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Crustal structure of the Mid-Polish Trough beneath the Teisseyre–Tornquist Zone seismic profile

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Abstract

A new seismic refraction and wide-angle reflection experiment in the Teisseyre–Tornquist Zone (TTZ) in Poland was conducting during July 1993 as an international Polish, Finnish, German and Swedish co-operation. The TTZ profile running in an SE–NW direction was exactly located in the central part of the Mid-Polish Trough in the zone of maximum subsidence (from Upper Permian to Upper Cretaceous). 19 shot points were placed along the 450 km profile. The interval between the shot points was about 25 km. 31 explosions (90 to 1000 kg of dynamite) were recorded in two deployments using 135 modern three-component seismic stations, with spacing of the recording sites of about 1.7 km. In this area, the depth of the consolidated basement, with a velocity of about 5.7–5.8 km/s, is 5 to 12 km deep. Nevertheless, the P-wave velocity is very low ($V_p < 6.1$ km/s) down to depths of 15–20 km. Below this complex, velocities of 6.5–6.6 km/s and 6.9–7.2 km/s were found and the thicknesses of the corresponding layers are 8–11 km and 9–14 km respectively. The total thickness of the crust varies from 35 to 41 km. The results are discussed in combination with other seismic results from this region, which were obtained from deep seismic sounding and deep near-vertical reflection profiles as well as surface wave studies.

Keywords: crustal structure; deep seismic sounding; Moho; Polish Basin; Trans-European Suture Zone; two-dimensional seismic modelling

1. Introduction

The determination of the crustal structure of the contact zone between the Precambrian Platform of Eastern Europe and Palaeozoic Platform of Central and Western Europe is still one of the major tectonic problems in Europe. In general, this zone is assumed to be the Trans-European Suture zone (TESZ), a first-order geotectonic unit, stretching form the Black Sea to the British Isles. In northwesternmost Poland, the LT-7 seismic profile showed that the crustal thickness near the TESZ/Teisseyre–Tornquist Zone (TTZ) was intermediate between that of the East European Craton to the east (~42 km) and that

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(~30 km) in the area to the west, near the Polish–German border (Guterch et al., 1991b, 1994; Guterch and Grad, 1996). In central and south-eastern Poland, early deep seismic sounding (DSS) studies showed that the TESZ is associated with a crustal root in SE Poland in which the thickness locally exceeds 50 km (Guterch et al., 1986). A tomographic analysis of shear wave velocity structure of the mantle under Europe shows that, in the region of Poland, the TESZ is a deep-seated structure separating regions with high S-wave velocities beneath the Precambrian Platform from low velocity regions under the Palaeozoic Platform (Zielhuis and Nolet, 1994). Another confirmation of the influence of the TTZ on the propagation of regional seismic waves was obtained from observations of several hundred earthquakes and explosions located in Europe. To explain the blockage of the seismic energy propagation of regional seismic events across the TTZ, the structural anomaly between eastern and western Europe must reach at least down to a depth of about 200 km (Schweitzer, 1995).

In addition to many DSS profiles recorded in Poland in the 1970s, a series of recent seismic studies in the Baltic–North Sea area have provided new insights into the lithospheric structure of the TESZ region: EUGENO-S (EUGENO-S Working Group, 1988), the British BIRPS programme (e.g. Klemperer and Hobbs, 1991), MONA LISA project (MONA LISA Working Group, 1997a,b), EGT (Blundell et al., 1992), BABEL (BABEL Working Group, 1993; Thybo et al., 1994), WARRS profiles 1 and 2 (Makris and Wang, 1994). The very large seismic experiment POLONAISE'97, just conducted in May 1997, targeted the deep structure of the TESZ in northwestern Poland (Guterch et al., 1997, 1998a). Preliminary results of this experiment are presented in other papers of this special issue of *Tectonophysics* (Guterch et al., 1999; Jensen et al., 1999; Środa and POLONAISE Working Group, 1999; Wilde-Piórko et al., 1999).

The subject of this paper is the seismic refraction and wide-angle reflection profile TTZ of 1993 running in an SE–NW direction and located exactly in the central part of the Mid-Polish Trough. Densely spaced shot points and modern receivers along the 450-km-long TTZ profile (Fig. 1) produced good quality data which permitted us to determine a seismic model of the crust in the contact zone of the Precambrian and Palaeozoic Platforms.

2. Geology and geophysical investigations of the study area

The TESZ is a broad, structurally complex zone of middle to late Palaeozoic accretion and deformation that separates the Precambrian terranes of the Baltic Shield and East European Craton from the younger terranes to the south (Berthelsen, 1992a,b, 1998). The TESZ is a manifestation of the complex collisions associated with the formation of Pangea during the Palaeozoic. Much of Poland and northern Germany is covered by a deep (>10 km) basin, usually called the Permian (Permian–Mesozoic) or Polish basin, which was filled with Permian and Mesozoic sedimentary rocks during a phase of extension after the Variscan orogeny. In northwestern Poland the basin is called the Mid-Polish Trough and parallels the edge of the East European Craton along the boundary between the Phanerozoic and Proterozoic European crustal domains. The Mid-Polish Trough approximately coincides with the TTZ which is a part of the TESZ (Dadlez, 1989, 1994, 1997; Ziegler, 1990; Kutek, 1997; Pharaoh et al., 1997).

The Polish Permian–Mesozoic Basin is interpreted by Kutek (1997) as a basin formed by an asymmetrical fault-bounded rift structure and a superimposed Upper Cretaceous sag basin. To some extent, a simple-shear mode of extension can be invoked to explain the evolution of the Polish Rift Basin. According to this interpretation, the present-day Mid-Polish Anticlinorium corresponds to the proximal zone of the Polish Rift, whereas several regions situated farther southwest (e.g. those of the Szczecin–Łódź–Nida Depression, the Fore–Sudetic and Kraków–Silesian Monoclines, the Upper Silesian Coal Basin and the Opole Depression) represent more distal portions of the rift basin.

Apart from seismic investigations, the TTZ/TESZ is also visible as a major change of

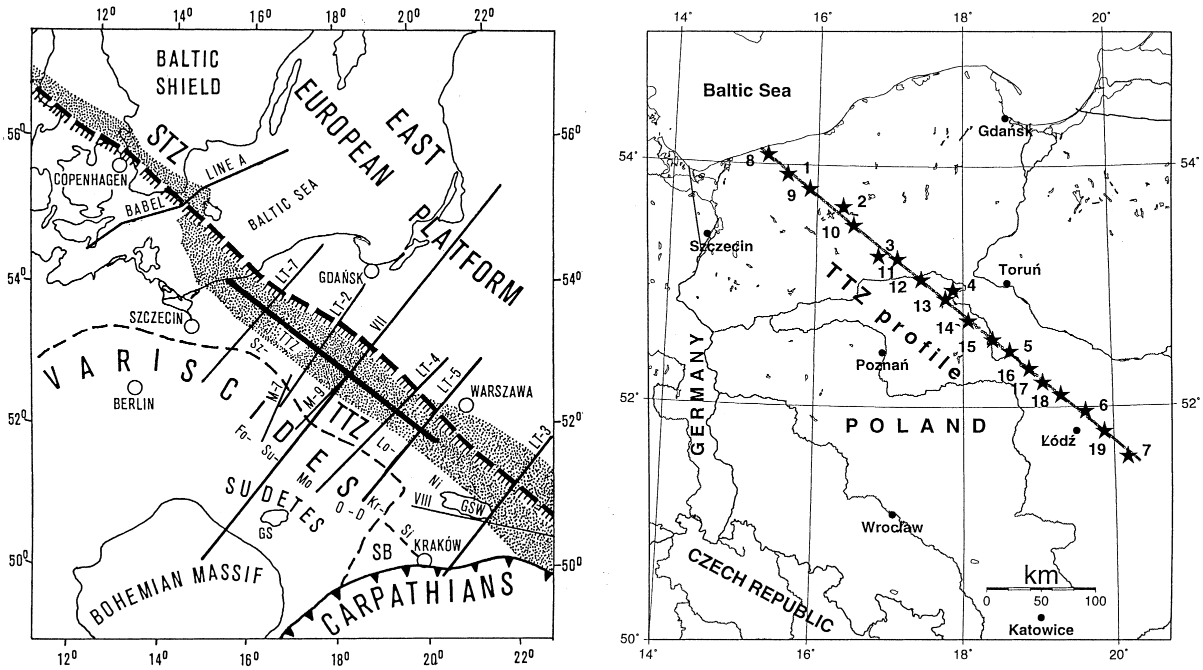

Fig. 1. Location of chosen DSS profiles in Poland (left) on the background of major tectonic units of central Europe [compiled from Bogdanov and Khain (1981), Guterch and Grad (1996) and Guterch et al. (1996a,b)] and location of the TTZ profile (right) with shot points (asterisks) and receiver positions (points). Abbreviations: GS = Sowie Mtns; GŚW = Holy Cross Mtns, SB = Upper Silesian Coal Basin; Fo-Su-Mo = Fore Sudetic Monocline; Kr-Si = Kraków–Silesian Monocline; O-D = Opole Depression; Sz-Lo-Ni = Szczecin–Łódź–Nida Depression; dotted area: Sorgenfrei–Tornquist Zone (STZ) and Teisseyre–Tornquist Zone (TTZ).

crustal structure in the magnetic and gravity fields (Tornquist, 1908; Jankowski, 1967; Grabowska and Raczyńska, 1991; Grabowska et al., 1991; Królikowski and Petecki, 1995; Królikowski and Wybraniec, 1996) as well as in the heat-flow data (e.g. Majorowicz and Plewa, 1979; Čermák et al., 1989).

The basic feature of Bouguer anomalies of the Polish Lowland is the presence of extensive depression down to −60 mGal; on this background, an increase of up to +15 mGal is noted corresponding to the Mid-Polish Anticlinorium. The Fore–Sudetic Monocline in the southwest and the East European Platform in the northeast are characterized by positive gravimetric anomalies of up to +20 mGal and +10 mGal respectively (Królikowski and Petecki, 1995; Królikowski and Wybraniec, 1996). A pronounced local anomaly near Kutno/Kłodawa/Łęczyca reflects the effects of salt tectonics widely developed in that area (see the 300–350 km distance range of the profile in Fig. 2, where the TTZ profile crosses the Kutno/Kłodawa/Łęczyca anomaly almost perpendicularly). The TTZ borders are outlined by the maxima of the horizontal gradient (Królikowski and Petecki, 1995, 1997; Jamrozik, 1998). Gravimetric modelling incorporating geological data and DSS results has been undertaken to determine the sources of the gravimetric anomalies and to evaluate a density model of the lithosphere under the Polish Lowland (Grabowska and Raczyńska, 1991; Królikowski and Petecki, 1997; Jamrozik, 1998). The tectonics and the varying density of the sedimentary rocks significantly contribute to the generation of gravimetric anomalies. The Bouguer anomaly map at the TESZ in northwest Poland, obtained after stripping off the three-dimensional (3-D) gravity effect of the sedimentary cover down to the Zechstein formation, is characterized by a high gravity anomaly of about +50 mGal (Królikowski and Petecki, 1997). In spite of some differences in the interpretation of

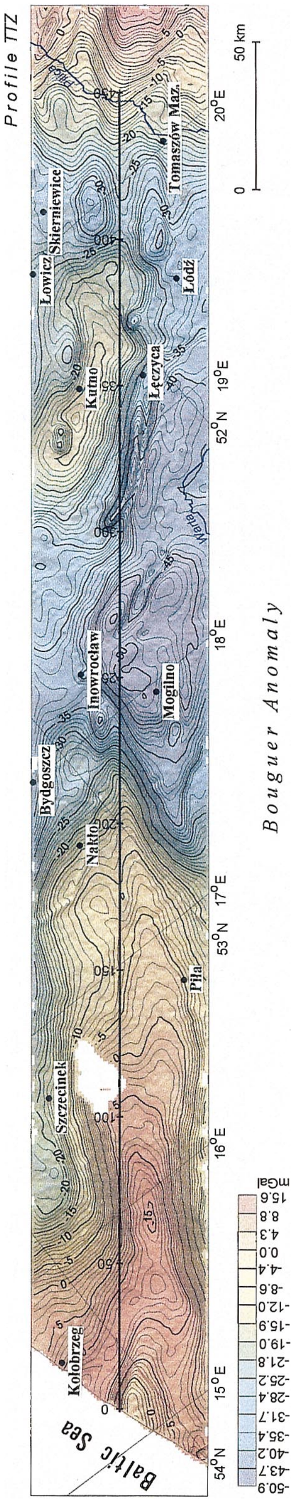

Fig. 2. Location of the TTZ profile plotted on the Bouguer anomaly map of the region (Królikowski and Petecki, 1995).

crustal densities and the gravity anomalies reported by Grabowska and Raczyńska (1991) and by Królikowski and Petecki (1997) for profiles crossing the TTZ/TESZ perpendicularly, the authors of both papers detected denser upper mantle beneath the TTZ (about 0.10–1.13 Mg/m^3 compared with neighbouring regions of the Fore–Sudetic Monocline and the East European Platform).

3. Data acquisition

A seismic refraction and wide-angle reflection experiment was carried out along the so-called TTZ profile in central and northwestern Poland in order to probe the deep structure of the contact zone between the Precambrian and Palaeozoic Platforms in the region of the TTZ. Major tectonic units of central Europe and the location of the TTZ profile are shown in Fig. 1. Seismic measurements along the TTZ profile were carried out in July 1993 as an international Polish, Finnish, German and Swedish co-operation (Grad et al., 1996). The TTZ profile running in an SE–NW direction was located exactly in the central part of the Mid-Polish Trough in the zone of maximum subsidence (Upper Permian to Upper Cretaceous). 19 shot points were located along the 450 km profile and the distance between shot points was about 25 km. Seven big shots of 800–1000 kg dynamite (SP01–SP07) and 12 smaller ones of 90–500 kg dynamite (SP08-SP19) were fired at night to minimize the level of seismic noise. Shooting was carried out using arrays of specially drilled boreholes, about 40 m deep and 10 m apart, each hole containing a maximum 50 kg of explosives. Some details of shot point locations, charges and shooting times are summarized in Table 1. Altogether, recordings of 31 explosions were made in two deployments using 135 modern mobile three-component seismic stations, with recording site spacings of about 1.7 km (Fig. 3). Time codes were obtained from DCF radio signals. The 'big' shots had to produce a strong enough signal to give good observations up to a range of about 300–400 km, whereas for 'small' shots the crustal phases were well recorded up to a distance of about 150–250 km.

Table 1
Details of the explosive sources used in the TTZ profile of July 1993. Coordinates of shot points and shot times (Central European Time)

Shot no.	W (kg)	φ	λ	July 10 (h:m:s)	July 11 (h:m:s)	July 16 (h:m:s)	July 18 (h:m:s)
SP01	1000	53°55′16″	15°34′58″	00:00:01.57	×	00:00:00.67	×
SP02	1000	53°39′28″	16°21′42″	00:20:01.97	×	00:20:00.99	×
SP03	1000	53°15′04″	16°51′10″	00:40:00.59	×	00:40:00.94	×
SP04	990	52°58′21″	17°51′52″	01:20:02.97	×	01:00:02.39	×
SP05	600	52°27′50″	18°37′39″	01:00:01.85	×	01:20:02.20	×
SP06	600	51°57′49″	19°37′36″	01:40:02.33	×	01:40:01.87	×
SP07	990	51°34′45″	20°10′47″	02:00:01.61	×	02:00:01.91	×
SP08	300	54°04′38″	15°18′10″	×	×	×	00:00:00.41
SP09	200	53°48′05″	15°53′52″	×	×	×	00:20:01.04
SP10	400	53°30′20″	16°30′25″	×	×	×	00:40:00.63
SP11	200	53°13′40″	17°06′46″	×	00:00:01.36	×	01:00:01.36
SP12	300	53°03′23″	17°26′03″	×	00:20:00.99	×	01:20:00.99
SP13	300	52°53′54″	17°45′44″	×	00:40:02.26	×	01:40:01.87
SP14	300	52°43′00″	18°04′11″	02:20:02.33	×	×	02:00:01.33
SP15	180	52°33′31″	18°23′44″	03:40:01.63	×	×	02:20:01.72
SP16	150	52°18′58″	18°53′05″	×	01:20:01.40	×	×
SP17	90	52°12′13″	19°03′31″	×	01:40:01.83	×	×
SP18	210	52°05′58″	19°17′54″	×	01:00:02.19	×	×
SP19	90	51°47′33″	19°52′18″	×	02:00:02.04	×	×

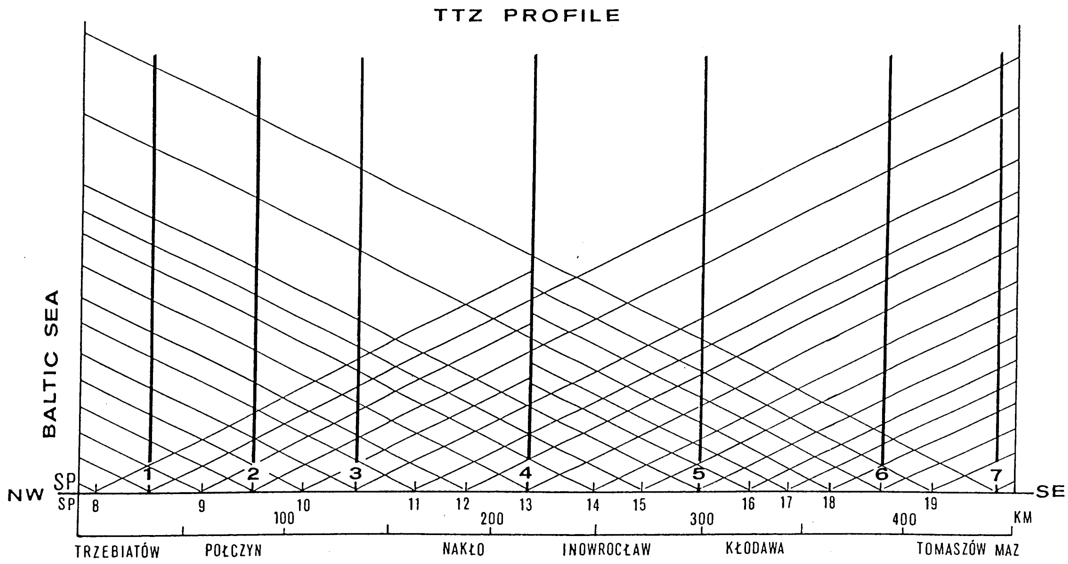

Fig. 3. Schematic system of records along the TTZ profile. Numbers 1–7 'big' shot points, 8–19 'small' shot points. For details see Table 1.

4. Wave field and modelling

A total of 19 seismic record sections form the basis for the interpretation of the crustal structure beneath the TTZ profile. Examples of normalized record sections, filtered in the 2–12 Hz frequency range and plotted with a reduction velocity of 8.0 km/s, are shown in Figs. 4–9. The data are of good quality with generally clear first arrivals of P waves up to 200–300 km for 'big' shot points and up to 150–200 km for 'small' ones. The correlated phases (Figs. 7–9) form a compact system of travel times and the differences of times in reciprocal points do not exceed 0.05 s. Between 0 and 20 to 30 km, first arrivals from sediments (Mesozoic, Zechstein and older Palaeozoic) are observed with velocities from about 2.0 to 5.2 km/s. Up to 120–180 km distance from the shot point, arrivals from the crystalline crust are observed in first onsets, with apparent velocities ranging from 5.7 to 6.6 km/s. Usually they appear as a sharp impulse in the 30–80 km distance range, changing to emergent at greater distances. Waves reflected within the crust are weak, particularly for the upper and middle crust; they are usually observed in intervals of 20–30 km length. Much stronger reflections are generated in the lower crust (e.g. for SP13 in the distance range from −80 to 130 km, Fig. 5; for SP08 in the distance range from 70 to 100 km, Fig. 4). For a few record sections, the coherent energy lying between crustal reflections and the Moho reflection (PmP) may be related to fine structure of the middle/lower crust. For example, arrivals from SP18 recorded in the SE direction (Fig. 4) contain strong coherent energy in the 60–100 km distance range at reduced times of 6–10 s, whereas symmetrically in the NW direction only very weak phases exist in the same distance and time range. Amongst later arrivals, the PmP phase reflected from the Moho is usually the strongest; however, its appearance changes from a very impulsive, relatively short pulse (e.g. for SP06 in the distance interval from −80 to 160 km, Fig. 6; for SP14 in the distance interval 90–140 km, Fig. 6) to a more emergent and complex wave train that may be as long as 1.0–1.5 s (e.g. for SP13 in the distance interval from −80 to −120 km, Fig. 5). Because the data quality is much the same everywhere along the profile, such variations in PmP presumably imply real variations in the nature of the transition zone between lower crust and upper mantle. An impulsive character

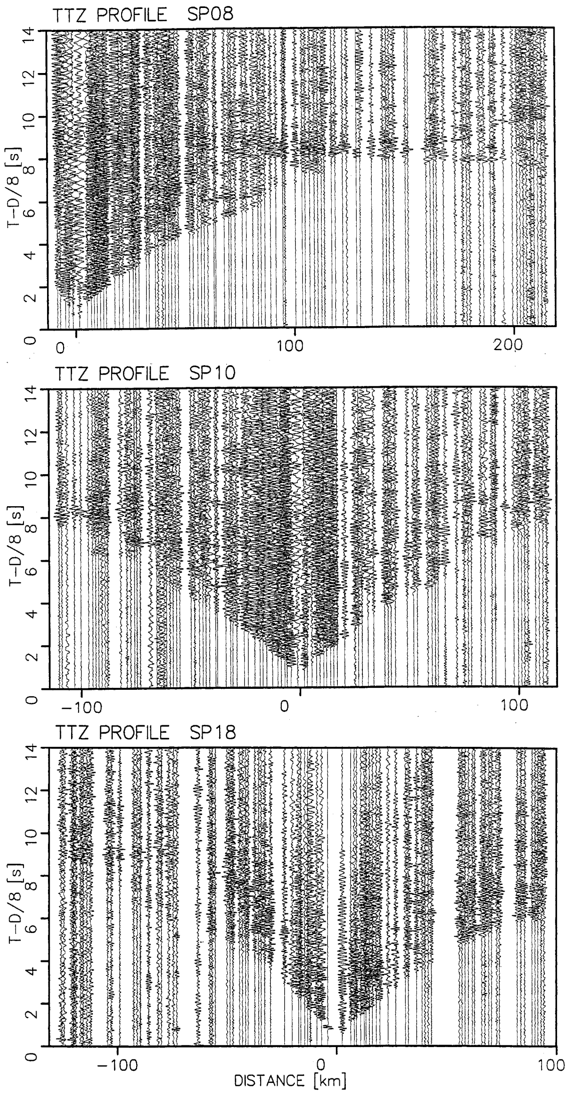

Fig. 4. Example of amplitude-normalized seismic record sections for SP08, SP10 and SP18; reduction velocity 8.0 km/s.

for the PmP reflections is observed mainly in the SE part of the profile, whereas in the NW part the PmP forms complex pulses.

The Pn waves refracted in the uppermost mantle are observed starting from a distance of about 150 km. They are characterized by a relatively high apparent velocity, about 8.2–8.4 km/s, and are recorded very well up to a distance of about 300 km (e.g. see SP06 in the NW direction in the distance range from −150 to −300 km and SP14 in both directions in the distance range of 140–220 km; Fig. 6).

In many cases, crustal waves continue quite strongly in the over-critical distances up to 180–220 km from the shot point (e.g. SP06 in Fig. 6 and SP08 in Fig. 4). They are very important for the modelling process, because they give information about crustal velocities; in particular, they indicate a limit for the maximum velocity within the crust. The comparison of amplitudes of over-critical crustal waves with the Pn phase during the dynamic modelling permits a precise determination of velocity gradients in the crust and uppermost mantle.

Reflected waves within the mantle lithosphere were recorded only fragmentarily at distances greater than 300 km (see for example SP06 in the distance from −320 to −380 km; Fig. 6). A corresponding reflector is estimated to be at about 70–80 km depth; these waves, however, are not discussed further in this paper.

The travel times of refracted and reflected P waves determined by the correlation process provide the basis for the determination of velocity distributions and depths of seismic boundaries in the crust. A two-dimensional (2-D) model was developed using the ray tracing package SEIS83 (Červený and Pšenčík, 1983) supported by the programs MODEL and XRAYS (Komminaho, 1997). The starting model for the forward modelling was based on seismic and geological information on the sedimentary cover that is known from deep drilling and petroleum prospecting investigations. However, because of the lower resolution of DSS data, the sedimentary cover of the model was generalized (particularly the seismic velocities known from well logging), resulting in a six-layer model for the uppermost sediments with velocities lower than 5.3 km/s (Permian–Mesozoic and old Palaeozoic). The generalized velocities are consistent with average values obtained by an analysis of more than 600 well logs in the Polish Lowland (Grad, 1987, 1991; Grad et al., 1990, 1991). In the kinematic modelling, the calculated travel times were compared with the experimental travel times. After the initial model had been altered, the travel times were successively recalculated many times, until a very good agreement between observed and

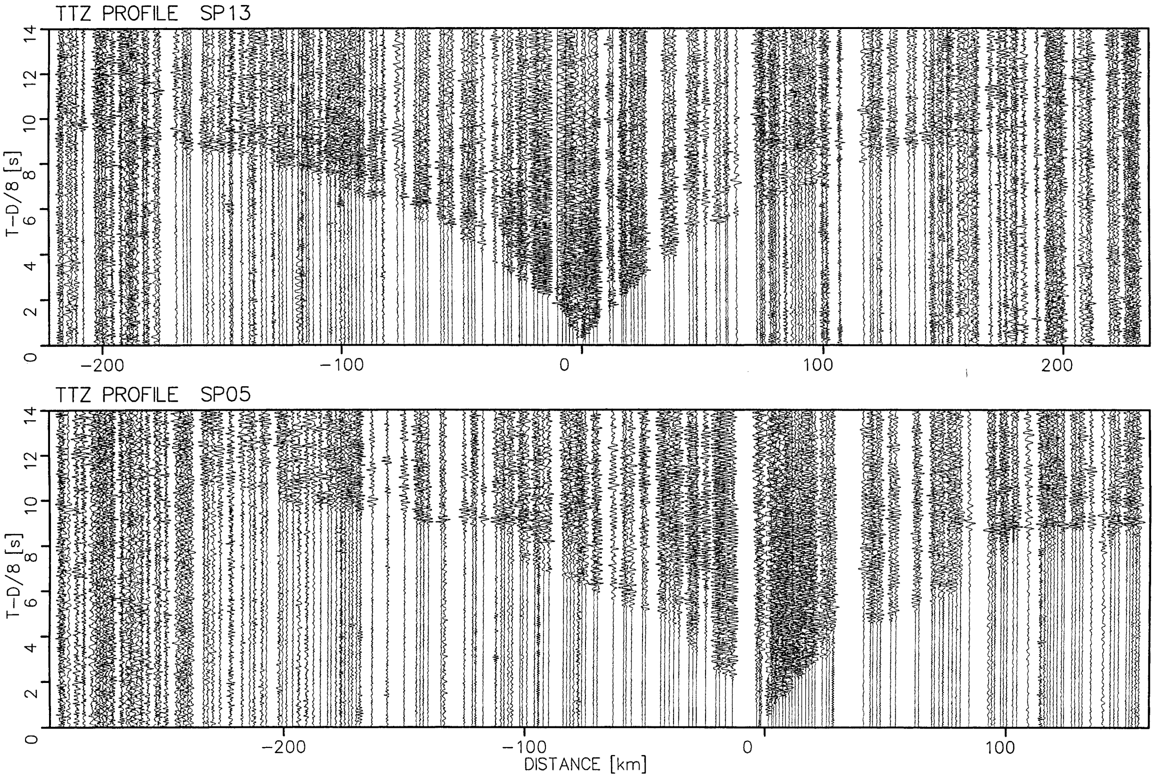

Fig. 5. Example of amplitude-normalized seismic record sections for SP13 and SP05; reduction velocity 8.0 km/s.

model-derived travel times (of the order of 0.1–0.2 s) was obtained. Different parts of the resulting 2-D crustal model are shown in Figs. 7–9. In addition, synthetic seismograms were calculated to control the velocity gradients within the layers and the velocity contrast at the seismic boundaries. The synthetic seismograms show a qualitatively good agreement with the relative amplitudes of the observed waves.

5. Crustal model

The 2-D velocity model along the TTZ profile is shown in Fig. 10a (upper part) and Fig. 10b (whole crust). A simplified sketch of the derived crustal structure, together with the Bouguer anomaly curve, is shown in Fig. 11. The generalized upper part of the sedimentary cover contains a complex of Cretaceous (velocity about 3.1 km/s), Jurassic and Triassic sediments (with velocities of 3.5–3.7 km/s in the NW part of the profile and 4.4–4.7 km/s in the SE part) overlying the Zechstein formation (with velocities of 4.4–5.0 km/s). This complex extends down to depths of about 3 km in the NW and about 5 km in the SE. Old Palaeozoic rocks below this complex are characterized by velocities of 4.7–5.3 km/s. The depth of the consolidated basement, characterized by velocities of 5.8–5.95 km/s, increases from NW (5–7 km) to SE (6–11 km). Velocities are still low below the consolidated basement, particularly in the NW part of profile, being only 5.9 km/s at 20 km depth, and 6.1 km/s at 20 km depth in the SW. In general, velocities in the SE part of the profile are about 0.1–0.2 km higher than in the NW part. The velocity boundary occurs at a distance of about 200–220 km along the profile and also manifests itself in other levels of the crust. A small intrusion of relatively high velocities

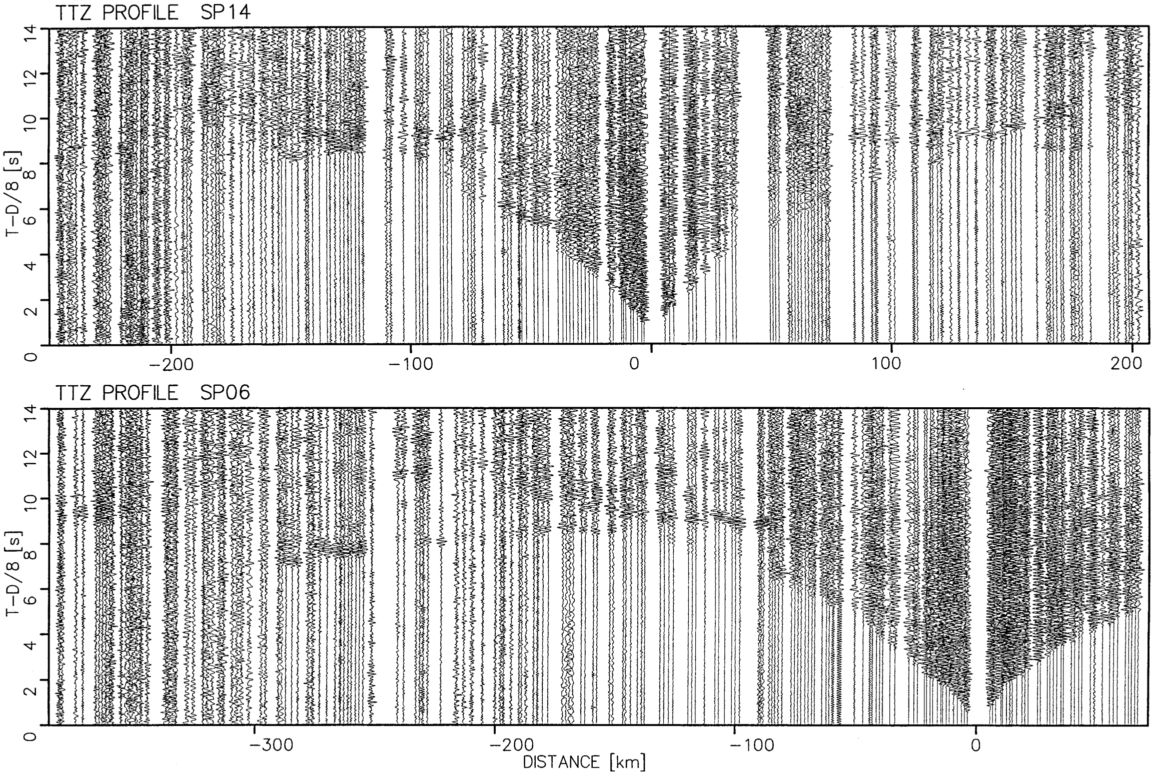

Fig. 6. Example of amplitude-normalized seismic record sections for SP14 and SP06; reduction velocity 8.0 km/s.

(about 6.35 km/s) was found at 11–13 km depth in the 130–170 km distance range along the line (the wave refracted from this body is observed in the respective travel-time branch of one shot point only; see first breaks for SP12 in the distance range of 110–140 km, Fig. 8).

In the lower crust, between about 20 and 40 km depth, two layers exist with velocities of 6.45–6.65 km/s and 6.95–7.20 km/s. The thickness of the first one is almost constant along the profile, 9–11 km. The thickness of the lowermost layer changes along the profile, it being 9–11 km in the NW part, and greater, 9–14 km, in the SE part of profile. In general, boundaries in the lower crust are better documented in the NW part of the profile. The total thickness of the crust increases from 35 km in the NW to 41 km at the SE end of the profile. In general, the crust is characterized by low-velocity gradients and velocity contrasts at seismic boundaries 0.4–0.5 km/s. The velocity beneath the Moho was found to be rather high: 8.2–8.4 km/s in the NW part, and about 8.4 km/s in the SE part of the profile.

6. Summary and discussion

The TTZ seismic profile runs along the axis of the Mid-Polish Trough in the zone of maximum subsidence. Densely spaced shots and receivers along this 450-km-long profile produced high-quality data that resolve a seismic model of the crust in the contact zone between the Precambrian and Palaeozoic Platforms. The generalized model of the sedimentary cover contains layers with velocities of 3.1–5.3 km/s. The depth to the consolidated basement, with velocities of 5.7–5.95 km/s is 5 to 12 km in this area; however, down to a depth of 15–20 km, velocities are still low: less than 5.9–6.1 km/s. Below this complex, velocities

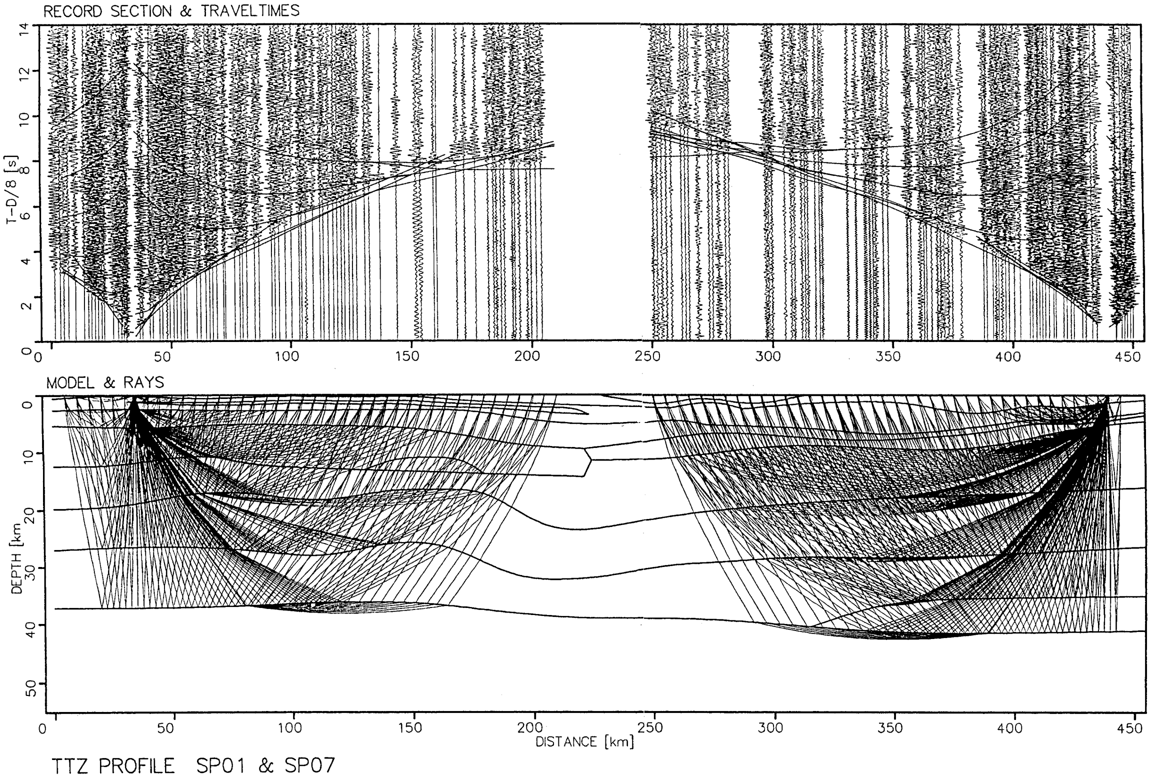

Fig. 7. Amplitude-normalized seismic record sections for SP01 and SP07 and theoretical travel times of P waves calculated for the crustal model. Reduction velocity 8.0 km/s. The bottom portion of the figure is a ray diagram with refracted and reflected waves in the model.

of 6.5–6.6 km/s and 7.0–7.2 km/s were found, and the thicknesses of the corresponding layers are 8–11 km and 9–14 km respectively. In general, the crust is characterized by low-velocity gradients and velocity contrasts at seismic boundaries 0.4–0.5 km/s. The total thickness of the crust increases from 35 km in the NW to 41 km in the SE end of the profile. Beneath Moho a rather high velocity of 8.2–8.4 km/s was found.

The velocity and depth uncertainties of the forward 2-D modelling are of the order of ±0.1 km/s and ±1–2 km respectively. So, the vertical and horizontal definition of the crustal structure appear well resolved, and the observed velocity and depth differences between the NW and SE blocks are about 0.2 km/s and 3–5 km respectively. The boundary between these parts of the profile occurs at a distance of about 200–220 km and is seen in all levels of the crust and uppermost mantle.

Low velocities in the TESZ area were observed earlier on refraction, near-vertical reflection and wide-angle reflection profiles, as well as from a surface wave study. Vertical reflection profiles near Poznań (SW from the TTZ profile, about 100 km from SP13) show interval velocities lower than 6.0 km/s down to 16–18 km depth (Guterch et al., 1996a, 1998b). Beneath refraction profiles M-9 and M-7, recorded in the 1970s and reinterpreted using 2-D forward modelling techniques, velocities of 5.7–5.8 km/s at about 12 km depth and 5.9 km/s at 17 km were found (Doan, 1989; Pyra, 1990; Guterch et al., 1991a, 1992). Beneath the LT-7 profile (crossing the TTZ profile at 80 km distance almost perpendicularly) velocities of 5.75–5.9 km/s were found in a depth range of 6–20 km (Guterch

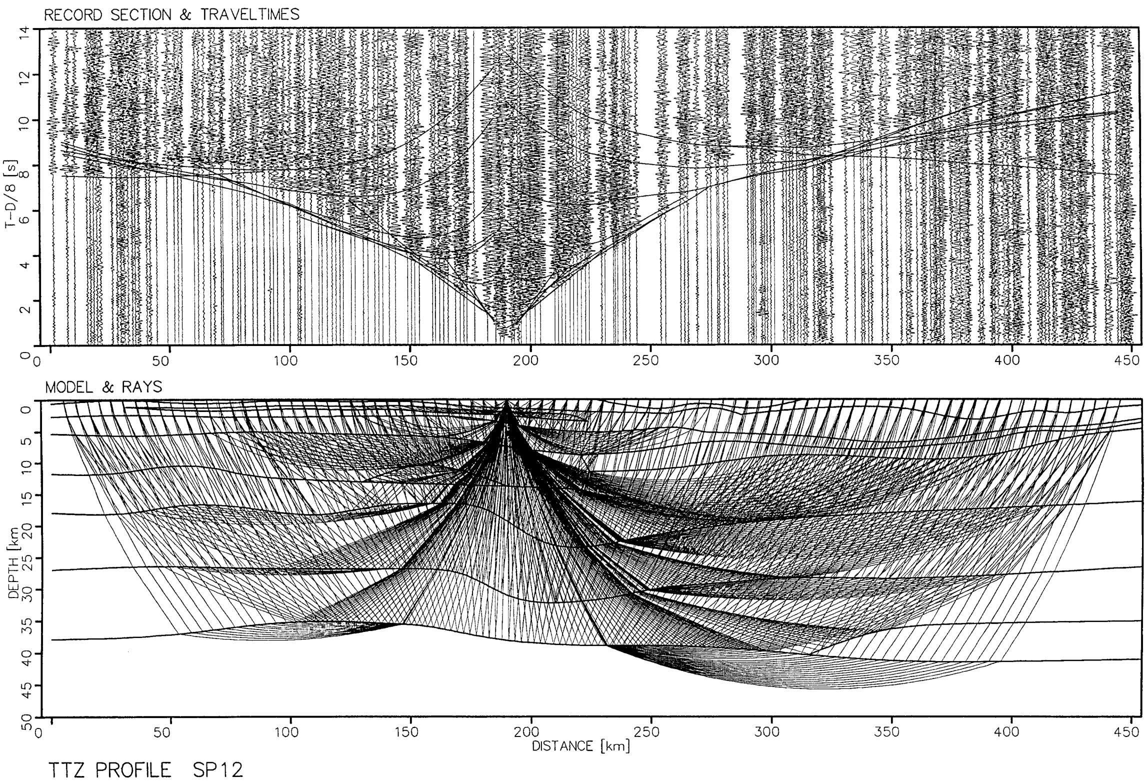

Fig. 8. Amplitude-normalized seismic record sections for SP12 and theoretical travel times of P waves calculated for the crustal model. Reduction velocity 8.0 km/s. The bottom portion of the figure is a ray diagram with refracted and reflected waves in the model.

et al., 1994). Low velocities in the TESZ area were also confirmed from a study of surface wave dispersion along profiles from Prague to Warsaw and from Prague to Uppsala (Novotný et al., 1995, 1997).

The high velocity body (~6.35 km/s) that was found at 11–13 km depth in the distance range of 130–170 km can be correlated with a high-density body 2.90–2.92 Mg/m^3 interpreted from positive residual anomalies by Królikowski and Petecki (1997). These masses occur mainly in the central part of the Polish Basin, within the TTZ, and may represent intrusive basic rocks of high density.

The coherent energy lying between the first arrivals and the PmP reflections may be related to fine structure of the middle and/or lower crust. A transparent upper crust and reflective middle and/or lower crust were previously found in the TESZ area mainly from deep near-vertical reflection profiles (Guterch et al., 1991a, 1992, 1996a, 1998b; MONA LISA Working Group, 1997b) and on the refraction and wide-angle reflection profile LT-7 (Guterch et al., 1994).

Crustal structure and depth of the Moho along the TTZ profile can be compared in relation to previous results for profiles LT-7, LT-2, VII, LT-4 and LT-5 (Fig. 1). The thickness of the crust in the NW part of profile TTZ corresponds to that beneath profile LT-7. Beneath the crossing point the profiles had practically the same velocity distribution and boundary depths: velocities lower than 6.0 km/s down to a depth of 18 km, two layers of about 9 km thickness with velocities of 6.5–6.6 and 7.1–7.2 km/s, and a total crustal thickness of 36 km. The thickness of the crust in the SE part of profile TTZ reaches a maximum value of 41 km, which is much less than about 50 km for the Moho depth beneath profiles VII, LT-4 and LT-5. The results from the new profile P4, recorded as part of the POLONAISE'97 project (Guterch et al.,

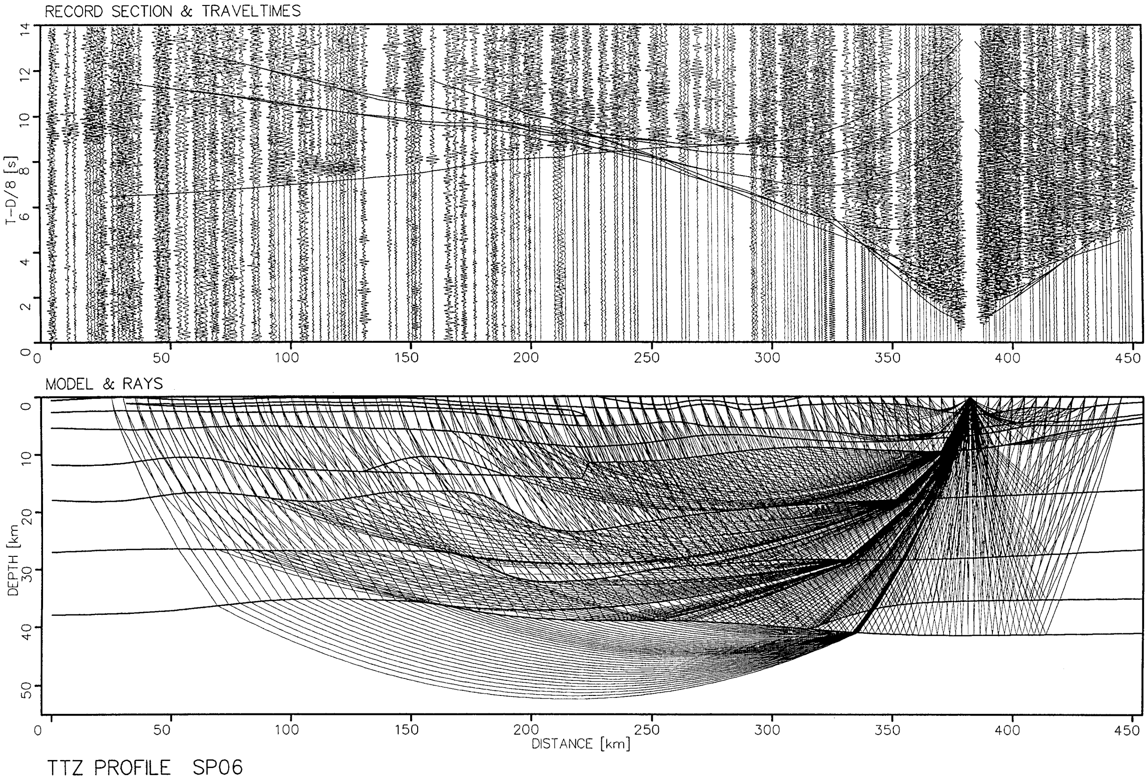

Fig. 9. Amplitude-normalized seismic record sections for SP06 and theoretical travel times of P waves calculated for the crustal model. Reduction velocity 8.0 km/s. The bottom portion of the figure is a ray diagram with refracted and reflected waves in the model.

1999), show that at the crossing point of the P4 and TTZ profiles the Moho depth is only about 40 km. However, a very distinct asymmetry between the maximum thickness of the sedimentary cover and the crustal root is observed. Further to the NE the crustal thickness in TESZ beneath the P4 profile reaches a value of 45–46 km.

In the uppermost mantle, velocities of 8.2–8.4 km/s were found in the NW part, and about 8.4 km/s in the SE part of the TTZ profile. Corresponding values of velocities at the Moho beneath profiles LT-7 and P4 are about 8.3 km/s. An impulsive character of the PmP reflections is predominantly observed in the SE part of the profile (sharp Moho), whereas in the NW part the PmP forms a complex pulse of up to 1.0–1.5 s in duration (complex crust–mantle transition).

At a distance of 200–220 km a discontinuity in the structure is seen in all levels of the crust. From a geological point of view, the difference of the structure corresponds to two parts of Polish Basin: a northwestern part (Pomerania) and a southwestern part (Kujawy). In general, the crustal structure under the NW part of the profile is very similar to that under the Palaeozoic Platform; this is particularly true in regard to the two lowermost layers with velocities of 6.45–6.65 and 6.95–7.05 km/s, and the total thickness of the crust (32–35 km). In the SE part of the profile, higher velocities near the bottom of the crust (~7.2 km/s) and a deeper Moho (~41 km) were found, which indicates some similarities to the cratonic crystalline crust of the Precambrian Platform. However, velocities in the uppermost mantle in both parts (~8.3–8.4 km/s) are higher than those observed beneath the Precambrian crust (~8.1 km/s). The data for the TTZ profile that runs parallel to the geological and tectonic structures are difficult to model (and interpret). The 2-D modelling does not take into account out-of-plane refractions and reflections,

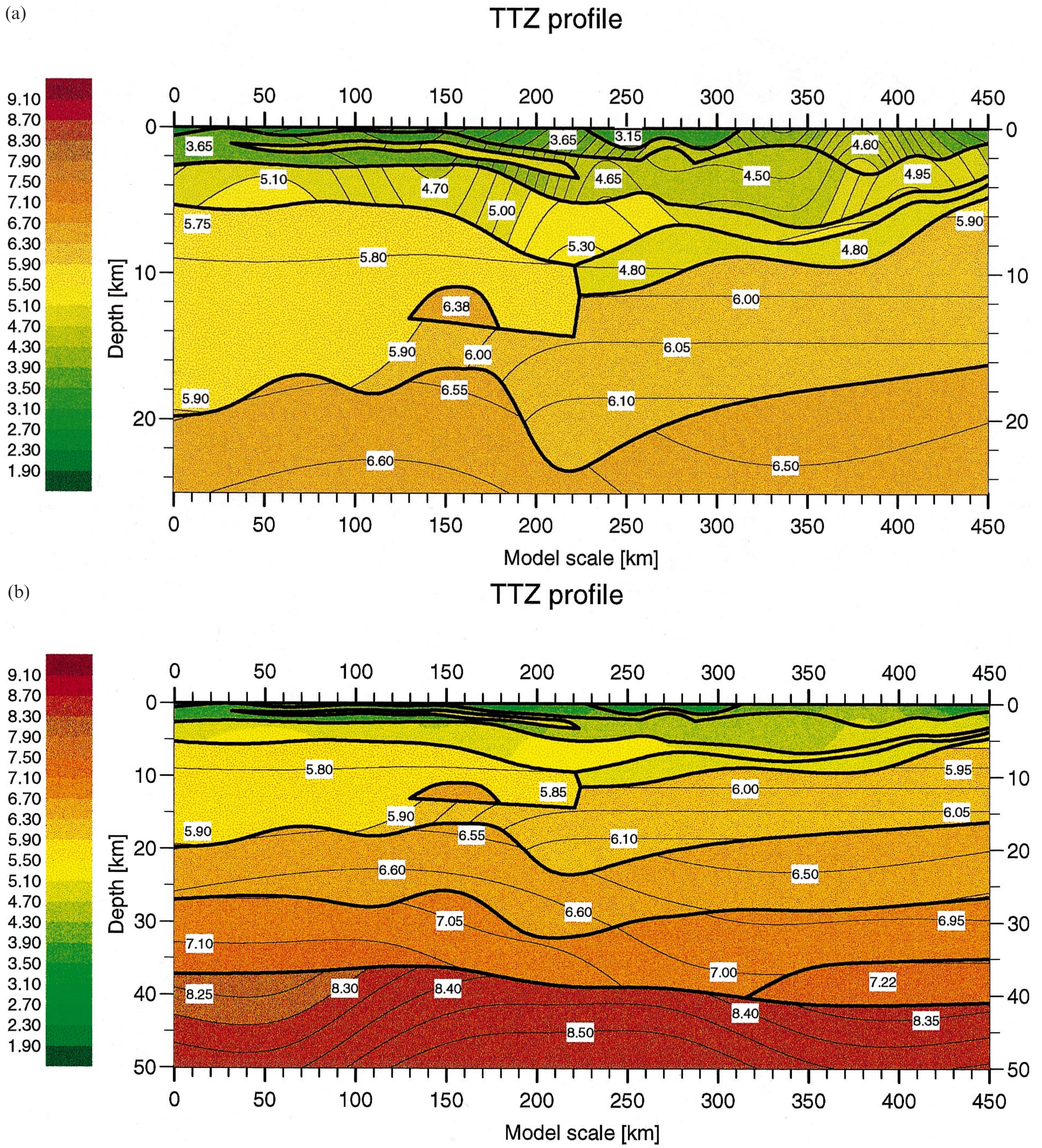

Fig. 10. The 2-D velocity model of the upper crust (a) and whole crustal structure (b) along the TTZ profile developed by forward ray tracing modelling. Thick lines are velocity discontinuities; thin lines are P-wave velocity isolines in kilometres per second.

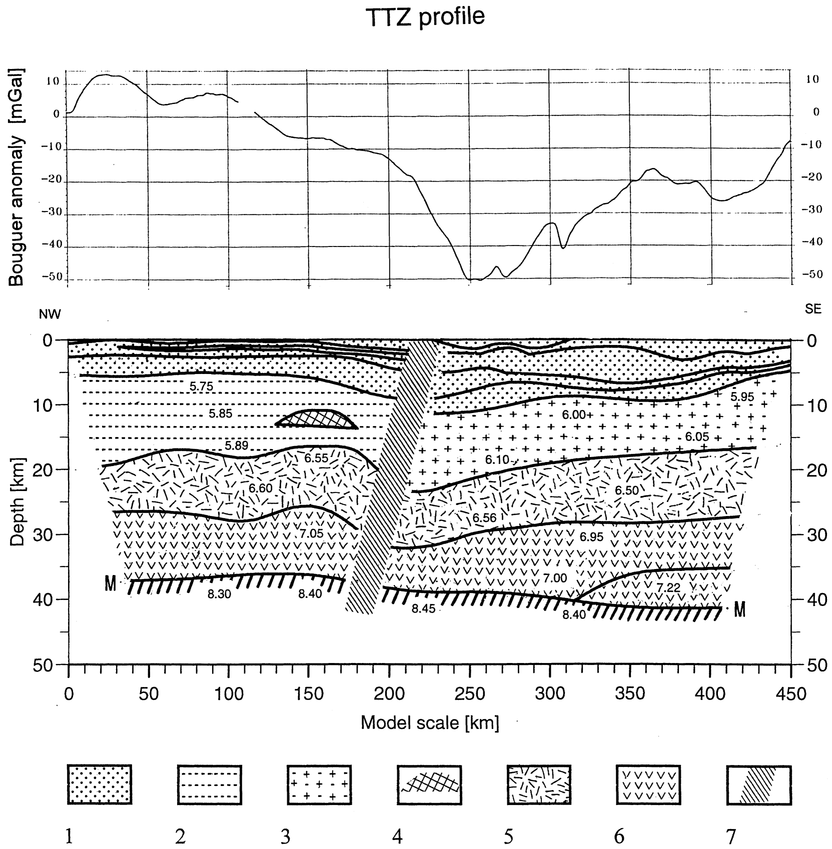

Fig. 11. Simplified sketch of the derived structure (bottom) together with Bouguer anomaly curve (top) along the TTZ profile: (1) sedimentary cover; (2) upper crust, the NW part of profile, velocities $V_p = 5.8$–5.9 km/s; (3) upper crust, the SE part of profile, velocities $V_p = 5.9$–6.1 km/s; (4) high velocity body in the upper crust, velocity $V_p \approx 6.35$ km/s; (5) middle crust, $V_p = 6.5$–6.6 km/s; (6) lower crust, $V_p = 6.95$–7.25 km/s; (7) zone of rapid lateral change of seismic structure, probably indicating a boundary between crustal blocks. M = Moho boundary.

which must have occurred in such a complicated region. In future, the data from the TTZ profile should be interpreted jointly with the LT-7 profile and POLONAISE'97 data using a 3-D approach.

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References

BABEL Working Group, 1993. Deep seismic reflection/refraction interpretation of crustal structure along BABEL profiles A and B in the southern Baltic Sea. Geophys. J. Int. 112, 325–343.

Berthelsen, A., 1992a. Mobile Europe. In: Blundell, D.J., Freeman, R., Mueller, St. (Eds.), A Continent Revealed — The European Geotraverse. Cambridge University Press, pp. 11–32.

Berthelsen, A., 1992b. From Precambrian to Variscan Europe. In: Blundell, D.J., Freeman, R., Mueller, St. (Eds.), A Continent Revealed — The European Geotraverse. Cambridge University Press, pp. 153–164.

Berthelsen, A., 1998. The Tornquist Zone northwest of the Carpathians: an intraplate-pseudosuture. Geol. Fören. Stockholm Förh. 120, 223–230.

Blundell, D., Freeman, R., Mueller, St. (Eds.), A Continent Revealed — The European Geotraverse 1992. Cambridge University Press, 275 pp.

Bogdanov, A.A., Khain, V.E. (Eds.), International Tectonic Map of Europe 1981. IGC Sub-Commission of the Tectonic Map of the World, Moscow.

Červený, V., Pšenčík, I., 1983. SEIS83 — numerical modelling of seismic wave fields in 2-D laterally varying layered structure by the ray method. In: Engdahl, E.R. (Ed.), in: Documentation of Earthquake Algorithm Rep. SE-35. World Data Center A for Solid Earth Geophysics, Boulder, pp. 36–40.

Čermák, V., Šafanda, J., Guterch, A., 1989. Deep temperature distribution along three profiles crossing the Teisseyre–Tornquist tectonic zone in Poland. Tectonophysics 164, 151–163.

Dadlez, R., 1989. Epicontinental Permian and Mesozoic basins in Poland. Kwart. Geol. 33, 175–198.

Dadlez, R., 1994. Strike-slip movements in the Polish Lowlands. Geol. Quart. 38 (2), 307–318.

Dadlez, R., 1997. Seismic profile LT-7 (northwest Poland): geological implications. Geol. Mag. 134 (5), 653–659.

Doan, T.T., 1989. Zastosowanie modelowania sejsmicznego w badaniach struktury skorupy i górnego plaszcza Ziemi. PhD Thesis, Archives of the Institute of Geophysics, University of Warsaw (in Polish, unpublished).

EUGENO-S Working Group, 1988. Crustal structure and tectonic evolution of the transition between the Baltic Shield and the North German Caledonides (the EUGENO-S Project). Tectonophysics 150, 253–348.

Grabowska, T., Raczyńska, M., 1991. Structure of the Earth's crust on the Polish Lowland in the light of gravimetric modelling. Publ. Inst. Geophys. Pol. Acad. Sci. A-19 (230), 85–110.

Grabowska, T., Koblański, A., Dolnicki, J., 1991. Deep structure of the Earth's crust in the Teisseyre–Tornquist Zone (TTZ) in Poland, based on magnetic and gravity studies. Publ. Inst. Geophys. Pol. Acad. Sci. A-20 (255), 81–89.

Grad, M., 1987. Prędkości fal sejsmicznych w pokrywie osadowej platformy wschodnioeuropejskiej. Kwart. Geol. 31 (1), 97–114 (in Polish with English abstract).

Grad, M., 1991. Seismic wave velocities in the sedimentary cover of the Palaeozoic Platform in Poland. Bull. Pol. Acad. Earth Sci. 39 (1), 13–22.

Grad, M., Trung Doan, T., Klimkowski, W., 1990. Sejsmiczne modelowanie pokrywy osadowej wzdłuż profilu przez platformę prekambryjską i paleozoiczną. Kwart. Geol. 34 (2), 393–410 (in Polish with English abstract).

Grad, M., Trung Doan, T., Klimkowski, W., 1991. Seismic models of sedimentary cover of the Precambrian and Paleozoic platforms in Poland. Publ. Inst. Geophys. Pol. Acad. Sci. A-19 (236), 125–145.

Grad, M., Guterch, A., Gaczyński, E., Janik, T., Materzok, R., Środa, P., Yliniemi, J., Komminaho, K., Luosto, U., Makris, J., Höing, K., Lund, C.-E., 1996. Preliminary results from new deep seismic refraction and wide angle reflection experiments in the Teisseyre–Tornquist Zone in Poland. EUROPROBE TESZ Workshop, Książ, Poland, 11–17 April. Abstracts.

Guterch, A., Grad, M., 1996. Seismic structure of the Earth's crust between Precambrian and Variscan Europe in Poland. Publ. Inst. Geophys. Pol. Acad. Sci. M-18 (273), 67–73.

Guterch, A., Grad, M., Materzok, R., Perchuć, E., 1986. Deep structure of the Earth's crust in the contact zone of the Palaeozoic and Precambrian Platforms in Poland (Tornquist–Teisseyre Zone). Tectonophysics 128, 251–279.

Guterch, A., Grad, M., Materzok, R., Perchuć, E., Janik, T., Gaczyński, E., Doan, T.T., Białek, T., Gadomski, D., Młynarski, S., Toporkiewicz, S., 1991a. Structure of the lower crust of the Paleozoic platform in Poland from seismic wide-angle and near-vertical reflection surveys. Publ. Inst. Geophys. Pol. Acad. Sci. A-19 (236), 41–62.

Guterch, A., Luosto, U., Grad, M., Yliniemi, J., Gaczyński, E., Korhonen, H., Janik, T., Lindblom, P., Materzok, R., Perchuć, E., 1991b. Seismic studies of crustal structure in the Teisseyre–Tornquist zone in northwestern Poland (preliminary report). Publ. Inst. Geophys. Pol. Acad. Sci. A19 (236), 147–156.

Guterch, A., Grad, M., Materzok, R., Perchuc, E., Janik, T., Gaczyński, E., Doan, T.T., Białek, T., Gadomski, D., Młynarski, S., Toprkiewicz, S., 1992. Laminated structure of the lower crust in the fore-Sudetic region in Poland, derived from seismic data. Phys. Earth Planet. Inter. 69, 217–223.

Guterch, A., Grad, M., Janik, T., Materzok, R., Luosto, U., Yliniemi, J., Lück, E., Schulze, A., Förste, K., 1994. Crustal structure of the transition zone between Precambrian and Variscan Europe from new seismic data along LT-7 profile (NW Poland and eastern Germany). C. R. Acad. Sci. Paris 319 Ser. II, 1489–1496.

Guterch, A., Grad, M., Gruszyńska, B., Bukowicki, J., Jakubowski, A., Pietrzyk, K., Stawinoga, J., Bystroń, M., 1996a. Crustal structure from deep seismic reflection data in the Permian basin in the region of TESZ (Poland). EUROPROBE TESZ Workshop, Książ, Poland, 11–17 April. Abstracts.

Guterch, A., Lewandowski, M., Dadlez, R., Pokorski, J., Wybraniec, S., Żytko, K., Grad, M., Kutek, J., Szulczewski, M., Żelaźnewicz, A., 1996b. Podstawowe problemy głębokich badań geofizycznych i geologicznych obszaru Polski. Publ. Inst. Geophys. Pol. Acad. Sci. M-20 (294) 44 pp. (in Polish with English summary)

Guterch, A., Grad, M., Thybo, H., Keller, G.R., 1997. New international seismic experiment in the Polish Basin POLONAISE'97, Special issue for the 15th World Petroleum Congress, Beijing, China. Oil and Gas News 7, 86–93.

Guterch, A., Grad, M., Thybo, H., Keller, G.R., Miller, K., 1998a. Seismic experiment spreads across Poland. EOS 79 (26), 302, 305

Guterch, A., Grad, M., Antonowicz, L., 1998b. Crustal structure from seismic near vertical reflection data in the Polish basin, 23rd General Assembly of the European Geophysical Society, Nice, France, 20–24 April. Ann. Geophys. 16 suppl. I, part I, C106.

Guterch, A., Grad, M., Thybo, H., Keller, G.R., POLONAISE Working Group 1999, POLONAISE'97 — international seismic experiment between Precambrian and Variscan Europe in Poland. Tectonophysics 314, 101–121.

Jamrozik, J., 1998. Trójwymiarowa dekonwolucja Eulera jako jedna z metod interpretacji anomalii siły ciężkości. Prz. Geol. 46 (5), 459–462 (in Polish).

Jankowski, J., 1967. The marginal structures of East European Platform in Poland on basis of data on geomagnetic field variations. Publ. Inst. Geophys. Pol. Acad. Sci. 14, 93–102.

Jensen, S.L., Janik, T., Thybo, H., POLONAISE Working Group 1999. Seismic structure of the Palaeozoic Platform along POLONAISE'97 profile P1 in southwestern Poland. Tectonophysics. this issue

Klemperer, S., Hobbs, R., 1991. The BIRPS Atlas. Deep Seismic Reflection Profiles Around the British Isles. Cambridge University Press.

Komminaho, K., 1997. Software manual for programs MODEL and XRAYS — a graphical interface for SEIS83 program package. University of Oulu, Department of Geophysics, Rep. No. 20, 31 pp.

Królikowski, C., Petecki, Z., 1995. Gravimetric Atlas of Poland. Państwowy Instytut Geologiczny, Warsaw.

Królikowski, C., Petecki, Z., 1997. Crustal structure at the Trans-European Suture Zone in northwest Poland based on gravity data. Geol. Mag. 134 (5), 661–667.

Królikowski, C., Wybraniec, S., 1996. Gravity and magnetic maps of Poland — historical background and modern presentation. Publ. Inst. Geophys. Pol. Acad. Sci. M18 (273), 87–92.

Kutek, J., 1997. The Polish Permo-Mesozoic Rift Basin. IGCP Project No. 369 Comparative Evolution of Peri-Tethyan Rift Basins, Abstract Book, 4th Annual Meeting and Fieldtrip, 29 August–3 September, Barcelona, Spain.

Majorowicz, J., Plewa, S., 1979. Study of heat flow in Poland with special regards to tectonophysical problems. In: Čermák, V., Rybach, L. (Eds.), Terrestrial Heat Flow in Europe. Springer, Berlin, pp. 240–252.

Makris, J., Wang, S.-R., 1994. Crustal structure at the Tornquist–Teisseyre zone in the Southern Baltic Sea. Z. Geol. Wiss. 22 1–2, 47–54.

MONA LISA Working Group, 1997a. MONA LISA — deep seismic investigations of the lithosphere in the southeastern North Sea. Tectonophysics 269, 1–19.

MONA LISA Working Group, 1997b. Closure of the Tornquist Sea: constraints from MONA LISA deep seismic reflection data. Geology 25 (12), 1071–1074.

Novotný, O., Proskuryakova, T.A., Shilov, A.V., 1995. Dispersion of Rayleigh waves along the Prague–Warsaw profile. Stud. Geoph. Geod. 39, 138–147.

Novotný, O., Grad, M., Lund, C.E., Urban, L., 1997. Verification of the lithospheric structure along profile Uppsala–Prague using surface wave dispersion. Stud. Geoph. Geod. 41, 15–28.

Pharaoh, T.C., England, R.W., Verniers, J., Żelaźniewicz, A., 1997. Introduction: geological and geophysical studies in the Trans-European Suture Zone. Geol. Mag. 134 (5), 585–590.

Pyra, E., 1990. Dwuwymiarowe modelowanie sejsmicznej struktury skorupy ziemskiej (profil M-7). M.Sc. Thesis, Archives of the Institute of Geophysics, University of Warsaw (in Polish, unpublished).

Schweitzer, J., 1995. Blockage of regional seismic waves by the Teisseyre–Tornquist zone. Geophys. J. Int. 123, 260–276.

Środa, P., POLONAISE Working Group 1999. P- and S-wave velocity model of the southwestern margin of the Precambrian East European Craton; POLONAISE'97, profile P3. Tectonophysics 314, 175–192.

Thybo, H., Abramovitz, T., Lassen, A., Schjøth, F., 1994. Deep structure of the Sorgenfrei–Tornquist zone interpreted from BABEL seismic data. Z. Geol. Wiss. 22 1–2, 3–17.

Tornquist, A., 1908. Die Feststellung des Südwestrandes des baltisch-russischen Schildes und die geotektonische Zugehörigkeit der ostpreußischen Scholle. Schr. Phys. -ökon. Ges. Königsberg 49 (1), 1–12.

Wilde-Piórko, M., Grad, M., POLONAISE Working Group 1999. Regional and teleseismic events recorded across the TESZ during POLONAISE'97. Tectonophysics 314, 161–174.

Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe. 2nd ed., Shell International Petroleum Maatschappij, The Hague, Elsevier, Amsterdam. 239 pp.

Zielhuis, A., Nolet, G., 1994. Shear-wave velocity in the upper mantle beneath central Europe. Geophys. J. Int. 117, 695–715.