ray tracing technique. All 13 profiles from the CELEBRATION 2000 experiment in the area of SE Poland were jointly interpreted with verification and control of the models at intersection points. The obtained models of the crust and uppermost mantle are very complex and show differentiation of the seismic structure between tectonic units in SE Poland. The depth of the Moho discontinuity in the investigated area varies between about 30 km to about 52 km. The area of the EEC is characterized by 40–44 km thick crust, with a local maximum of up to 52 km. This local maxims correlates with the contact zone between Fennoscandia and Sarmatia. In the area SW of the craton edge, the Moho is 32–38 km deep, with two local maxima detected in the Outer Carpathians (42–44 km depth), divided by a local minimum at *ca*. 32 km depth. Another local minimum (*ca*. 32 km) was found below the boundary between the Małopolska and Upper Silesia units. A third local minimum, detected in the SE part of the area (*ca*. 36 km), coincides with the Narol Unit postulated by Janik *et al*. (2005). The Moho depth is presented in Figure 9A. In general, sub-Moho velocities vary between 7.9 and 8.2 km/s along the profiles. The HVUM with velocities *Vp* ~8.4 km/s detected previously beneath the P4, P1, TTZ profiles extends to SE, and was detected also beneath the CEL21 and CEL14 profiles. In the south-east, the HVUM is partly overlapped by a sub-Moho layer with a normal velocity of *Vp* ~8.1 km/s.

The lower crust could be separated by a line running approximately along the Polish–Slovak border into areas of lower crust with $Vp = 6.7–7.0$ km/s (to the north), and $Vp < 6.6$ km/s (to the south). The high velocity lower crust was found also in the Upper Silesian Unit. Very low velocities, $Vp = 6.2–6.3$ km/s, at depths of 20–30 km (middle crust) were detected below the Radom–Łysogóry and Małopolska units. We can extend the area of observed anisotropy postulated from Środa (2006) ($Vp = 5.6–6.4$ km/s; Fig. 9B) into the upper crust (depth 8–17 km) around the CEL14 profile. High velocity bodies were detected at depths of 15–30 km below the EEC edge, in the area which partly overlaps the Lower Carboniferous volcanogenic rocks found in the Lublin Trough

(Żelichowski and Kozłowski, 1983). Malinowski *et al.* (2005) was interpreted the HVB noted on the CEL02 profile, as a result of the Neoproterozoic break-up of the Rodinia supercontinent. Approximately in the same area, the middle crust with velocity *Vp* = 6.4–6.5 km/s is uplifted (up to 15–10 km) in comparison to the neighbouring areas. This uplift could be explained as an effect of the collision of the EEC with the tectonic units to the south.

Acknowledgements. The CELEBRATION 2000 Working Group comprises W. Czuba, R. Dadlez, E. Gaczyński, M. Grad, A. Guterch, E. Hegedüs, T. Janik, G. R. Keller, M. Malinowski, T. Tiira, A. K. Tokarski, M. Rauch, A. Ślączka, P. Środa, J. Vozár , J. Yliniemi, A. Żelaźniewicz. Funding for CELEBRATION 2000 experiment has come from several institutions. In Poland, this project was supported by the State Committee for Scientific Research (KBN, grant PCZ 06/21/2000), Ministry of the Environment, the National Fund for Environmental Protection and Water Management (862/2005/Wn), and Polish Oil and Gas Company through the Association for Deep Geological Investigation in Poland (ADGIP). Much of the instrumentation was provided by IRIS/PASSCAL that is supported by the U.S. National Science Foundation (NSF). Most of the actual instruments were purchased through grants to the University of Texas at El Paso (Texas Higher Education Coordinating Board, NSF/MRI and DoD). Field work and data acquisition in the CELEBRATION 2000 project were carried out as an international collaboration. The public domain GMT package (Wessel and Smith, 1995) was used to produce some of the figures. Constructive comments made by R. W. England and M. Jarosiński on an early version of the manuscript are gratefully acknowledged.

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