DE GRUYTER OPEN

Acta Geophysica
vol. 63, no. 3, June 2015, pp. 698-714
DOI: 10.1515/acgeo-2015-0019

Seismic Wave Velocities in Deep Sediments in Poland: Borehole and Refraction Data Compilation

Marcin POLKOWSKI and Marek GRAD

Institute of Geophysics, Faculty of Physics, University of Warsaw, Warsaw, Poland
e-mail: marcin.polkowski@igf.fuw.edu.pl

A b s t r a c t

Sedimentary cover has significant influence on seismic wave travel times and knowing its structure is of great importance for studying deeper structures of the Earth. Seismic tomography is one of the methods that require good knowledge of seismic velocities in sediments and unfortunately by itself cannot provide detailed information about distribution of seismic velocities in sedimentary cover. This paper presents results of *P*-wave velocity analysis in the old Paleozoic sediments in area of Polish Lowland, Folded Area, and all sediments in complicated area of the Carpathian Mountains in Poland. Due to location on conjunction of three major tectonic units – the Precambrian East European Craton, the Paleozoic Platform of Central and Western Europe, and the Alpine orogen represented by the Carpathian Mountains the maximum depth of these sediments reaches up to 25 000 m in the Carpathian Mountains. Seismic velocities based on 492 deep boreholes with vertical seismic profiling and a total of 741 vertical seismic profiles taken from 29 seismic refraction profiles are analyzed separately for 14 geologically different units. For each unit, velocity *versus* depth relations are approximated by second or third order polynomials.

Key words: vertical seismic profiling, seismic refraction profiles, seismic velocity analysis, sedimentary cover, Poland.

Ownership: Institute of Geophysics, Polish Academy of Sciences;

1. INTRODUCTION

The structure of the sedimentary cover in the area of Poland is very complex due to complicated geological structure of three major tectonic units: the Precambrian East European Craton (EEC), the Paleozoic Platform of Central and Western Europe (PP), and the Alpine orogen represented by the Carpathian Mountains (Pożaryski *et al.* 1982, Znosko 1975, 1979; Berthelsen 1992, 1998). All these units differ in tectonic age, geological history and development, and require individual analysis on *P*-wave velocities. Such differentiated layer of sediments has great influence on seismic wave travel times and good knowledge of seismic velocity distribution is crucial for global and regional tomography.

The thickness of the sedimentary cover varies from 300 m in NE Poland to about 16 000 m in area of Trans European Suture Zone and 25 000 m in the Carpathians (Skorupa 1974, Czuba *et al.* 2002, Grad *et al.* 1990, 1991; Janik *et al.* 2011). The structure of sediments is well studied for layers of Tertiary and Quaternary, Cretaceous, Jurassic, Triassic, and Permian by over 100 000 geological boreholes from which over 1000 boreholes had vertical seismic profiling done (VSP; Grad and Polkowski 2012). Range of borehole surveying is limited to approximately 5000 m in depth (the deepest borehole in Poland, Kuźmina-1, has 7541 m depth; Moryc and Łydka 2000). Below that level other sources have to be introduced, such as deep seismic refraction. Poland is very well covered with seismic refraction profiles from multiple experiments:

- **POLONAISE'97** (Guterch *et al.* 1999): P1 (Jansen *et al.* 1999), P2 (Janik *et al.* 2002), P3 (Środa *et al.* 1999), P4 (Grad *et al.* 2003a), P5 (Czuba *et al.* 2001).
- **CELEBRATION 2000** (Guterch *et al.* 2003): CEL01 (Środa *et al.* 2006), CEL02 (Malinowski *et al.* 2005), CEL03 (Janik *et al.* 2005), CEL04 (Środa *et al.* 2006), CEL05 (Grad *et al.* 2006), CEL10 (Grad *et al.* 2009), CEL06, CEL11, CEL12, CEL13, CEL14, CEL21, CEL22, CEL23 (Janik *et al.* 2009).
- **SUDETES 2003** (Grad *et al.* 2003c): S01 (Grad *et al.* 2008), S02, S03, S06 (Majdański *et al.* 2006).
- other profiles: LT-2, LT-4 (Grad *et al.* 2005), LT-7 (Guterch *et al.* 1994), M07, M09 (Grad *et al.* 1991), TTZ (Grad *et al.* 1999).

Seismic refraction profiles provide detailed data about seismic velocities along profile down to 40-80 km depth, depending on profile length and type of seismic sources used. To allow combination of data from profiles with data from boreholes with VSP and to remain compatible with the result form previous analysis for shallower sediments, the "virtual boreholes" are introduced being vertical velocity to depth relations taken from 2D velocity mod-

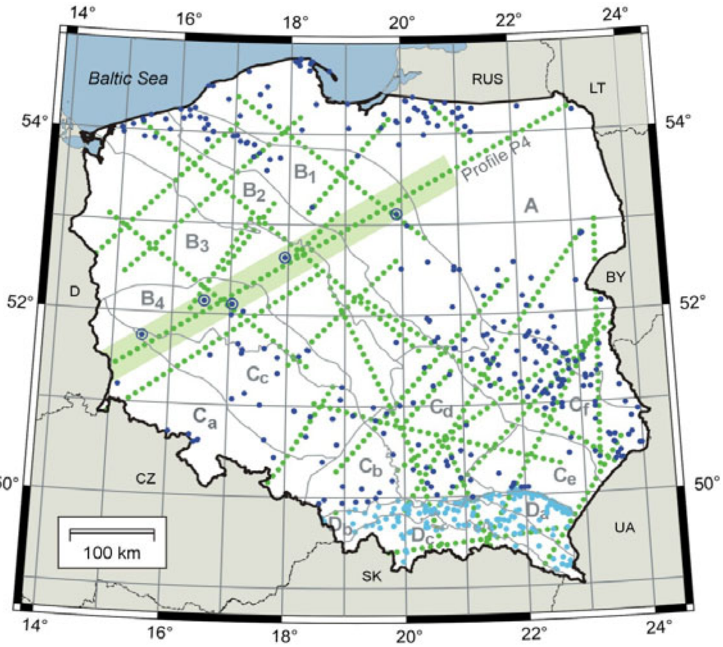

Fig. 1. Location map of boreholes used in this study on the background of the geological division of Poland (Sokołowski 1968). Dark blue dots symbolize boreholes reaching old Paleozoic outside the Carpathians, light blue dots symbolize boreholes in the Carpathians, green dots symbolize "virtual boreholes" (see text for explanation) from seismic refraction profiles, light green rectangle marks part of P4 profile from Fig. 2, blue circles marks boreholes locations shown in Fig. 2.

els for certain location among profile paths. "Virtual boreholes" can be calculated at any location on the profile and in this paper they are calculated for every 10th km of all profiles within the territory of Poland (Fig. 1). Data from "virtual boreholes" is later analyzed in the same manner as standard geological borehole with VSP (Grad and Polkowski 2012).

To keep the compatibility with previous analysis, the same division for regional and local units is taken (Sokołowski 1968). The area of Poland is divided into 4 regional units and a total of 14 local sub-units (Fig. 1) including: A – East European Craton, B – Polish Lowland (B_1 – marginal synclinorium, B_2 – Pomorze–Kujawy anticlinorium, B_3 – Szczecin–Łódź synclinorium, B_4 – northern fore-Sudetic monocline), C – Folded Area (C_a – Sudety Mts. and fore-Sudetic block, C_b – Upper Silesian block, C_c – southern fore-Sudetic monocline, C_d – Miechów synclinorium, Goleniów anticlinorium, Holy Cross anticlinorium; C_e – San elevation, C_f – Lublin synclinorium), D – Carpathians (D_a – Outer Carpathians, D_b – Silesian unit, D_c – Magura unit and Inner Carpathians).

Locations of boreholes providing velocity information for old Paleozoic sediments for East European Craton, Polish Lowland, and Folded Area, locations of boreholes providing velocity information for Carpathian sediments and locations of virtual boreholes taken for further analysis among the regional division are shown on the map in Fig. 1. As can be noted from this figure, the distribution of boreholes is not uniform. Especially, in units B_2 and B_3, where sedimentary cover is very thick, no boreholes reach the old Paleozoic sediments. Fortunately, this area is well covered with virtual boreholes due to high density of seismic profiles there.

The goal of this paper is to provide, together with previous results (Grad and Polkowski 2012), complete knowledge about velocity-depth relations for the whole area of Poland, individually for 14 separate units, for all sediments: Tertiary and Quaternary, Cretaceous, Jurassic, Triassic, Permian, old Paleozoic, and all Carpathian Sediments. All these relations can be used in the future for creating 3D model of *P*-wave velocities of entire crust in Poland, which is of great importance for studying deeper structures with different methods, including seismic tomography, surface wave inversion and receiver function. Additionally, it could be used for gravity, magnetic, and heat flow analysis.

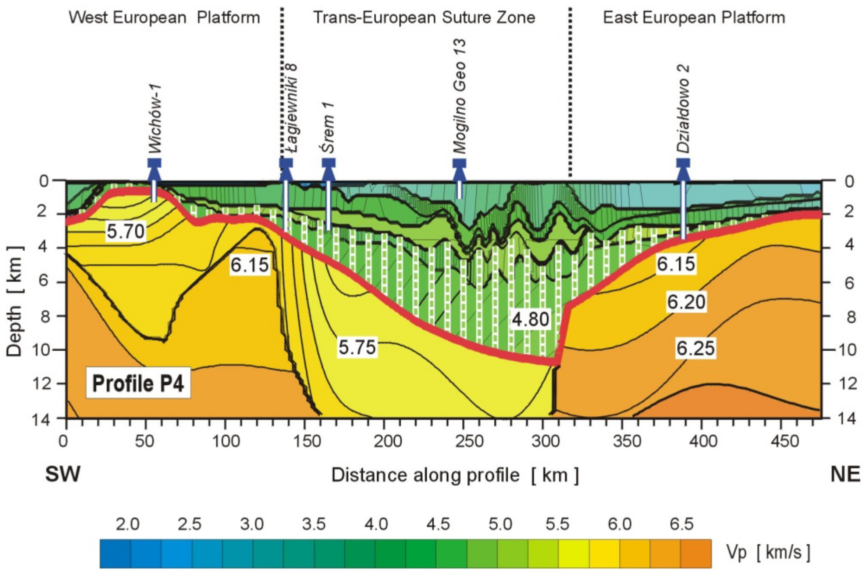

Fig. 2. Section of the upper crust beneath refraction seismic profile P4. Colors correspond to *P*-wave velocity; thick red line marks floor of sediments, white lines with borehole symbols show locations of boreholes (with depth range) located close to the profile line, green dashed lines show locations and ranges of "virtual boreholes" in the old Paleozoic sediments.

2. VSP AND REFRACTION DATA

For this study, a total of 833 554 m of vertical seismic profiles from 498 boreholes were analyzed, including 299 295 m of VSP in old Paleozoic sediments in the area of East European Craton, Polish Lowland, and Folded Area, and 534 259 m from the Carpathian Mountains (all sediments). Additionally, to cover areas and depths not reached by boreholes, 29 seismic refraction profiles were processed. To allow common processing for borehole VSP data and refraction data "virtual boreholes" are introduced. Figure 2

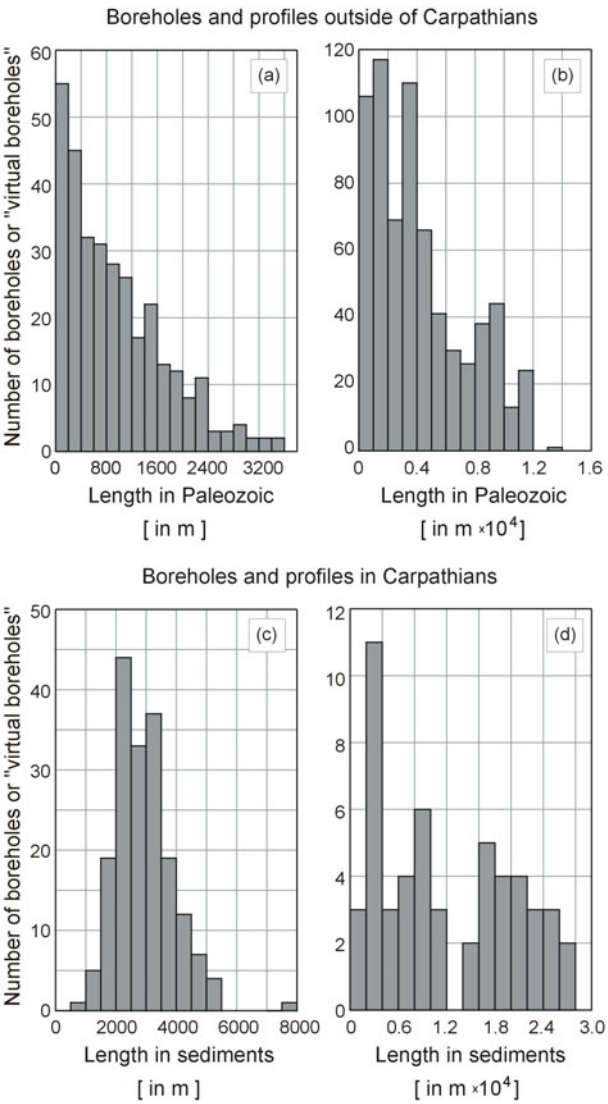

Fig. 3: (a) Distribution of borehole amount with length in the old Paleozoic sediments outside the Carpathians, $n = 316$, total length 299 295 m; (b) Distribution of "virtual borehole" amount with length in the old Paleozoic sediments outside the Carpathians, $n = 688$, total length 2 862 618 m; (c) Distribution of borehole amount with length in all Carpathian sediments, $n = 182$, total length 534 259 m; (d) Distribution of "virtual borehole" amount with length in Carpathian sediments, $n = 53$, total length 604 226 m.

presents part of refraction profile P4 with "virtual boreholes" in old Paleozoic sediments and locations with depth of geological boreholes located close to the profile path. To equalize importance of refraction and borehole data sets "virtual boreholes" are taken from profiles every 10th km 741 "virtual boreholes" are analyzed and provide 3 466 844 m of virtual VSP, including 604 226 m in the Carpathians. Figure 3 shows histograms of analyzed lengths of boreholes VSP for both standard and "virtual boreholes" separately outside the Carpathians and in the Carpathians.

Sediments in the Carpathians are well mixed, fractured, trusted, and folded, creating flysch deposits that are composed of different age rocks (Tertiary and Quaternary, Cretaceous, Jurassic). Structure of these deposits, and even older rocks, makes them very difficult to differentiate, so in this paper all Carpathian sediments are analyzed together.

To allow further analysis, all data were recalculated (interpolated) to provide velocity data with 1-m interval (Grad and Polkowski 2012) and classified to units A, B_1, B_2, B_3, B_4, C_a, C_b, C_c, C_d, C_e, C_f, D_a, D_b, D_c, and layers Tertiary and Quaternary, Cretaceous, Jurassic, Triassic, Permian, old Paleozoic, Carpathian Sediments.

3. VELOCITY–DEPTH ANALYSIS

In this paper, 17 velocity *versus* depth relations are provided, including 1 relation for the old Paleozoic sediments for the East European Craton (unit A), 4 relations for the old Paleozoic sediments in the Polish Lowland (units B_1, B_2, B_3, and B_4), 5 relations for the old Paleozoic sediments in the Folded Area (units C_a, C_b, C_c, C_d, C_e, and C_f), and 3 relations for all sediments in the Carpathians (units D_a, D_b, and D_c). Additionally, 3 relations for combined units $B_1 + B_2 + B_3$ (part of the Polish Lowland with deepest old Paleozoic sediments), $C_d + C_e + C_f$ (part of the Folded Area with deepest old Paleozoic sediments), and $D_a + D_b + D_c$ (whole Carpathians, all sediments) are presented. All relations are calculated using the same three step method (Grad and Polkowski 2012), here described briefly.

Firstly, from the whole data set containing information about depth, velocity and belongingness to layer and unit for both real and "virtual boreholes" values for requested unit and layer are selected (for example, old Paleozoic in unit B_1 or all sediments in unit D_a). In Figures 4 and 5 these are shown as thin blue (for real boreholes) and green (for "virtual boreholes") lines.

Secondly, moving averages of velocities are calculated with depth. Length of moving averages window is set to 50 m. This step is necessary to event weight of large amount of data at low depths with significantly smaller amount of data at greater depths. In Figures 4 and 5, the moving average is shown as a thick red line.

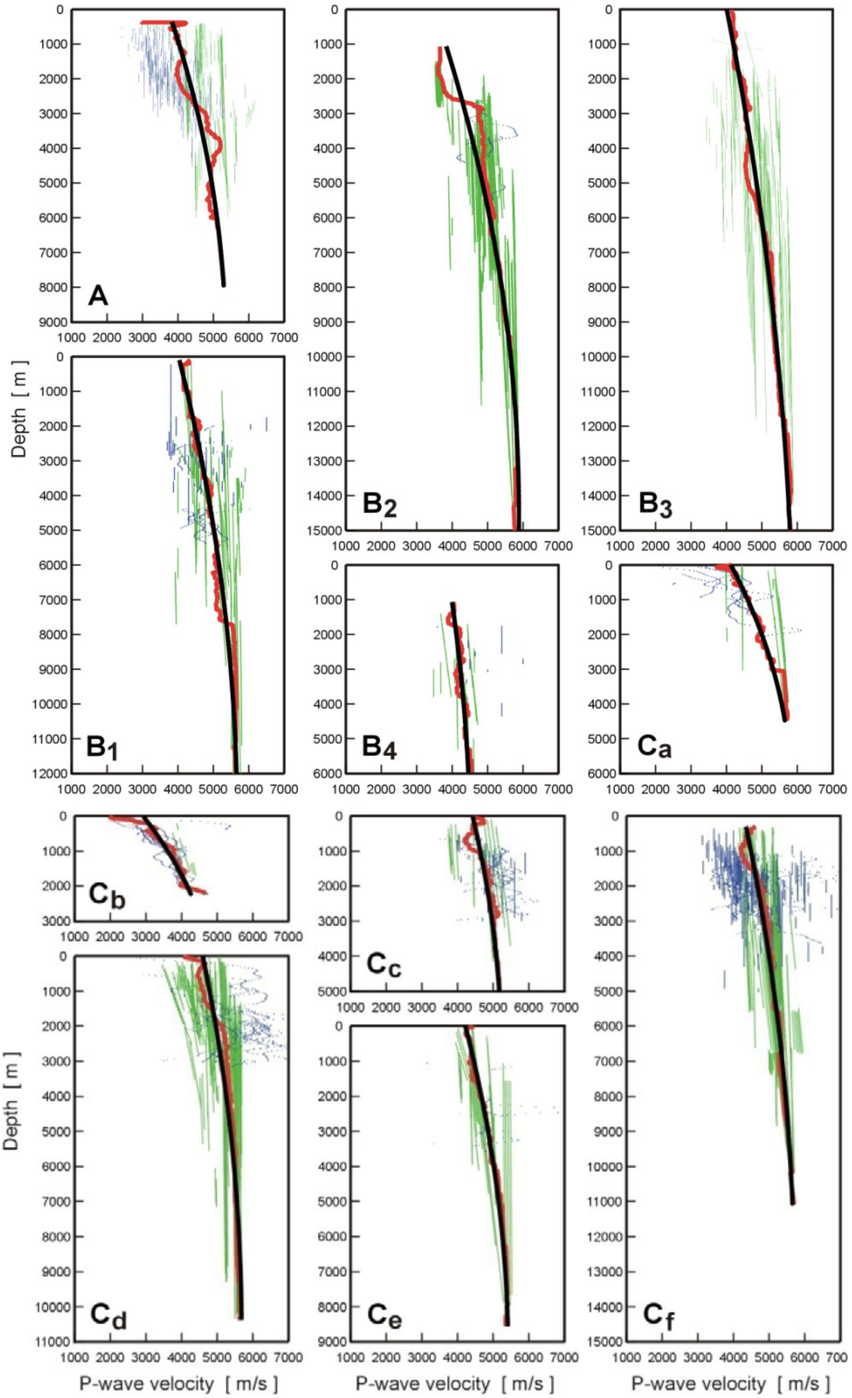

Fig. 4. Caption on next page.

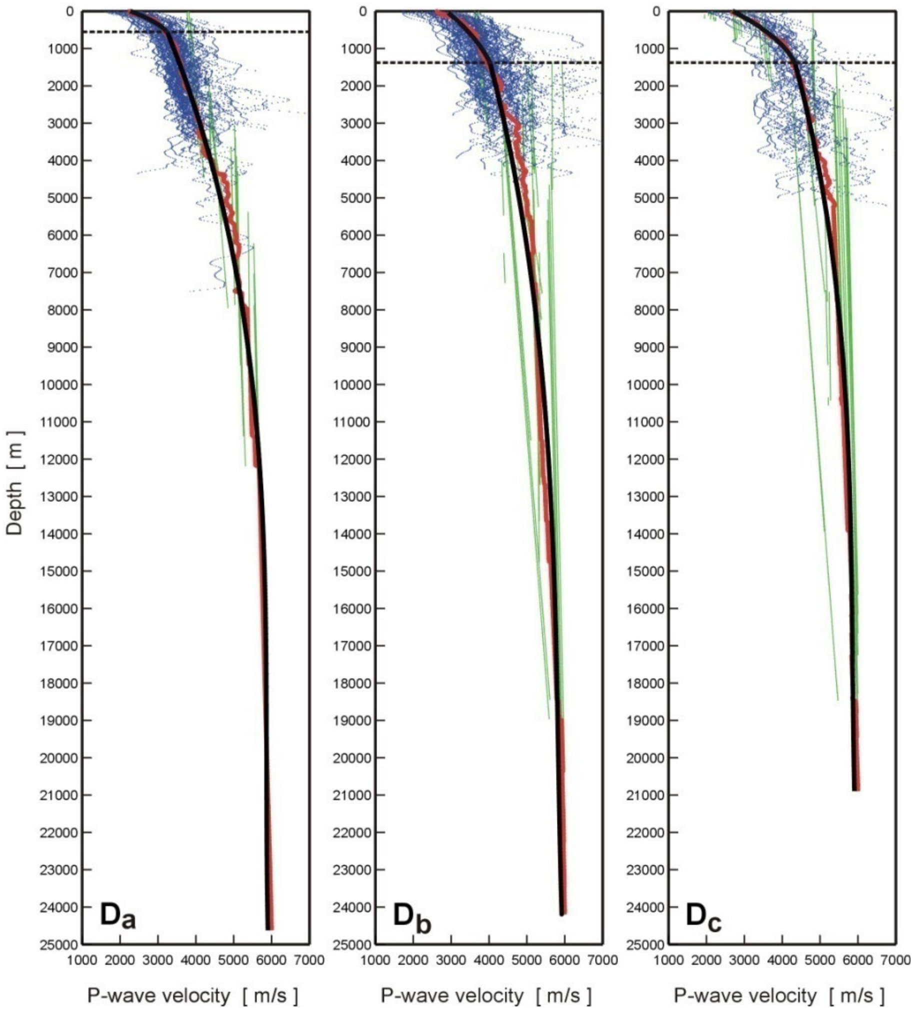

Fig. 5. *P*-wave seismic velocities for all Carpathian sediments. The dashed black line shows split between two polynomials range – see Table 1 for details. Other explanations as in Fig. 4.

Fig. 4. *P*-wave seismic velocities for the old Paleozoic sediments measured in boreholes (thin blue lines) and "virtual boreholes" (thin green lines) along with moving of velocities average with depth (thick red lines) and fitted polynomial (thick black lines). Polynomial coefficients are provided in Table 1. Division into geological units corresponds to Fig. 1. See text for more explanation.

Table 1

Velocity [m/s] – depth [m] formulas for sedimentary cover in Poland

Unit	Coefficients of $V(z) = a + bz + cz^2 + dz^3$	Depth range	Amount of data used
A	$a = (3713.91 \pm 8.17) \times 10^0$ $b = (3330.38 \pm 28.14) \times 10^{-4}$ $c = (-1696.92 \pm 20.49) \times 10^{-8}$	U: 370 m L: 7975 m	NB: 90 NR: 110 LB: 97818 m LR: 167039 m
B_1	$a = (4015.50 \pm 3.96) \times 10^0$ $b = (2454.40 \pm 10.69) \times 10^{-4}$ $c = (-908.10 \pm 6.05) \times 10^{-8}$	U: 113 m L: 12000 m	NB: 39 NR: 61 LB: 25827 m LR: 201183 m
B_2	$a = (3496.23 \pm 8.36) \times 10^0$ $b = (3276.80 \pm 18.12) \times 10^{-4}$ $c = (-1123.87 \pm 8.38) \times 10^{-8}$	U: 1074 m L: 15000 m	NB: 11 NR: 97 LB: 3455 m LR: 733880 m
B_3	$a = (4008.77 \pm 3.36) \times 10^0$ $b = (1926.90 \pm 7.71) \times 10^{-4}$ $c = (-492.01 \pm 3.72) \times 10^{-8}$	U: 17 m L: 15083 m	NB: 2 NR: 111 LB: 1070 m LR: 599516 m
B_4	$a = (3835.62 \pm 5.53) \times 10^0$ $b = (1597.08 \pm 20.18) \times 10^{-4}$ $c = (-939.99 \pm 15.95) \times 10^{-8}$	U: 1074 m L: 6299 m	NB: 10 NR: 41 LB: 2315 m LR: 39481 m
C_a	$a = (4124.86 \pm 6.49) \times 10^0$ $b = (5142.60 \pm 31.59) \times 10^{-4}$ $c = (-389.17 \pm 3.22) \times 10^{-7}$	U: 0 m L: 4486 m	NB: 8 NR: 18 LB: 6861 m LR: 28306 m
C_b	$a = (2917.78 \pm 12.24) \times 10^0$ $b = (777.71 \pm 7.78) \times 10^{-3}$ $c = (-798.76 \pm 10.38) \times 10^{-7}$	U: 24 m L: 2239 m	NB: 11 NR: 7 LB: 10199 m LR: 3530 m
C_c	$a = (4422.02 \pm 5.45) \times 10^0$ $b = (2309.69 \pm 24.60) \times 10^{-4}$ $c = (-1627.97 \pm 23.29) \times 10^{-8}$	U: 31 m L: 5200 m	NB: 22 NR: 26 LB: 19890 m LR: 56098 m
C_d	$a = (4592.94 \pm 4.85) \times 10^0$ $b = (2026.58 \pm 14.56) \times 10^{-4}$ $c = (-939.73 \pm 9.16) \times 10^{-8}$	U: 0 m L: 10382 m	NB: 27 NR: 100 LB: 16854 m LR: 531541 m
C_e	$a = (42180.95 \pm 29.76) \times 10^{-1}$ $b = (2520.55 \pm 10.14) \times 10^{-4}$ $c = (-1314.63 \pm 7.24) \times 10^{-8}$	U: 0 m L: 8557 m	NB: 13 NR: 26 LB: 1430 m LR: 105376 m

to be continued

Table 1 (continuation)

Unit	Coefficients of $V(z) = a + bz + cz^2 + dz^3$	Depth range	Amount of data used
C_f	$a = (4288.87 \pm 3.55) \times 10^0$ $b = (2077.59 \pm 9.96) \times 10^{-4}$ $c = (-762.90 \pm 5.89) \times 10^{-8}$	U: 310 m L: 11089 m	NB: 83 NR: 79 LB: 113576 m LR: 396668 m
D_a	$a = (2276.41 \pm 11.40) \times 10^0$ $b = (261.32 \pm 5.85) \times 10^{-2}$ $c = (-158.23 \pm 6.29) \times 10^{-5}$	U: 0 m L: 565 m	NB: 72 NR: 10 LB: 213734 m LR: 118150 m
	$a = (3016.23 \pm 4.35) \times 10^0$ $b = (4220.82 \pm 12.72) \times 10^{-4}$ $c = (-2088.78 \pm 9.98) \times 10^{-8}$ $d = (3454.46 \pm 22.16) \times 10^{-13}$	U: 566 m L: 24620 m	
D_b	$a = (2877.34 \pm 12.93) \times 10^0$ $b = (1191.07 \pm 29.85) \times 10^{-3}$ $c = (-261.42 \pm 14.45) \times 10^{-6}$	U: 0 m L: 1385 m	NB: 82 NR: 21 LB: 221191 m LR: 209400 m
	$a = (3648.06 \pm 6.53) \times 10^0$ $b = (2909.68 \pm 19.36) \times 10^{-4}$ $c = (-1361.34 \pm 15.41) \times 10^{-8}$ $d = (225.89 \pm 3.47) \times 10^{-12}$	U: 1386 m L: 24198 m	
D_c	$a = (2706.20 \pm 7.28) \times 10^0$ $b = (1871.75 \pm 16.80) \times 10^{-3}$ $c = (-501.60 \pm 8.13) \times 10^{-6}$	U: 0 m L: 1379 m	NB: 28 NR: 22 LB: 99334 m LR: 276676 m
	$a = (3936.66 \pm 5.38) \times 10^0$ $b = (3110.79 \pm 17.30) \times 10^{-4}$ $c = (-1729.00 \pm 15.07) \times 10^{-8}$ $d = (330.72 \pm 3.76) \times 10^{-12}$	U: 1380 m L: 20891 m	
B_1 B_2 B_3	$a = (3903.84 \pm 3.58) \times 10^0$ $b = (2330.96 \pm 8.24) \times 10^{-4}$ $c = (-688.49 \pm 3.97) \times 10^{-8}$	U: 17 m L: 15083 m	NB: 52 NR: 269 LB: 30352 m LR: 1534579 m
C_d C_e C_f	$a = (44291.22 \pm 30.41) \times 10^{-1}$ $b = (2015.43 \pm 8.73) \times 10^{-4}$ $c = (-792.44 \pm 5.25) \times 10^{-8}$	U: 0 m L: 11089 m	NB: 123 NR: 205 LB: 131860 m LR: 1033585 m
D_a D_b D_c	$a = (3797.94 \pm 5.63) \times 10^0$ $b = (2741.71 \pm 14.79) \times 10^{-4}$ $c = (-1233.88 \pm 10.76) \times 10^{-8}$ $d = (1925.83 \pm 22.79) \times 10^{-13}$	U: 1500 m L: 24620 m	NB: 182 NR: 53 LB: 534259 m LR: 604226 m

Explanations: U – upper depth limit of function domain, L – lower depth limit of function domain, NB – number of boreholes in the unit, NR – number of virtual boreholes in the unit, LB – total length of boreholes in the unit, LR – total length of virtual boreholes in the unit. Last 3 relations are given for combined units $B_1 + B_2 + B_3$ (part of the Polish Lowland with deepest old–Paleozoic sediments), $C_d + C_e + C_f$ (part of the Folded Area with deepest old Paleozoic sediments), and $D_a + D_b + D_c$ (whole Carpathians, all sediments).

Lastly, the final velocity *versus* depth formulas is calculated by fitting polynomials to moving averages. For the area of East European Craton, Polish Lowland, and Folded Area, second order polynomials are used. For the Carpathians where total thickness of sediments exceeds 20 000 m and all sediments are analyzed, two polynomials are introduced to better fit data at full depth range: second order for 500-1500 m of sub surface sediments, and third order for deeper sediments. Both polynomials are intersecting, so the overall result is a continuous function, but not a smooth function. In Figures 4 and 5 velocity *versus* depth result polynomials are shown as thick black lines. All polynomials and their coefficients are given in Table 1.

Note that depth values increase downward and zero corresponds to terrain level.

Figure 4 shows data and analysis results for the old Paleozoic sediments in the East European Craton, Polish Lowland, and Folded Area, while Fig. 5 shows the data and analysis results for the Carpathian sediments.

In areas of the East European Craton, the Polish Lowland, and the Folded Area *P*-wave seismic velocities in the old Paleozoic sediments increase slowly with depth, reaching up to 5500-6000 m/s at depths of 8000-11 000 m. Calculated moving averages are smooth and second order polynomials fit them very well. The largest velocity increase with depth can be observed in unit C_b, where the old Paleozoic sediments reach only the 2500 m depth.

In the Carpathians, where all the sediments are analyzed, a significant increase of velocity with depth, from about 2000 m/s at the surface to about 4500 m/s at 1000 m depth is observed. For deeper sediments, velocity increases slower with depth and for depths over 15 000 m the speed remains almost constant, not exceeding 6000 m/s.

4. SUMMARY AND CONCLUSION

Velocity *versus* depth formulas presented in this and previous paper (Grad and Polkowski 2012) provide full knowledge of *P*-wave velocities in the whole sedimentary cover in Poland. In this paper, VSP data was combined with seismic refraction profiles data to provide velocity *versus* depth relations for the old Paleozoic sediments in the area of East European Craton, Polish Lowland and Folded Area, and for all Carpathian sediments. Thickness of sediments in Poland reaches up to about 25 000 m, but *P*-wave velocities do not exceed 6000 m/s, making knowledge about seismic velocities in sediments very important.

To provide verification of the presented results, velocity *versus* depth relations for combined units $B_1 + B_2 + B_3$ (part of the Polish Lowland with deepest old Paleozoic sediments), $C_d + C_e + C_f$ (part of the Folded Area with deepest old Paleozoic sediments), and $D_a + D_b + D_c$ (whole Carpathians, all sediments) were calculated and compared to similar studies from other deep sedimentary basins: the Baikal Southern Basin and the Southernwest Siberia (Suvorov and Mishen'kina 2005), the German Basin and the North Sea

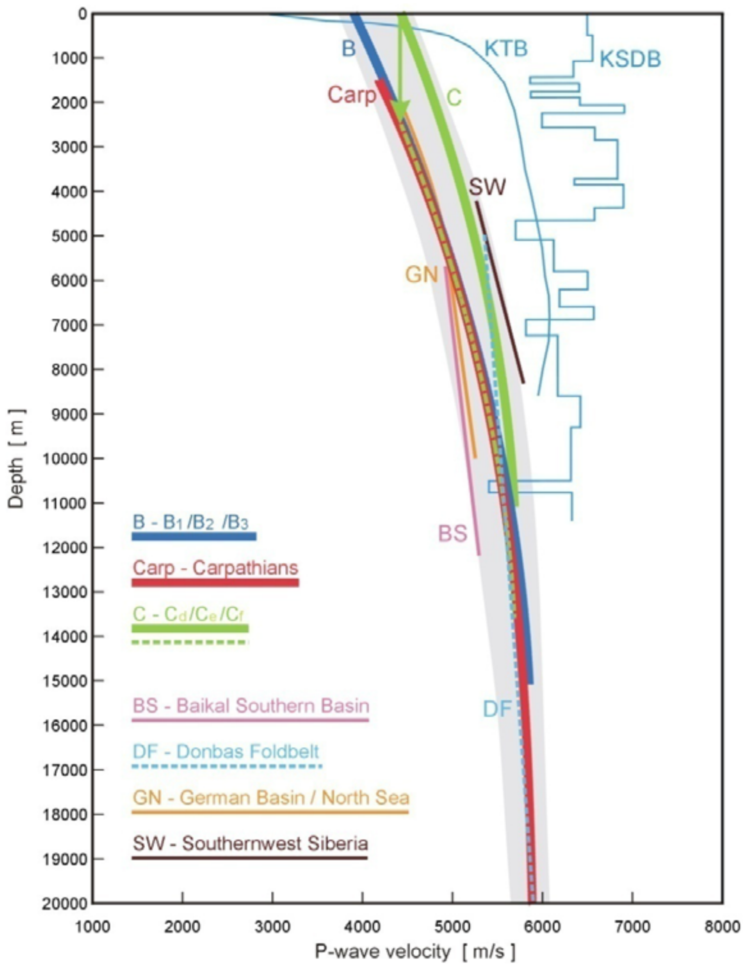

Fig. 6. Comparison of results for combined units $B_1 + B_2 + B_3$ (part of the Polish Lowland with deepest old Paleozoic sediments, thick blue line), $C_d + C_e + C_f$ (part of the Folded Area with deepest old Paleozoic sediments, thick green line), and $D_a + D_b + D_c$ (whole Carpathians, all sediments, thick red line) with similar studies from other deep sedimentary basins: the Baikal Southern Basin, and the Southernwest Siberia (Suvorov and Mishen'kina 2005), the German Basin and the North Sea Basin (Nielsen *et al.* 2005), the Donbas Foldbelt (Grad *et al.* 2003b), and two deep boreholes: Kola Superdeep Borehole (KSDB) in Kola Peninsula in north-eastern Russia and Kontinentales Tiefbohrprogramm Borehole (KTB) from Germany (Smithson *et al.* 2000).

Basin (Nielsen *et al.* 2005), and the Donbas Foldbelt (Grad *et al.* 2003b). All these results show some similarities: velocities are ±300 m/s with similar velocity gradients in the whole depth range. Additionally, two deep boreholes: Kola Superdeep Borehole (KSDB) in Kola Peninsula in northeastern Russia and Kontinentales Tiefbohrprogramm Borehole (KTB) from Germany (Smithson *et al.* 2000) are compared to results from this paper. The KSDB borehole is drilled through *ca.* 12 000 m of the Precambrian rocks including *ca.* 7000 m of the Proterozoic supracrustal rocks and *ca.* 5000 m of the Archean gneisses, while KTB is located in a terrain of Hercynian metamorphic rocks in southern Germany and reaches over 9000 m deep. Because of that, velocities in those boreholes are much bigger than velocities in the sediments in Poland. All comparisons are presented in Fig. 6.

Comparison of the velocity *versus* depth relations for combined units can lead to an interesting observation: the velocity-depth relation for part of the Folded Area ($C_d + C_e + C_f$) is shifted by *ca.* 2500 m in relation to two other combined units ($B_1 + B_2 + B_3$, $D_a + D_b + D_c$), which are almost identical. This shift might be a result of an uplift of this area in tectonic history. Material might have been deposited deeper and later, after it was compacted, the whole area might have been uplifted so now it has characteristic velocities for deeper sediments. Scherbaum (1982) made similar observation in Germany. This effect might also be a result of local anisotropy between vertical velocity (to which VPS measurements are sensitive) and horizontal velocity (measured by refraction). This could be a very interesting topic for further analysis.

Acknowledgments. The VSP data collected in the 1980s are from the Archives of the PBG Geophysical Exploration; more recent data are from the Central Geological Archives. The public domain GMT software (Wessel and Smith 1998, Wessel *et al.* 2013) has been used to produce map in Fig. 1. National Science Centre Poland provided financial support for this work by NCN grant DEC-2011/02/A/ST10/00284.

References

Berthelsen, A. (1992), From Precambrian to Variscan Europe. **In:** D. Blundell, R. Freeman, and S. Mueller (eds.), *A Continent Revealed – The European Geotraverse*, Cambridge University Press, Cambridge, 153-164.

Berthelsen, A. (1998), The Tornquist Zone northwest of the Carpathians: An intraplate pseudosuture, *GFF* **120**, 2, 223-230, DOI: 10.1080/11035899801202223.

Czuba, W., M. Grad, U. Luosto, G. Motuza, V. Nasedkin, and POLONAISE P5 Working Group (2001), Crustal structure of the East European Craton along the POLONAISE '97 P5 profile, *Acta Geophys. Pol.* **49**, 2, 145-168.

Czuba, W., M. Grad, U. Luosto, G. Motuza, V. Nasedkin, and POLONAISE P5 Working Group (2002), Upper crustal seismic structure of the Mazury complex and Mazowsze massif within East European Craton in NE Poland, *Tectonophysics* **360**, 1-4, 115-128, DOI: 10.1016/S0040-1951(02)00352-9.

Grad, M., and M. Polkowski (2012), Seismic wave velocities in the sedimentary cover of Poland: Borehole data compilation, *Acta Geophys.* **60**, 4, 985-1006, DOI: 10.2478/s11600-012-0022-z.

Grad, M., T. Trung Doan, and W. Klimkowski (1990), Seismic models of sedimentary cover of the Precambrian and Palaeozoic Platforms in Poland, *Kwart. Geol.* **34**, 2, 393-410 (in Polish).

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

Grad, M., T. Janik, J. Yliniemi, A. Guterch, U. Luosto, T. Tiira, K. Komminaho, P. Środa, K. Höing, J. Makris, and C.E. Lund (1999), Crustal structure of the Mid-Polish Trough beneath the Teisseyre-Tornquist Zone seismic profile, *Tectonophysics* **314**, 1-3, 145-160, DOI: 10.1016/S0040-1951(99) 00241-3.

Grad, M., S.L. Jensen, G.R. Keller, A. Guterch, H. Thybo, T. Janik, T. Tiira, J. Yliniemi, U. Luosto, G. Motuza, V. Nasedkin, W. Czuba, E. Gaczyński, P. Środa, K.C. Miller, M. Wilde-Piórko, K. Komminaho, J. Jacyna, and L. Korabliova (2003a), Crustal structure of the Trans-European suture zone region along POLONAISE'97 seismic profile P4, *J. Geophys. Res.* **108**, B11, 2541, DOI: 10.1029/2003JB002426.

Grad, M., D. Gryn, A. Guterch, T. Janik, R. Keller, R. Lang, S.B. Lyngsie, V. Omelchenko, V.I. Starostenko, R.A. Stephenson, S.M. Stovba, H. Thybo, and A. Tolkunov (2003b), DOBREfraction'99 – velocity model of the crust and upper mantle beneath the Donbas Foldbelt (East Ukraine), *Tectonophysics* **371**, 1-4, 81-110, DOI: 10.1016/S0040-1951(03)00211-7.

Grad, M., A. Špičák, G.R. Keller, A. Guterch, M. Brož, E. Hegedűs, and SUDETES 2003 Working Group (2003c), SUDETES 2003 seismic experiment, *Stud. Geophys. Geod.* **47**, 3, 681-689, DOI: 10.1023/A:1024732206210.

Grad, M., A. Guterch, and A. Polkowska-Purys (2005), Crustal structure of the Trans-European Suture Zone in Central Poland – reinterpretation of the LT-2, LT-4 and LT-5 deep seismic sounding profiles, *Geol. Quart.* **49**, 3, 243-252.

Grad, M., A. Guterch, G.R. Keller, T. Janik, E. Hegedűs, J. Vozár, A. Ślączka, T. Tiira, and J. Yliniemi (2006), Lithospheric structure beneath trans-Carpathian transect from Precambrian platform to Pannonian basin:

CELEBRATION 2000 seismic profile CEL05, *J. Geophys. Res.* **111**, B3, B03301, DOI: 10.1029/2005JB003647.

Grad, M., A. Guterch, S. Mazur, G.R. Keller, A. Špičák, P. Hrubcová, and W.H. Geissler (2008), Lithospheric structure of the Bohemian Massif and adjacent Variscan belt in central Europe based on profile S01 from the SUDETES 2003 experiment, *J. Geophys. Res.* **113**, B10, B10304, DOI: 10.1029/2007JB005497.

Grad, M., E. Brückl, M. Majdański, M. Behm, A. Guterch, CELEBRATION 2000 Working Group, and ALP 2002 Working Group (2009), Crustal structure of the Eastern Alps and their foreland: Seismic model beneath the CEL10/Alp04 profile and tectonic implications, *Geophys. J. Int.* **177**, 1, 279-295, DOI: 10.1111/j.1365-246X.2008.04074.x.

Guterch, A., M. Grad, T. Janik, R. Materzok, U. Luosto, J. Yliniemi, E. Lück, A. Schulze, and K. Förste (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 II* **319**, 12, 1489-1496.

Guterch, A., M. Grad, H. Thybo, G.R. Keller, and POLONAISE Working Group (1999), POLONAISE '97 — an international seismic experiment between Precambrian and Variscan Europe in Poland, *Tectonophysics* **314**, 1-3, 101-121, DOI: 10.1016/S0040-1951(99)00239-5.

Guterch, A., M. Grad, G.R. Keller, K. Posgay, J. Vozár, A. Špičák, E. Brückl, Z. Hajnal, H. Thybo, O. Selvi, and CELEBRATION 2000 Experiment Team (2003), CELEBRATION 2000 seismic experiment, *Stud. Geophys. Geod.* **47**, 3. 659-669, DOI: 10.1023/A:1024728005301.

Janik, T., J. Yliniemi, M. Grad, H. Thybo, T. Tiira, and POLONAISE P2 Working Group (2002), Crustal structure across the TESZ along POLONAISE'97 seismic profile P2 in NW Poland, *Tectonophysics* **360**, 1-4, 129-152, DOI: 10.1016/S0040-1951(02)00353-0.

Janik, T., M. Grad, A. Guterch, R. Dadlez, J. Yliniemi, T. Tiira, G.R. Keller, E. Gaczyński, and CELEBRATION 2000 Working Group (2005), Lithospheric structure of the Trans-European Suture Zone along the TTZ-CEL03 seismic transect (from NW to SE Poland), *Tectonophysics* **411**, 1-4, 129-156, DOI: 10.1016/j.tecto.2005.09.005.

Janik, T., M. Grad, A. Guterch, 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.

Janik, T., M. Grad, A. Guterch, J. Vozár, M. Bielik, A. Vozárova, E. Hegedűs, C.A. Kovács, I. Kovács, G.R. Keller, and CELEBRATION 2000 Working Group (2011), Crustal structure of the Western Carpathians and Pannonian Basin: Seismic models from CELEBRATION 2000 data and geological implications, *J. Geodyn.* **52**, 2, 97-113, DOI: 10.1016/j.jog.2010.12.002.

Jansen, S.L., T. Janik, H. Thybo, and POLONAISE Profile P1 Working Group (1999), Seismic structure of the Palaeozoic Platform along POLONAISE'97 profile P1 in northwestern Poland, *Tectonophysics* **314**, 1-3, 123-143, DOI: 10.1016/S0040-1951(99)00240-1.

Majdański, M., M. Grad, A. Guterch, and SUDETES 2003 Working Group (2006), 2-D seismic tomographic and ray tracing modelling of the crustal structure across the Sudetes Mountains basing on SUDETES 2003 experiment data, *Tectonophysics* **413**, 3-4, 249-269, DOI: 10.1016/j.tecto.2005.10.042.

Malinowski, M., A. Żelaźniewicz, M. Grad, A. Guterch, T. Janik, and CELEBRATION Working Group (2005), Seismic and geological structure of the crust in the transition from Baltica to Palaeozoic Europe in SE Poland – CELEBRATION 2000 experiment, profile CEL02, *Tectonophysics* **401**, 1-2, 55-77, DOI: 10.1016/j.tecto.2005.03.011.

Moryc, W., and K. Łydka (2000), Sedimentation and tectonics of the Upper Proterozoic-Lower Cambrian deposits of the southern Małopolska Massif (SE Poland), *Geol. Quart.* **44**, 1, 47-58.

Nielsen, L., H. Thybo, and M. Glendrup (2005), Seismic tomographic interpretation of Paleozoic sedimentary sequences in the southeastern North Sea, *Geophysics* **70**, 4, R45-R56, DOI: 10.1190/1.1996908.

Pożaryski, W., W. Brochwicz-Lewiński, and H. Tomczyk (1982), Sur la caractére hétérochronique de la Ligne Teisseyre-Tornquist, entre Europe centrale et orientale, *C. R. Acad. Sci. Paris II* **295**, 691-696 (in French).

Scherbaum, F. (1982), Seismic velocities in sedimentary rocks – indicators of subsidence and uplift?, *Geol. Rundsch.* **71**, 2, 519-536, DOI: 10.1007/BF01822381.

Skorupa, J. (1974), Seismic velocity map of Poland 1:500000, Wyd. Geol., Warszawa.

Smithson, S.B., F. Wenzel, Y.V. Ganchin, and I.B. Morozov (2000), Seismic results at Kola and KTB deep scientific boreholes: velocities, reflections, fluids, and crustal composition, *Tectonophysics* **329**, 1-4, 301-317, DOI: 10.1016/S0040-1951(00)00200-6.

Sokołowski, J. (1968), Geology and structure of the regional units of Poland from the point of view oil exploration. **In:** J. Biernat (ed.), *Surowce Mineralne*, Vol. 1, 7-58 (in Polish).

Suvorov, V.D., and Z.R. Mishen'kina (2005), Structure of sedimentary cover and basement beneath the South Basin of Lake Baikal inferred from seismic profiling, *Russ. Geol. Geophys.* **46**, 11, 1141-1149.

Środa, P., and POLONAISE Profile P3 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**, 1-3, 175-192, DOI: 10.1016/S0040-1951(99)00243-7.

Środa, P., W. Czuba, M. Grad, A. Guterch, A.K. Tokarski, T. Janik, M. Rauch, G.R. Keller, E. Hegedűs, J. Vozár, and CELEBRATION 2000 Working

Group (2006), Crustal and upper mantle structure of the Western Carpathians from CELEBRATION 2000 profiles CEL01 and CEL04: seismic models and geological implications, *Geophys. J. Int.* **167**, 2, 737-760, DOI: 10.1111/j.1365-246X.2006.03104.x.

Wessel, P., and W.H.F. Smith (1998), New, improved version of Generic Mapping Tools released, *Eos Trans. AGU* **79**, 47, 579, DOI: 10.1029/98EO00426.

Wessel, P., W.H.F. Smith, R. Scharroo, J. Luis, and F. Wobbe (2013), Generic Mapping Tools: Improved version released, *EOS Trans. AGU* **94**, 45, 409-420, DOI: 10.1002/2013EO450001.

Znosko, J. (1975), Tectonic units of Poland against the background of the tectonics of Europe, *Geol. Inst. Anniv. Bull.* **252**, 61-75.

Znosko, J. (1979), Teisseyre-Tornquist tectonic zone: some interpretative implications of recent geological and geophysical investigations, *Acta Geol. Pol.* **29**, 4, 365-382.

Received 11 July 2014
Received in revised form 24 September 2014
Accepted 26 September 2014