Huge contrasts of the lithospheric structure revealed by new generation seismic experiments in Central Europe

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Abstract. Beginning in 1997, Central Europe, between the Baltic and Adriatic Seas, has been covered by an unprecedented network of seismic refraction experiments (Fig.1A). These experiments — POLONAISE'97, CELEBRATION 2000, ALP 2002, and SUDETES 2003 — have only been possible due to a massive international cooperative effort. International Consortium consisted of more than 30 institutions from 16 countries in Europe and North America — Austria, Belarus, Canada, Croatia, Czech Republic, Denmark, Finland, Germany, Hungary, Lithuania, Poland, Russia, Slovakia, Slovenia, Turkey, and the United States. The majority of the recording instruments was provided by the IRIS /PASCAL Instrument Center and the University of Texas at El Paso (USA), the Geological Survey of Canada, and other countries. For example, in the CELEBRATION experiment, the total number was 1230 stations and 147 shot points located along seismic lines of a total length of about 9000 km. A large number of seismic sources and stations in all experiments means that besides 2-D approach along profiles, also 3-D approach could be implemented in data interpretation. Total length of seismic profiles in all experiments is about 20,000 km.

Key words: *POLONAISE'97, CELEBRATION 2000, ALP 2002, SUDETES 2003 seismic experiments, Earth's crust, lithosphere, crustal structure, Trans-European Suture Zone, Carpathians, ALPS, Pannonian Basin, Bohemian Massif*

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As reflected in structures within the Trans-European Suture Zone (TESZ), Alps and Carpathians, Bohemian Massif, and Pannonian Basin regions (Fig. 1B), Central Europe has experienced a complex tectonic history that includes three geologically recent periods of mountain building due to accretion of terranes during the Caledonian and Variscan orogenies and the collisional events of the Alpine orogeny. In addition, extension has affected the region on several occasions. First, the super-continent Rodinia broke up near the Cambrian-Precambrian boundary and formed the rifted margin of southwest Baltica; extension was widespread after the Variscan orogeny, especially in the Polish-North German Basin; and the Eger rift formed during the Cenozoic.

When viewed from a larger perspective, the Palaeozoic tectonic evolution of Europe involved a series of orogenic pulses resulting from the collision and suturing of Baltica, Laurentia (the North American palaeo-continent), Gondwana (Africa/South America), intervening terranes like Avalonia and the Bohemian Massif, and transported crustal blocks to form the supercontinent Pangea.

The TESZ region (Caledonides, Tornquist-Teisseyre zone area, Fig. 1B) is a broad zone of deformation that extends across Europe from the British Isles to the Black Sea region that formed as Europe was assembled from a complex collage of terranes during the late Palaeozoic. These terranes were accreted along the margin of Baltica (East European Craton, EEC) that was formed during the break-up of Rodinia. The tectonic evolution of this region shares many attributes with the Appalachian/Ouachita origin (e.g., Keller & Hatcher, 1999) and is certainly of global importance to studies in terrane tectonics and continental evolution. The TESZ is far more complex than a single suture but in a broad sense it is the boundary between the accreted terranes and Baltica. The Bohemian Massif is mostly located in the Czech Republic and it is a large, complex terrane whose origin can be traced to northern Gondwana (Africa). In southern Poland, several structural blocks such as the Małopolska Massif (Fig. 1B) are located adjacent to Baltica and were probably transported laterally along it, similar to the Cenozoic movement of terranes along the western margin of North America.

The younger Carpathian Mountains and Pannonian Basin were also targeted by these experiments. These features are the result of intricate Mesozoic/Cenozoic plate interactions in the Mediterranean region as the Tethys Ocean closed during convergence of Europe and Afro-Arabia. During the Cenozoic, complex interactions among small plates caused the Carpathian arc to evolve into its strongly arcuate shape. These plate interactions have been interpreted to involve subduction of oceanic areas and produced considerable Neogene volcanism. Back arc extension was the dominant process that formed the Pannonian Basin that contains up to 8 km of Neogene strata in its subbasins. This region is still tectonically active as evidenced by seismicity that extends to depths of ~200 km in the Vrancea region north of Bucharest.

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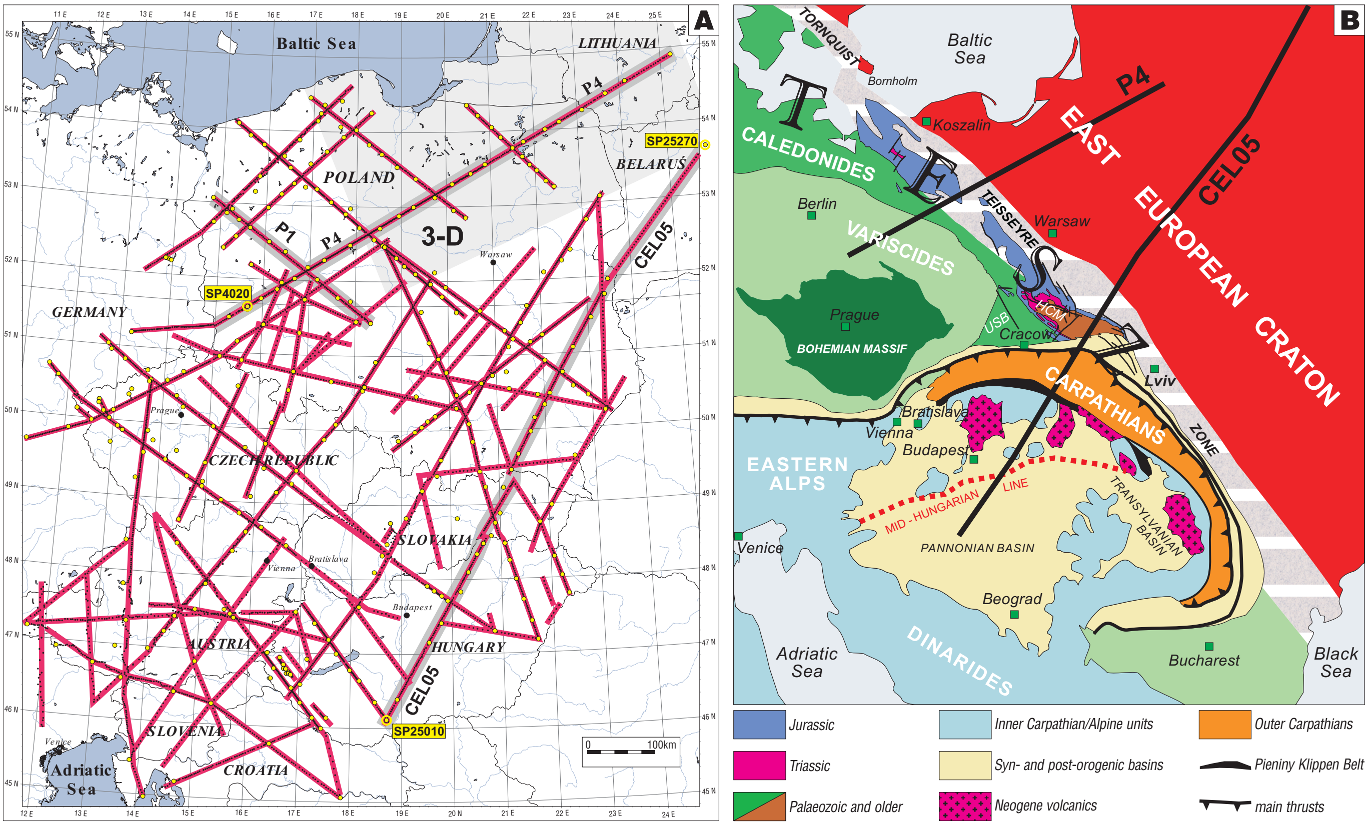


Fig. 1. ati n seis i pr iles ade in entral ur pe during P B P and e peri ents le t Pin lines s w seis i pr iles t tal lengt a wit a seis i re eiver p siti ns s all la d ts ell w d ts s w igs t l ati ns re lines s w p siti n P pr iles P and P and B pr ile ell w ir les s w l ati n s t p ints P P and P r w i re rd se ti ns wit t grap i dels are s wn in igs and e gre area in P land s ws t e area investigati ns presented in ig t e rig t l ati n P pr ile P and B pr ile against t e a gr und a si pli ied te t ni ap entral ur pe l r ss untains rans ur pean suture ne B pper ilesia Bl

Main aims of the seismic experiments

e P B pr gra used nsidera le attenti n n t e stru ture and te t ni s entral ur pe and reated an envir n ent t at spawned a new generati n large seis i e peri ents in t e regi n in e t e lit sp eri stru ture in t e regi n is ver ple t e need r a appr a was re gni ed earl e irst t e new e peri ents was P uter et al and s wed w u uld e learned r even a dest verage Śr da et al series even larger e peri ents as ll wed in rapid su essi n and t ese e peri ents B P and are t e us t is series spe ial n tri uti ns uter et al Brue l et al rad et al ese e peri ents als relate t er an B pr e t t e B seis i t grap e peri ent and nu er us e er an pr e ts n t e ge d na i s t e West B e ia V gtland seis i a tive regi n s a result t ese e peri ents a netw r seis i re ra ti n pr iles n w e tends al ng t e rans ur pean uture ne regi n P land t e B e ian assi Pann nian Basin t r ug t e arpat ians and lps t t e driati ea and t e inarides ig B

e prin ipal spe i i g als t ese e peri ents are t

❏ investigate t e deep stru ture t e s ut western argin t e ast ur pean rat n s ut ern Balti a and its relati ns ip t unger terranes

❏ delineate t e a r terranes and rustal l s in t e regi n e g B e ian assi pper ilesian Bl and l s e p sed in t e l r ss untains ig B

❏ investigate t e rigin and stru tural ra ew r t e Pann nian Basin and its su asins

❏ investigate t e nature and e tent t rust aulting al ng t e n rt ern r nt t e arpat ian untains

❏ investigate t e stru ture and ev luti n t e astern lps and t eir relati ns ips wit ad a ent eatures

❏ investigate t e stru tural relati ns ips etween t e stru tural ele ents t e B e ian assi and ad a ent eatures

❏ nstru t a t ree di ensi nal del t e lit sp eri stru ture in t e area

❏ evaluate t e i pli ati ns t e art dels derived r natural res ur es and eart ua e a ards

❏ evaluate and devel p ge d na i dels r t e te t ni ev luti n t e regi n

e P e peri ent uter et al set t e stage r t e eginning a new p ase internati nal perati n stud t e lit sp eri stru ture entral ur pe is e peri ent was ver e e tive ut it also showed that much additional seismic data coverage was needed to unravel the complex structure of this region. Thus, a consortium of 28 institutions organized the massive CELEBRATION 2000 experiment that covered significant parts of thirteen countries. The Austrian Group led the subsequent ALP 2002 experiment that targeted the Eastern Alps and adjacent areas of Hungary, Slovenia, Croatia and the Czech Republic. The groups from the Czech Republic and Poland led the most recent experiment (SUDETES 2003) that covered most of the Czech Republic and Poland, as well as adjacent parts of Germany, Slovakia, and Hungary. Together, these experiments will provide an unprecedented three-dimensional image of the evolution and assembly of a continent.

Examples of results

POLONAISE'97 tomographic crustal model P4. The first step of the seismic interpretation of the POLONAISE'97 data was to undertake two-dimensional tomographic inversions of the profile data using the approach of Hole (1992). This modelling was for first arrivals only and travel time picks were carefully checked for reciprocity of corresponding shot points. The results of the inversion for POLNAISE'97 profile P4 is shown in Fig. 2. The Moho may be represented by the 8.0 km/s velocity isoline. The 6.0 km/s velocity isoline is interpreted as representing the top of the crystalline basement. The velocity model P4 shows that the depth of the Moho, approximated by the 8.0 km/s velocity isoline, is 32–37 km under the Palaeozoic Platform and 43–45 km under the Precambrian Platform, and about 50 km under the Teisseyre-Tornquist zone (TTZ) in the TESZ region. A depth of isoline 6.0 km/s has maximal values 16–20 km in the Polish basin. This indicates that the sedimentary cover in the Polish basin might be as thick as 20 km. A distinct asymmetry, between maximal thickness of the sedimentary cover and the crustal root associated with TTZ, is observed along profile P4.

CELEBRATION 2000 tomographic crustal model *CEL05*. CELEBRATION 2000 profile CEL05 is the longest made in this experiment. Its length is 1420 km, and it runs from the Pannonian Basin in the territory of Hungary, to the East European Craton on the territory of Belarus, and northwestern Russia (Fig. 1A). This profile runs approximately along the line Pecs–Presov–Krosno–Lublin–Brest–Velke Luki. The southwestern part of the profile (0–200 km) is in the area of Pannonian Basin, then the profile crosses Carpathians and their foredeep, TESZ including Małopolska Massif, Lublin Trough, and the Tornquist-Teisseyre Zone

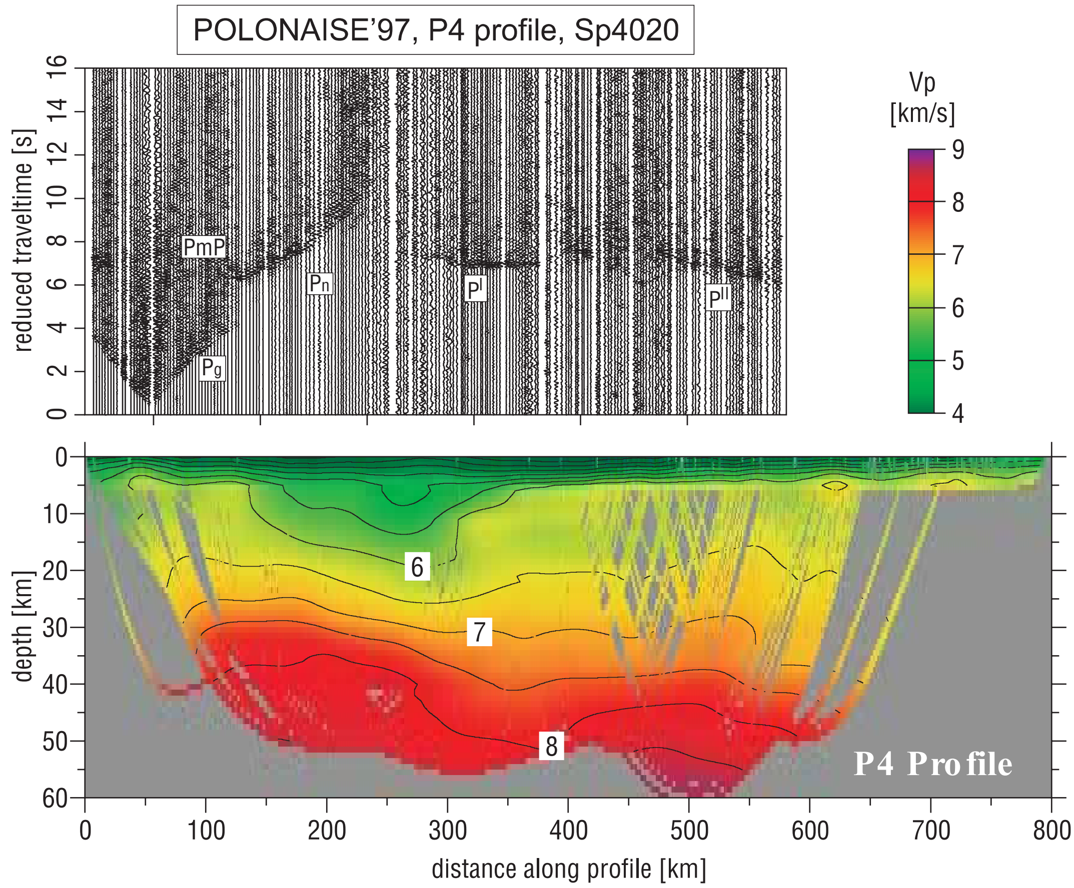


Fig. 2. Example of seismic section recorded during POLONAISE'97 experiment (Guterch et al., 1999). Seismic waves from shot point SP4020 located closely to Polish-German border (see Fig. 1A) were recorded along P4 profile. Note good quality seismic waves recorded up to distance ca. 600 km from the shot point. Pg — wave reflected from the crystalline basement, Pn and PmP — waves refracted and reflected from the crust — mantle seismic discontinuity, P^{I} and P^{II} — lower lithospheric waves from the depth 60–90 km. Below — seismic tomographic model of the crustal structure for POLONAISE'97 profile P4

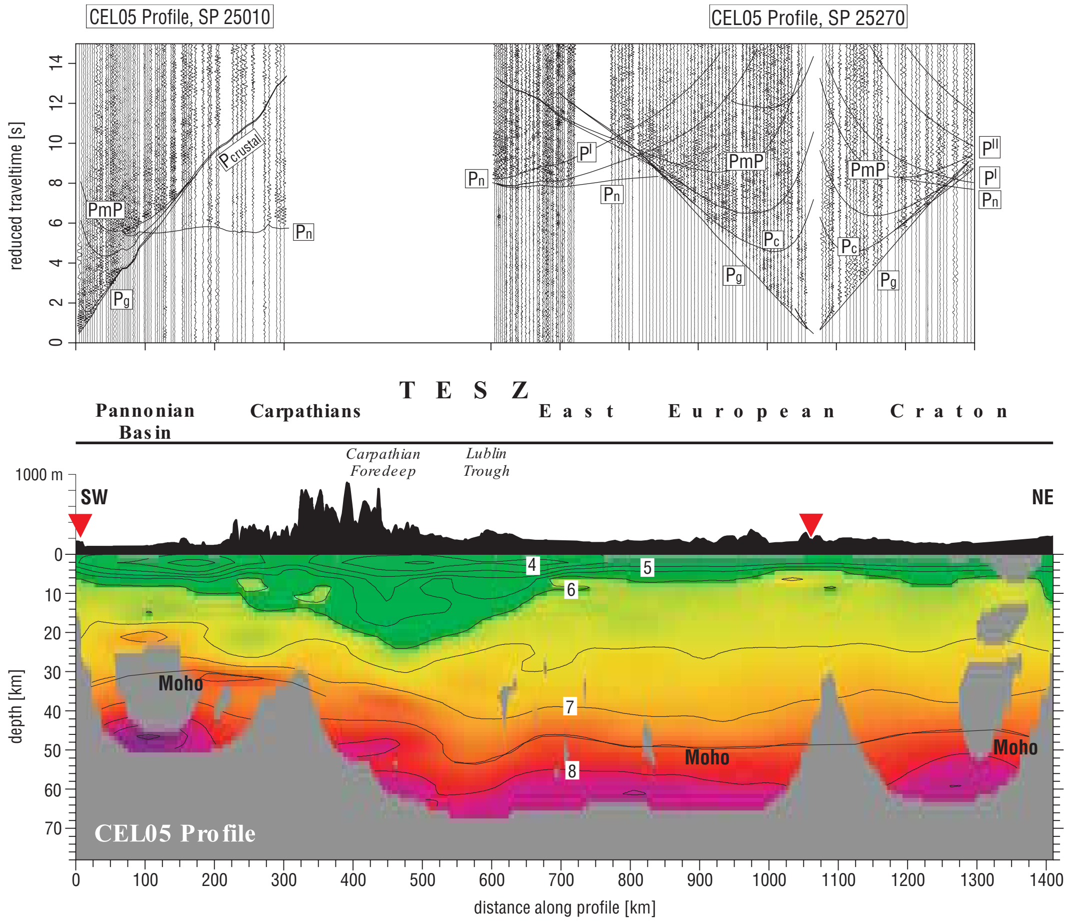


Fig. 3. Examples of seismic sections recorded during CELEBTARION 2000 experiment. Seismic waves from shot points SP25010 and SP25270 (see Fig. 1A) were recorded along CEL05 profile. Note good quality seismic waves recorded up to distance ca. 500 km from the shot point. Below — seismic tomographic model of the crustal structure for CELEBRATION 2000 profile CEL05. Other explanations as in Fig. 2

(TTZ). The northeastern part of the profile (700–1420 km) crosses the East European Craton. Along the most of its length, the profile runs trough lowland area with an average altitude of about 200 m a.s.l. In the Carpathians (200–500 km along the profile), it runs trough area at 400 to ca. 900 m a.s.l. (see topography along profile shown together with tomographic model of the structure in Fig. 3). The recordings from 26 explosions made along profile CEL05 were made using over 360 modern seismic recorders, with a nominal station spacing of 3 km (in the territory of Hungary, Slovakia, and Poland) or 5 km spacing (in Belarus and Russia). More details about the layout of the experiment are provided by Guterch et al. (2001, 2003).

The first model of CEL05 profile was derived using tomographic inversion for the first-arrival travel times. In the tomographic inversion program package FAST (Zelt & Barton, 1998) was used. The velocity distribution, derived from first arrival travel time tomography, is shown in Fig. 3. The FAST inversion, software was not designed to define interface with velocity contrast. Thus, an interface (for example Moho) should be presented by the isoline that is the average of the velocities above and below the interface.

Thus, we believe that the Moho is best represented by the velocity isoline 7.5 km/s (not 8.1 km/s which is expected for the uppermost mantle). In the same time an average velocity for the deepest sediments (~5.8 km/s) and crystalline basement (~ 6.1 km/s) is close to 6.0 km/s, so this velocity isoline could well have represented the sediments-basement boundary. If so, we have in the distance interval 250–650 km along the profile, a deep sedimentary basin where top of the crystalline basement reaches ca. 20 km deep. The depth of Moho beneath Pannonian Basin (0–300 km along the profile) is ca. 30 km only, while beneath the EEC it reaches 40–45 km, and even over 50 km in the TESZ region (ca. 600 km of the profile).

In the tomographic inversion method, the final model of the structure in great part depends on the initial model. In such a complicated area, the simple initial one-dimensional model could be not satisfactory, however first arrival tomographic inversion gives a relatively quick and simple possibility for the verification of data correctness, as well as reveals the first general pattern of the structure.

POLONAISE'97 ray-tracing crustal model P1. A high resolution model of seismic velocity variation along POLONAISE'97 profile P1 in northwestern Poland is presented in Fig 4. Despite its location behind the Variscan Deformation Front, the model indicates that the crust below the profile has a Caledonian origin or, alternatively, originates from Baltica, and that Variscan deformation was thin-skinned in this area. The seismic model shows several new findings for the study area:

❑ Sediment thickness decreases southwestward from 6 to 3 km. There is indication for tectonic activity during deposition of the Palaeozoic sequence.

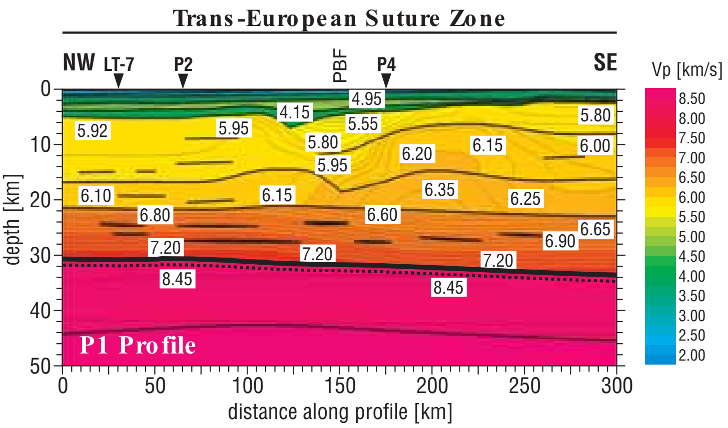


Fig. 4 . The 2-D seismic velocity model along POLONAISE'97 profile P1 developed by forward ray-tracing technique (Jensen et al., 1999). The profile runs along the Trans-European Suture Zone (in the Polish Basin) almost parallelly to the edge of the East European Craton. The thick solid lines are layer boundaries and thin lines are isovelocity contours in km/s. Triangles refer to cross points with seismic profiles LT-7, P2 and P4. PBF — Poznań–Bydgoszcz Fault

❑ The seismic velocities are very low (6.1–6.2 km/s) down to 20 km depth, indicative of rocks of sedimentary or volcanic origin.

❑ The lower crust is characterized by high velocity (6.7–7.5 km/s), a high vertical velocity gradient, and strong, ringing reflectivity.

❑ The crust is 30–33 km thick along the profile with a gradual southeastward thickening.

❑ The P_4 velocity of the sub-Moho mantle is high (>8.2 km/s).

The area south of the CDF in northern Germany and southern Denmark shows similar characteristic features which indicates that the crust between the southeastern North Sea and Poland originates from the same microcontinent East Avalonia, which was amalgamated to Baltica during the Caledonian orogeny.

POLONAISE'97 ray-tracing crustal and lithospheric models P4. POLONAISE'97 profile P4 was designed to cross the main tectonic features of the TESZ (Fig. 1A, B). All of the crustal models, derived during the POLONAISE'97 study, show generally the same strong structural variations from the Palaeozoic Platform in the southwest, across the TESZ region, onto the EEC to the northeast. In each model, the crustal thickness varies considerably along the profile: 30–35 km in the Palaeozoic Platform area, ~ 45 km below and due northeast of the TESZ, ~43 km in the Polish part of the EEC, and ~50 km in Lithuania. The upper crustal structure of the Palaeozoic Platform and EEC is different, and they are divided by the deep (~20 km) Polish basin. The 800 km long POLONAISE'97 P4 crustal model is the result that best delineates this structure. Our efforts to model the data from

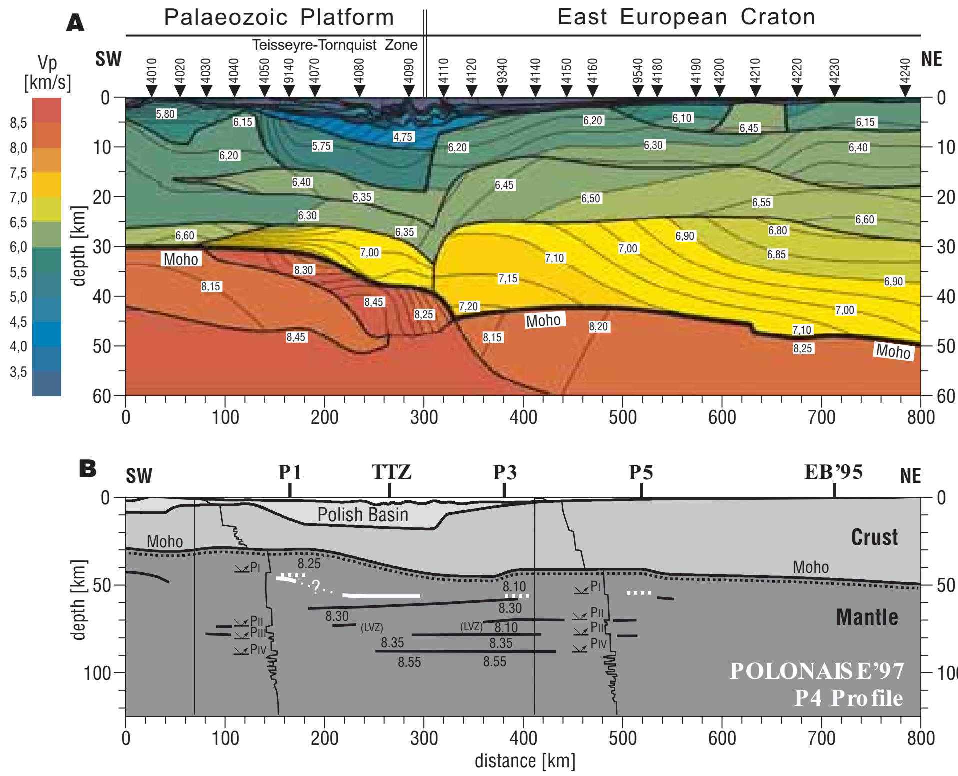


Fig. 5. The 2-D seismic velocity model along POLONAISE'97 profile P4 developed by forward ray-tracing technique for the crust (upper) and a simplified sketch of the lithospheric structure (bottom). The profile P4 runs across the Trans-European Suture Zone almost perpendicularly to the edge of the East European Craton. The thick solid lines are layer boundaries and thin lines are isovelocity contours (in km/s). "Moho" is crust–mantle boundary. Numbered triangles show shot points along profile. Note thin Palaeozoic Platform crust (ca. 30 km), thick crust of the East European Craton (ca. 45–50 km) and thick sedimentary basin in the Teisseyre-Tornquist Zone with P-wave velocities lower than 6 km/s down to ca. 20 km depth. Apart of lower lithospheric reflectors beneath profile P4 (thick black lines) reflectors from the parallel profile P2 (thick white lines) and profiles P1, P3 and P5 (dotted white lines) were marked. Black bars show cross points with seismic profiles P1, TTZ, P3, P5 and EUROBRIDGE

this profile, employing a variety of two-dimensional ray tracing results of the crust, are presented in Fig. 5A and provide the following conclusions (Grad et al., 2003):

❑ The Polish Basin is a large structure (125 km wide) that filled with sedimentary strata during the Palaeozoic and Mesozoic. The fill in this basin (Vp< 6.0 km/s) reaches thickness of ~20 km. This basin is asymmetric, with its northeast margin being most abrupt. The crystalline crust under this basin in only ~20 km thick today, indicating that the lithosphere of Baltica was either thinned drastically or terminated along the northeast margin of the basin.

❑ The crust of the accreted terranes to the southwest is relatively thin and similar to that found in other noncratonal areas of Western Europe. The East European Craton has a thick (~45 km) three-layered crust.

❑ The lower crust is relatively fast (vp >7.0 km/s) along most of the P4 profile. However, lower values to the southwest may indicate the termination of Baltica.

❑ High velocity (~8.35 km/s) uppermost mantle lies beneath the Avalonia/Variscan terranes and may be due to rifting and/or subduction.

❑ Reflections from within the mantle lithosphere in the southwest portion of profile P4 suggest the presence of a northwest dipping body in the mantle.

❑ Two general tectonic models are consistent with the observed velocity structure, and they both involved an abrupt discontinuity in lithospheric structure at the southwest edge of the EEC. Also, suturing along structures with moderate dips appears evident. In any case, the Variscan orogeny appears to be a "soft" collision in this region that did not greatly deform the pre-Permian strata

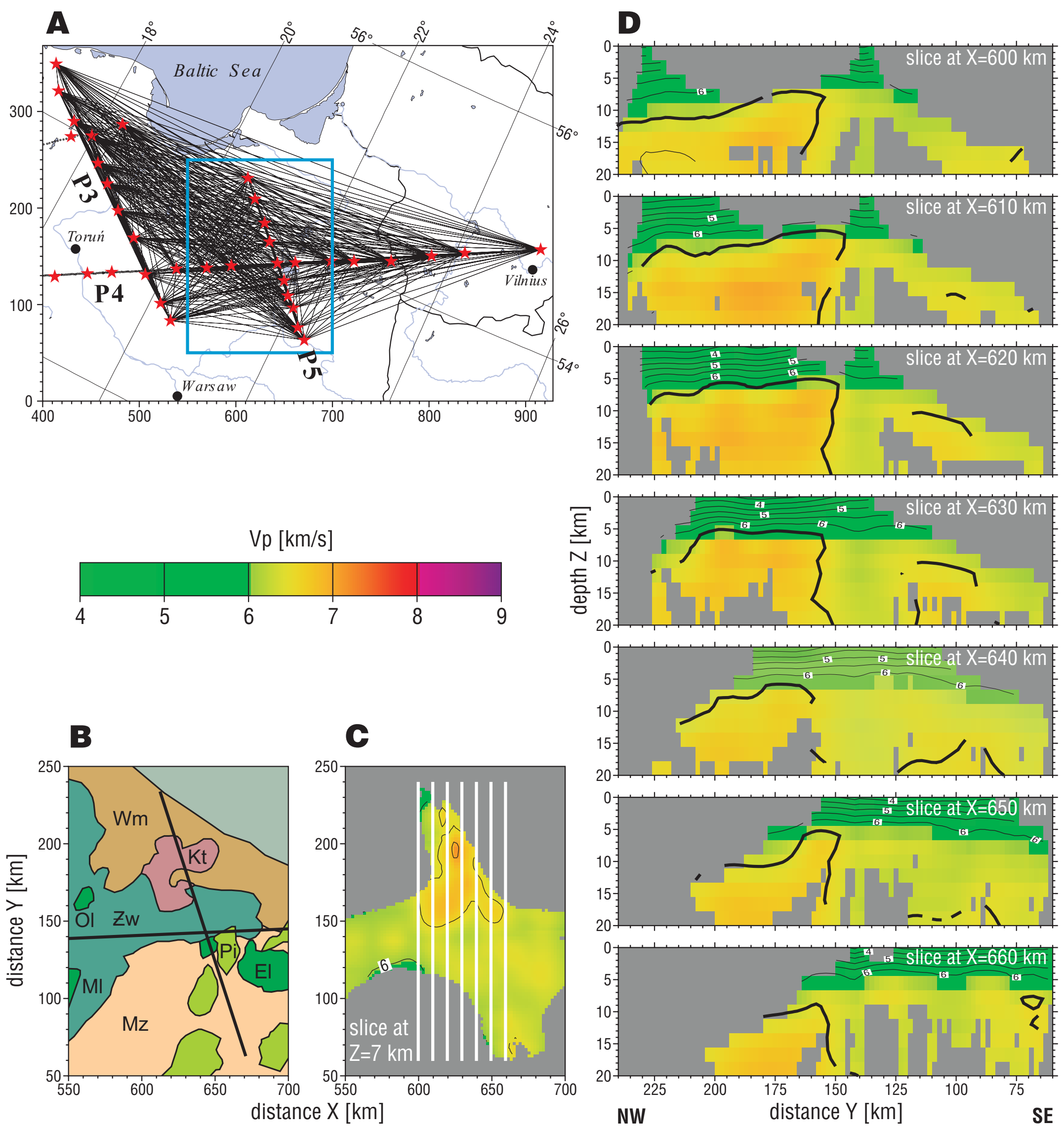


Fig. 6. Results of 3-D investigations in NE Poland in the area of POLONAISE'97 profile P5 (Czuba et al., 2002). The map (A) shows the area of investigation (bottom and left scale in kilometres, according to a 3-D model by Środa et al., 2002; top and right scale in geographical coordinates). Lines show schematic ray paths connecting shot points and recording stations (only about 15% used in inversion are shown). Blue rectangle marks area of the map (B) shows the tectonic scheme of the EEC crystalline basement and the area of horizontal slice (C) at the depth of 7 km. The right panel (D) shows vertical profiles for X=600, 610, 620, 630, 640, 650 and 660 km (location in Fig. 6C)

(~15 km thick) in the Polish basin associated with the rifted margin odf Baltica.

Densely spaced shots and receivers along the POLONAISE'97 profiles produced high-quality data extending to long offsets that resolve seismic models of the crust and lower lithosphere in the wide zone of the contact between Precambrian and Palaeozoic Europe. A simplified sketch of the resulting two-dimensional lithospheric model along the P4 profile is shown in Fig. 5B.

In all POLONAISE'97 profiles, the P^I phase indicates a shallow mantle reflector at depths ca. 8–12 km below the Moho. Phases due the features in the lower lithosphere are observed only beneath the longest profile P4. We found reflectors at depths of about 70, 80 and 90 km in the central part of the TESZ region (180–420 km along the profile P4). Complex high and low velocities in the lower lithosphere have been interpreted from other seismic experiments close to the TESZ region, as well as within EEC and the Baltic Shield.

The depth to the reflective zone correlates with the heat flow, such that it is more shallow in "hot" areas than in cold areas, a feature also observed along the FENNOLORA seismic long range profile.

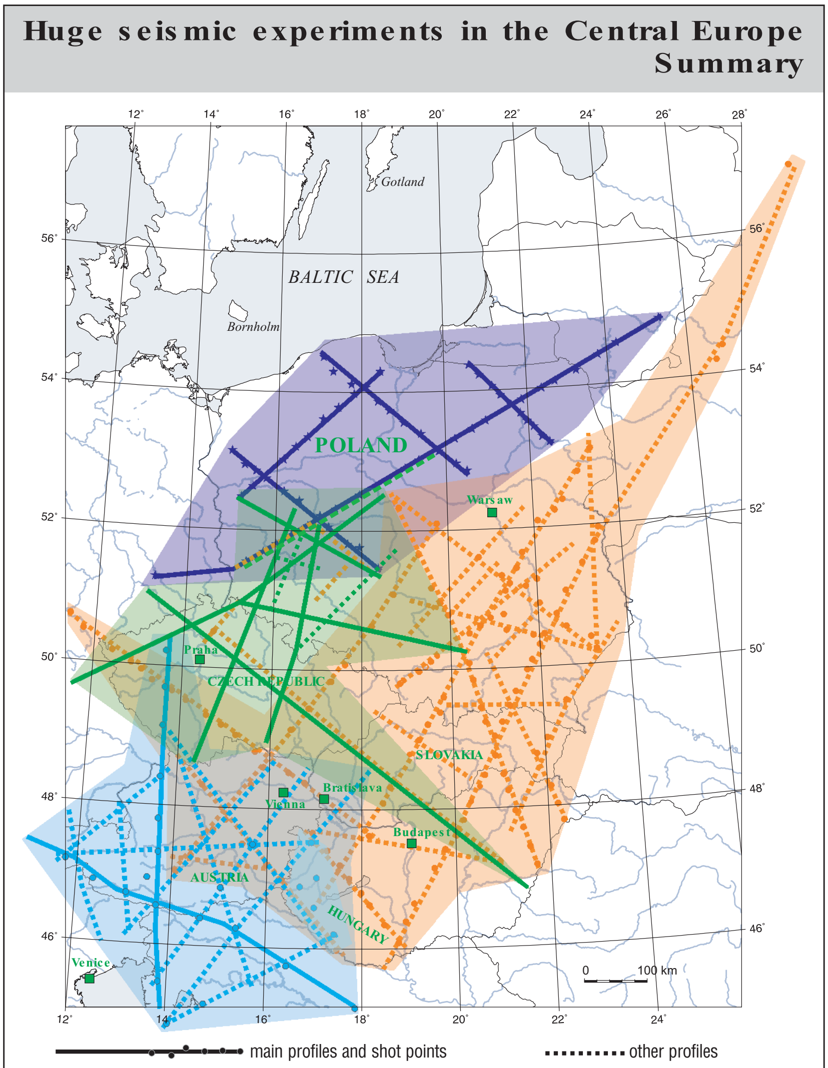
Our main finding is the presence of a series of seismic reflectors in the depth level from the Moho to about 90 km, the deepest interpretable level with the current data set. A seismic reflector generally occurs at about 10 km depth below Moho throughout the study area and adjacent areas, independent of the actual depth to the Moho. In general, the reflectivity of the uppermost mantle is stronger beneath the Palaeozoic Platform and TESZ than beneath the EEP. The deepest interpreted seismic reflector with zone of high reflectivity may mark a change in upper mantle structure from an upper zone characterized by seismic scatterers of small vertical dimension to a lower zone with vertically larger seismic scatterers, possible caused by inclusions of partial melt.

Example of three-dimensional tomographic modelling

POLONAISE'97 profile P5. The next step in seismic modelling was a three-dimensional tomographic inversion for all POLONAISE'97 data. The geometry of recordings in the area of the P5 profile is shown in Fig. 6A (only about 15% of ray paths northeast of the profile P3 is shown).

The tomographic inversion package of Hole (1992) uses an efficient method of determining the seismic velocity distribution in the three-dimensional medium using first arrivals.

The results of three dimensional investigations in the area of the POLONAISE'97 profile P5 for the vertical cross sections (XY) is shown in Fig 6. The map (Fig. 6B) shows the tectonic terrans and the slice at 7 km deep (Fig. 6C) with profiles for X= 600, 610, 620, 630, 640, 650, and 660 km (Fig. 6D). Thick lines in cross-sections are the



Experiment	shots	stations	length
POLONAISE'97	64	613	2000
CELEBRATION 2000	147	1240	8900
ALP 2002	32	1124	4500
SUDETES 2003	52	956	3450

Fig. 7. Layout of the POLONAISE'97, CELEBRATION 2000, ALP 2002 and SUDETES 2003 seismic experiments in Central Europe

velocity isolines 6.5 km/s. A high-velocity body was found between 150 and 230 km. It is the shallowest at X= 610–620, dipping both to NE and SW. In the distance range of 80–120 km and at a depth >10 km, another high velocity body is observed, which spatially corresponds to the Biebrza complex or the Pisz intrusion.

Similar results were obtained in other regions under study.

In summary, layout of the POLONAISE'97, CELEBRATION 2000, ALP 2002, SUDETES 2003 seismic experiments in Central Europe, and area of investigations are presented in Fig. 7.

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