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Deep reflection seismic experiments in western Poland

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The paper presents the interpretation of a composite seismic profile recorded to 18 s TWT which crosses western Poland from the south to north. The interpretation is based on data along the profiles GB-2, GB-2B-96 and 25-III-82 collected between 1987 and 1996. Two reflection horizons bordering the crystalline crust have been recognized: in the top — **SK**, and in the base (Moho — **M**). The Caledonian complex is distinguished in the northern part of the profile GB-2 north of the Dolsk Zone. The results obtained allow determination of crustal structure down to the Moho. Several deep fault zones have been delimited (in the regions of Dolsk, Szamotuły and Trans-European Fault) which cut the entire crust. Crustal thickness ranges from approximately 30 km in the Palaeozoic platform up to about 40 km along the Trans-European Suture Zone.

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INTRODUCTION

Reflection surveys of extended record length provide information on deep crustal structure. Published results from international projects include, for example, from Canada (Jackson *et al.*, 1998) and, from Europe (DEKORP-BASIN Research Group, 1999). The latter paper shows the results of seismic surveys and their geological interpretation from an area immediately west of Poland.

Deep seismic surveys (DSS) in Poland were initiated by the Geological Institute in the mid-eighties. Their record quality was variable. Despite equivocal interpretations, it seems useful to show the results and images of deep geological structure image thus acquired. The middle and northern part of the seismic line (Fig. 1) that includes the profiles GB-2 (profiles 2-I-92/93, 2-III-87, 2-I-92), GB-2B-96 and 25-III-82 is a southerly continuation of the profile GB-2A which was discussed in a separate paper (Cwojdziński, *et al.*, 1995).

All the profiles, except 25-III-82, were carried out using methods which allowed acquisition of records up to 18 s TWT. Profile 25-III-82 was produced during Permian-Mesozoic investigations, but with extended record length. Geophysical and geological interpretations carried out using FOCUS software refers to the profile GB-2B-96.

Future regional, seismic and borehole studies should focus on achieving closer correlation between the Polish profiles and results of regional seismic experiments performed by the DEKORP Consortium, in particular for the recent profiles PQ2-005 and PQ2-002 (DEKORP-BASIN Research Group, 1998), and the profile Basin 9601 (DEKORP-BASIN Research Group, 1999).

GEOLOGICAL BACKGROUND

The seismic profile discussed crosses western Poland from the south to north. The tectonics of this area has been studied by numerous boreholes and by a dense network of reflection seismic profiles down to the base of the Zechstein only. The Permian-Mesozoic structural complex is composed of the Precambrian Platform sedimentary cover in the north, the Fore-Sudetic Monocline superimposed on folded Variscan complexes in the south, and the Mid-Polish Trough (MPT) of poorly explored basement. The Mid-Polish Swell (MPS) was formed along the axis of the MPT by tectonic inversion around the Cretaceous and Tertiary boundary. The deeper geological structure is less well known, particularly in its middle part where the base of the Zechstein has not been reached by boreholes. In the northeast, folded Ordovician and Silurian rocks have been encountered.

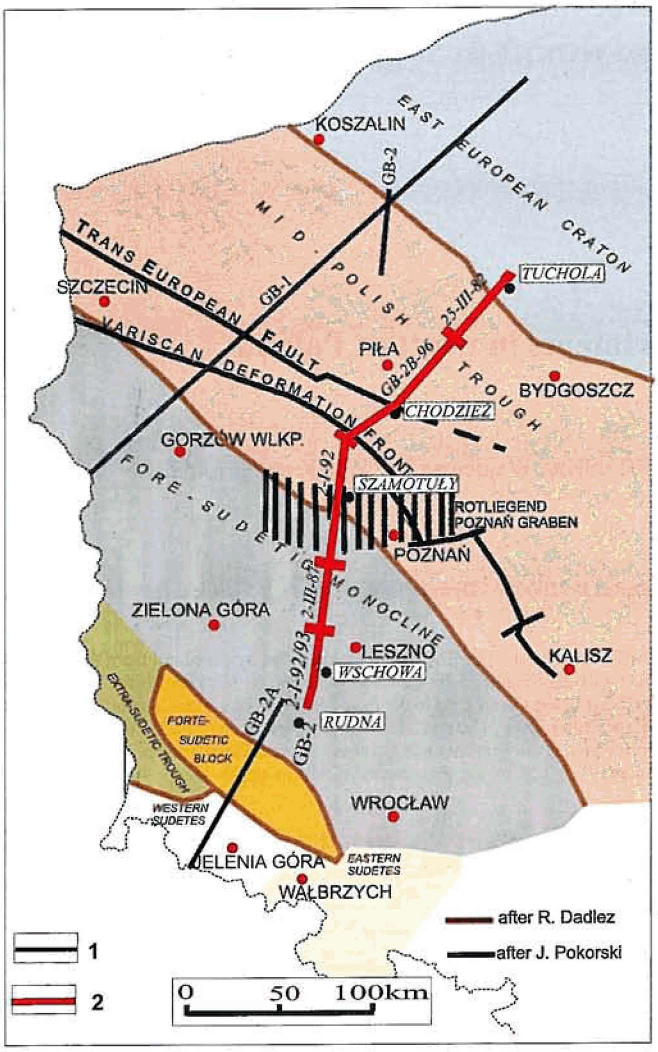

Fig. 1. Location sketch-map of deep seismic profiles

1 — deep seismic profiles not interpreted in this study, 2 — interpreted profiles

They are covered with Devonian and Carboniferous platform deposits. In the south-west, immediately beneath the Permian, folded Carboniferous deposits occur.

Deep seismic soundings (DSS — Guterch *et al.,* 1986, 1994) revealed a subdivision of this area into three crustal blocks: in the north — an elevated block of the East European Craton with a three-layered crust; in the south — the Variscan Block with a two-layered crust; and in the middle — a block of unidentified origin with a three-layered crust. The two lower layers show an affinity to the two lower layers of the cratonic crust, but they are thinner. The upper layer has anomalously low V_g values of 5.8–5.9 km/s. The southwestern boundary of the elevated region of the craton is the Teisseyre-Tornquist line (zone). The middle belt has recently been called the Trans-European Suture Zone (TESZ). The middle and southern blocks are usually jointly named the Palaeozoic platform. While the geotectonic position of the northern and southern blocks is beyond doubt, the middle block of the crust is variably interpreted: (1) as a Caledonian fold and thrust belt (Berthelsen, 1992); (2) as a strongly downfaulted marginal zone of the craton with a highly modified crust (Berthelsen, 1998); (3) as a mozaic of tectonostratigraphic terranes, either of exotic origin (Pożaryski, 1991; Franke, 1994; Aleksandrowski, 1998) or proximal in nature (Dadlez, in press).

The profiles run from the north to west from the Sudetes, across the Fore-Sudetic Monocline and Szczecin Trough, and then turn north-east towards the East European Platform.

SOURCE DATA AND RESEARCH METHODS

The Rudna–Tuchola profile consists of sections carried out in the years 1982–1996. There are five sections: 2-I-92/93, 2-III-87, 2-I-92, GB-2B-96 and 25-III-82 (Fig. 1). In the southern and middle part of the profile (Rudna–Wschowa–Szamotuły) the sections are located on the Fore-Sudetic Monocline. The profiles along the Szamotuły–Chodzież–Tuchola line are situated on the Palaeozoic platform within the Piła Block. In its northeastern part the profile crosses the Koszalin–Chojnice Zone and enters the East European Platform area.

Basic fieldwork parameters were as follows: distance between channels = 50 m, minimum offset = 200 m, maximum offset = 6150 m (5950+200). The record time was 18 s with a sample interval of 2 miliseconds. Coverage was sixty-fold, to a maximum. The seismic source was dynamite, though along the profile GB-2B-96, in areas threatened by permanent hydrostatic unbalancing, vibroseis was used. Depths of shot points were 15–30 m, and the mean explosive charge at shotpoint was of 22.8 kg.

The topography of the areas crossed by the seismic profiles is varied, affecting the final quality of the results. An irregular stacking chart and the use of many replacement spreads unfavourably influenced the wave image record.

Data processing, carried out in the Department of Geophysics of the Polish Geological Institute using SPARC station 2 hardware and CogniSeis FOCUS software proceeded in the following stages: data preparation and input, demultiplex, filtration using notch filter 50 Hz, spherical divergence compensation, editing, static corrections, filtration F-K, equalization and scaling, common-depth-point sorting, velocity analyses every 2.5 km, dynamic corrections, muting varying along the line, common-depth-point stack, band pass filtering varying through time, coherent detection, equalization, dekonvolution F-X, scaling and time-depth conversion. The time-depth conversion problem required the construction of a velocity model. In order to attain this, complex velocities along the interpreted profiles were determined. For sedimentary rocks, complex velocities were calculated on the basis of mean velocities measured in boreholes located both on the profile and in the immediate proximity. Those were boreholes drilled in the regions of Niechlów, Ujazd, Grodzisk, Zabartowo and Chojnice, in particular these exceeding 3000 m in depth: Siekówko 1, Bukowiec 2, Rudnik 1, Bródki 3, Podrzewie 2, Zabartowo 1, Tuchola IG 1 and Nicponie 1.

In order to determine the velocity model for deeper-lying layers, published data from DSS profiles (deep seismic

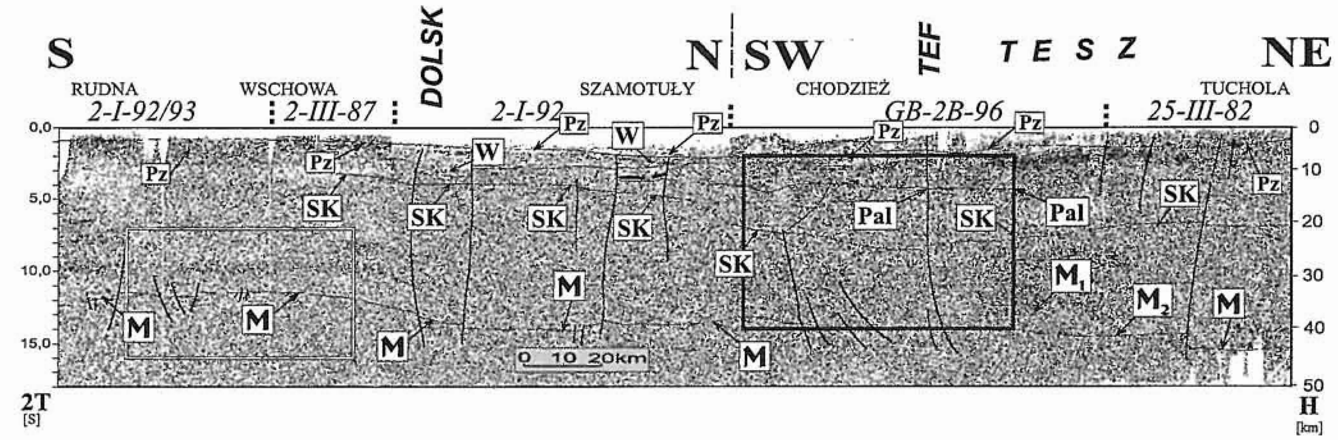

Fig. 2. Time seismic section Rudna–Tuchola

M — Moho (**M_1** — reflectors associated with the base of crust, **M_2** — reflectors in the upper mantle), **SK** — top of the crystalline crust, **W** — base of the Variscides, **Pal** — base of the lower part of the platform cover — Upper Palaeozoic, **Pz** — base of the upper part of the platform cover — Zechstein and Mesozoic; TEF — Trans-European Fault; TESZ — Trans-European Suture Zone; white rectangle — segment shown in Fig. 3; black rectangle — segment shown in Fig. 4

soundings) were used (Guterch *et al.*, 1975) and the velocity models to a depth of 50 km were obtained. 7–8 velocity layers were distinguished. The first one reaches a depth of 2–4 km and is characterized by velocities of 2950–3400 m/s. The next layers display velocities of 3800–4300, 5600–6000 and 5800–6300 m/s and extend down to 20 km. Below this depth, layers with velocities of 5700–6700, 6600, 7000 and 7700–7800 m/s are distinguished. In profile GB-2B-96, velocities of 8300 m/s are assumed for depths greater than 35 km (i.e. in the mantle), and in profile 25-III-82 — below 45 km. However, it must be stressed that the depth-converted version is an approximation. Both time and depth scales are shown in profiles (Figs. 2 and 5) to help geological interpretation.

In the case of vibroseis records, a band pass filter of frequency 5-10-40-50 was used before stack instead of a notch filter and F-K filter, because of their much poorer qualities resulting from the extremely difficult relief.

GEOPHYSICAL INTERPRETATION OF SEISMIC DATA

The data presented here comprises several reflection seismic sections obtained during 1982, 1987, 1992, 1993 and 1996. This long period adversely affected the quality of the data, and in particular resulted in a lack of unified parameters works. This caused difficulties in data processing and, in spite of the modern graphic station and software used then, the seismic sections obtained display varying qualities.

The sedimentary succession was recorded clearly but the main purpose of the studies was the interpretation of seismic data from beneath the base of the Zechstein. These gave an impression of the underlying geological structure, despite the imperfection of the field data (Fig. 2).

The sub-Zechstein boundaries are difficult to correlate due to a lack of continuity of characteristic dynamic features which might enable identification of geological boundaries and of any reasonable stratigraphical control.

However, beneath the base of the Zechstein fragments of boundaries were observed along the whole profile, though their dynamics and traceability vary. These boundaries seem to reflect geological reality because of their high stacking velocities and often discordant position in relation to superjacent boundaries. However, it cannot be precluded that some of these boundaries have been created by multiple oscillation seismic waves between superjacent boundaries.

Different seismograms have been obtained from different parts of the profile. In some of them reflectors are easily legible, in others they are affected by strong interference, and in others the signal-to-noise ratio is so unfavourable that it is impossible to trace the reflectors in individual seismograms. This is particularly, true of the top parts of structures and of major fault zones.

Noise included that from low frequency waves, which could not be reduced during fieldwork but which were eliminated later due to high coverage. Noise also stemmed from diffraction waves generated in the vicinity of faults, small structures or pinchouts. Multiple reflectors were recorded along profiles with different intensities. Multiple reflectors originating from Lower Cretaceous and Upper Jurassic deposits were particularly strong. These were partly eliminated by high coverage and a large ΔT value between real reflectors. Many of them sum, giving apparent boundaries. Multiple reflectors produce strong noise which renders the correlation of deeper boundaries in some parts difficult or impossible.

The wave image between the top of the crystalline basement and the Moho is heterogenous and strongly deformed. However, the Moho boundary was recorded and appears between Rudna and Wschowa and in the vicinity of Chodzież as a lowest reflector of a set of reflectors (Figs. 3 and 4).

A characteristic element of the seismic sections are fault zones, visible in both shallow and deep parts of profile.

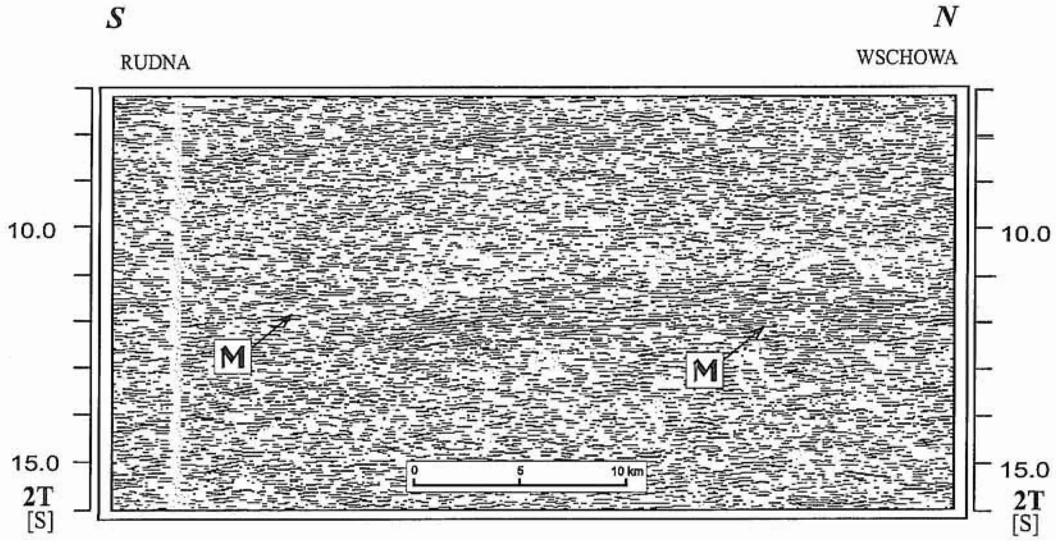

Fig. 3. Southern segment of the time seismic section, shown in Fig. 2

In profile GB-2 (Fig. 2) the best results were obtained from the southern part (Fig. 3), though even here reliable and precise separation of useful reflection waves from noise is difficult. Deeper reflectors showing higher dynamics are observed at places in the northern part of profile GB-2 (Fig. 2), and therefore the interpretation of boundaries is easier and more reliable here. Reflection waves originating from deeper-lying seismic boundaries are distinguishable due to their low frequency and relatively high dynamic energy. Beneath this zone, there are only single discontinuous reflectors whose recognition is uncertain.

Three major parts of the Earth's crust can be distinguished with reference to the wave image in seismic sections (Fig. 2) which differ in their reflectivity:

1. Sedimentary cover.

Two component units can be distinguished: the Zechstein-Mesozoic deposits with continuous, horizontal seismic boundaries, and beneath — a unit within which seismic boundaries are dipping in different directions. Reflection waves from the Zechstein-Mesozoic rocks can be correlated over long distances, and their tectonic structure has been imaged. The lower unit, of Palaeozoic rocks, is bounded at the top by the boundary Z1' which corresponds to the base of the Zechstein (**Pz**). Its base is bounded by the base of the Palaeozoic (**Pal**) (Figs. 2 and 5). Many reflection phases of increased amplitude have been recorded within this unit, though these are characterized by low energy when compared with the Permo-Mesozoic reflectors. The base of the sedimentary cover is drawn at a change in record character visible in the seismic sections. The amount of energy, and therefore the number of reflectors, considerably decreases beneath this boundary. It probably corresponds to the refraction boundary of $V > 6000$ m/s.

Two stages can be distinguished lower part of the cover:

— Old-Palaeozoic (Caledonian), folded and variably tectonized,

— Young-Palaeozoic (Variscan), with a blocky structure (above boundary **W**).

2. The upper crystalline crust.

The next two seismic complexes correspond to crystalline rocks. The frequency of reflection waves in the upper part of the crystalline crust considerably decreases, its top being drawn at a refraction boundary of $V > 6000$ m/s (Młynarski, 1982). Its base coincides with the most frequently observed zones of discordant seismic boundaries. The main part of the complex is transparent (homogenous: almost lacking reflectors) with a more distinct reflector at the top. Zones of increased reflection alternate with „silent zones" in the southern part of profile GB-2.

3. The lower crystalline crust.

Reflectors characterized by relatively high dynamics and low frequency are recorded in the lower parts of the seismic sections. This is the laminated lower crust of considerably increased reflectivity (Fig. 2 and 3). In different parts of the profile, the record quality of seismic waves, their occurrence interval and continuity are different, whereas their overall character remains similar. This is a group of waves which cannot be unquestionably correlated at the same phase along the whole section. The strongest reflector occurs at the base of this zone and may be the Moho discontinuity. A rapid diminution of energy occurs below this in the mantle, where the recorded fragmentary reflectors are characterized by low dynamics.

In general, the lower crust in the southern part of the profile is recorded as a fairly thick (~10 km), homogenously layered zone. Towards the north its structure changes. It is also layered (Fig. 4) but distances between particular groups of reflectors are considerably greater and breaks in wave correlation are frequently observed.

The most varied image comes from the northern part of the profiles GB-2B-96 and 25-III-82 (Fig. 2). In the northeastern part of profile GB-2B-96 and in the southwestern part of profile 25-III-82, boundaries dipping in different directions with traveltimes of 4–6 and 12–15 s are worth noting. The record deteriorates in the middle part of profile 25-III-82. These variations may result from deep geological structure, and a significant role is played by fault zones which occur here. A broad

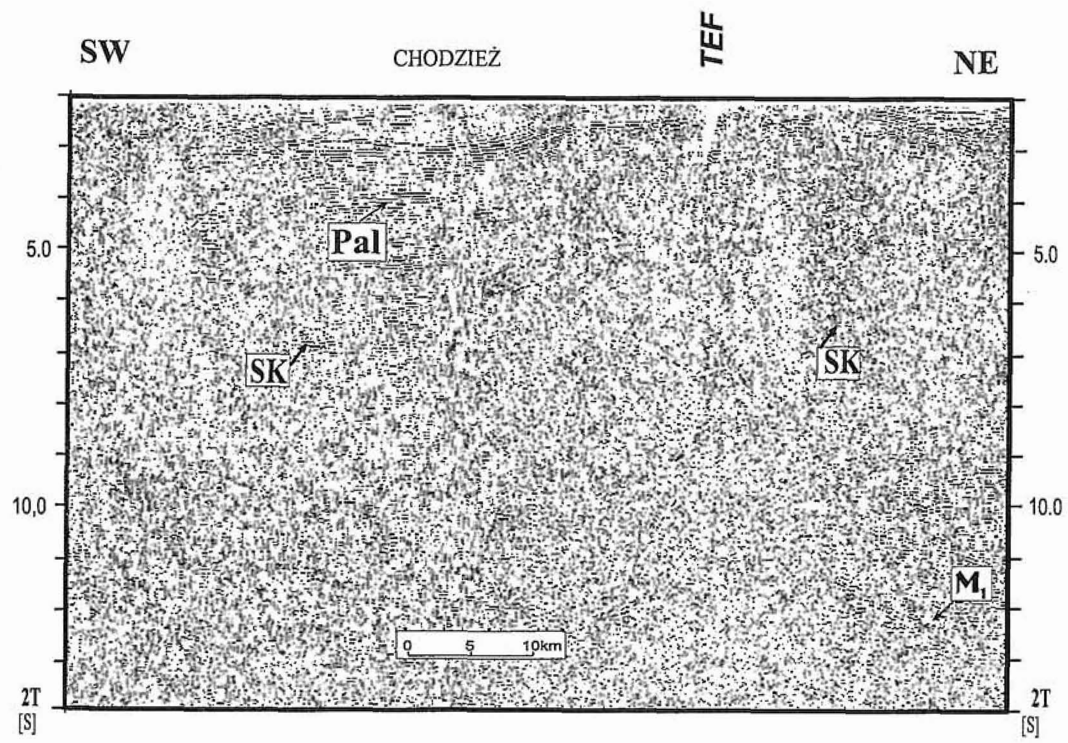

Fig. 4. Northern segment of the time seismic section, shown in Fig. 2

zone of lowered intensity of boundaries recorded in the middle part of the profile may be due to fault zones, transverse in relation to the strike of major geological units.

GEOLOGICAL INTERPRETATION

The analysed profile, in its southern part, crosses the Outer Variscides slightly oblique to the direction of tectonic transport, whereas in its northern part, after turning to the north-east, it crosses the Mid-Polish Trough (Fig. 1). This profile has yielded new data for two segments of the Palaeozoic platform in the Polish Lowlands: the Fore-Sudetic Monocline and Mid-Polish Trough. The laterally variable elevetions of the crystalline crust, the thin-skinned character of the Variscan orogen, the enigmatic intra-Variscan elevations of the Wielichowo and Brenno regions (they formed the later, Permian and Mesozoic Kościan Elevation being a part of the Wolsztyn Ridge) located in the central part of the externides and of unknown geological structure, are distinct in the Variscan platform area. The relationship between the geological structure of the sedimentary cover and crystalline crust (particularly as regards fault tectonics) is also distinct within the Variscan sector. Reflectors from the north-eastern part, which embraces the Caledonian platform, suggest the presence of folded Lower Palaeozoic.

SEISMIC SECTION GB-2

Part of the Rudna–Wschowa–Szamotuły profile (GB-2) includes three sections (Fig. 1): the southern (2-I-92/93), middle (2-III-87) and northern (2-I-92). In this part, the crystalline crust is defined by two reflection horizons: a lower horizon **M** (Moho boundary) and an upper horizon **SK** (top of the crystalline crust). In the southern and middle parts, the reflection horizon **M** can be reliably traced. It occurs here at traveltimes of 11.5–12 s, that correspond to depths from 32 to 34 km. To the north, between Wschowa and Szamotuły, the boundary gradually dips to a traveltime of 13 s, i.e. to a depth of approximately 39 km, and reaches the Dolsk Fault, which was recorded in earlier refraction profiles (Guterch *et al.*, 1983). The Dolsk Fault, which is at least of a regional significance, is well marked and can also be traced within the sedimentary cover. The effects of activity on this fault can be observed, for example, in palaeotectonic and palaeogeographical maps of the Upper Rotliegend (Pokorski, pl. 3, 4 and 10 in: Dadlez *et al.*, 1998) in which reactivated faults separate a palaeohigh, the Wolsztyn Ridge (in the south), from the asymmetric and showing strongly subsiding Poznań Graben (in the north). North of the Dolsk Fault (Fig. 5), the Moho surface descends to traveltimes of 13–14 s, corresponding to depths of approximately 39–40 km, and remains at that level beneath the Poznań Graben, with a small elevation in its extreme north. The deepest level of the Moho beneath the Poznań Graben suggests not only a crustal origin for this structure but also associated tectonic activity during the late Palaeozoic.

The top of the crystalline crust (reflectors **SK**) is not so distinct as its base. In the extreme south it seems to occur at a traveltime of approximately 3 s, and then towards the north, after a largely conjectuctural course, it culminates within the Wschowa Block where it ascends to about 2.5 s, within reach of boreholes. In this sector, though, the record is unreliable (see Fig. 5). The top of the crystalline crust in the northern part of the profile GB-2 is more reliable. In the vicinity of Szamotuły,

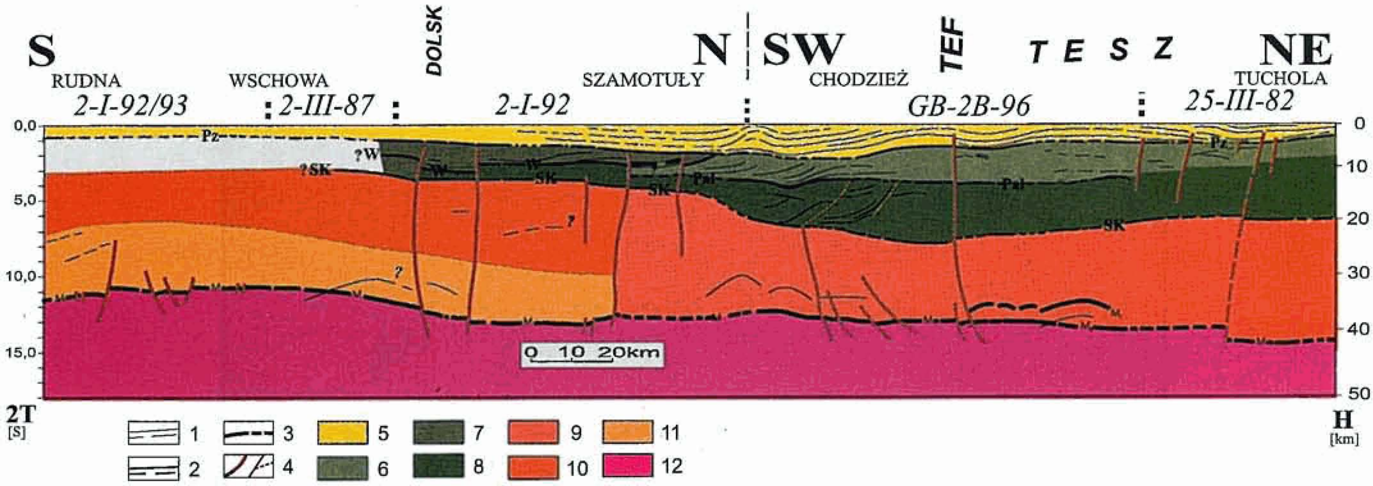

Fig. 5. Reflection seismic profiles GB-2, GB-2B-96 and 25-III-82, with geological interpretation shown in Fig. 1

1 — reflection boundaries, 2 — reflection boundaries of tectonic complexes, 3 — Moho, 4 — faults and fault zones, 5 — platform cover — Zechstein-Mesozoic, 6 — platform cover — Upper Palaeozoic, 7 — Variscides (including Rotliegend platform deposits along section 2-I-92), 8 — Caledonides (may include relics of Palaeozoic platform cover along section 2-I-92), 9 — crystalline crust, 10 — crystalline crust — homogenous layer, 11 — crystalline crust — laminated layer, 12 — upper mantle; other explanations see Fig. 2

reflectors **SK** descend and occur at depths of approximately 9–12 km (4–5 s). The crystalline crust is two-layered in the Variscan basement here, a conclusion is confirmed by refraction profiles (Guterch *et al.*, 1994, 1997). The thickness of the crystalline crust is moderately constant at 26–30 km in this sector. The lower part of the crystalline crust (laminated layer) is about 10 km thick, whereas its upper part (transparent or homogenous layer) attains a thickness of from 16 up to 20 km. Similar values were reported in the refraction profiles LT-4 and LT-5 (Guterch *et al.*, 1983), and were identical in profile LT-7 (Guterch *et al.*, 1994).

The interpretation of the upper part of profile GB-2 is hypothetical, as is the interpretation of the crystalline crust presented above. The reflection horizon **W** occurs only in the northern part of the profile between Dolsk and Szamotuły. It has been assumed that it is related to the contact of the Variscide externides thrust over Caledonian(?) basement, i.e. the flysch or flysch-like younger Palaeozoic, mainly Carboniferous, with folded and metamorphosed lower Palaeozoic. Caledonian basement has been distinguished only in the northern part of the profile from the Dolsk Fault as far as the end of the profile, i.e. beneath the Poznań Graben, where it does not exceed 4 km in thickness. Its is presumably absent south of the Dolsk Fault.

Platform deposits, probably of Devonian and Lower Carboniferous age, have been tentatively distinguished above the folded Lower Palaeozoic and beneath folded and thrust Variscan units in the northern part of the profile. They are approximately 2 km thick, and are presumably represented by deep-water, basinal facies.

The Variscan complex, composed of folded Upper Palaeozoic rocks, extends between the reflection horizons **W** and **Pz** (base of the Zechstein). The folded Upper Palaeozoic rocks (mainly Carboniferous) cannot be separated within this interval from the lowermost part of the horizontal platform cover (Rotliegend including effusive rocks), due to very poor reflector quality or lack of reflectors.

In the northern part of profile GB-2, Variscan rocks are 4 km thick and they are presumably thrust over the Caledonides. Both these complexes show typical thin-skinned tectonics. In the middle part, the Variscan complex is strongly reduced in thickness, whereas in the south it thickens again. Metamorphic schists, which were previously considered to be of Proterozoic age (Oberc, 1983), have been drilled beneath the Rotliegend and thin Carboniferous deposits in two boreholes (Brenno 1 and Święciechowa 1) located between Wschowa and Poznań. It seems more probable that these rocks represent the Variscan Phyllite Zone (Norddeutsche Phyllit Zone) appearing here in a tectonic window. This zone is quite well documented in the German Variscides (Lokhorst, 1997) and is related to the Central European Suture Zone.

The reflection horizon **Pz** is characterized by an almost continuous record and both its image and the image of the whole Zechstein-Mesozoic platform complex is clear and unambiguous. The base of the Zechstein is constrained by boreholes, though a considerable divergence (of the order of several hundred metres) takes place between the base of the Zechstein determined from boreholes (Obrzycko 1, 3, Pniewy 1, Rokietnica 2) and the base drawn in the studied profile.

GEOLOGICAL CROSS-SECTIONS GB-2B-96 AND 25-III-82

The crystalline crust extends between the reflection horizons **M** (Moho) and **SK** (top). Its thickness ranges from approximately 15 to 25 km. The crust is thinnest in the extreme southwest near Chodzież, and thickest in the north-east. Two reflection horizons (**M$_1$** and **M$_2$**) have been distinguished in short fragments of the profile in deeper parts of the crystalline crust. An upper reflection horizon (**M$_1$**) forms irregular and not very broad elevations (domes). The reflectors either show a differentiation of the laminated crust (if **M$_2$** is the equivalent of Moho) or the lower horizon might represent changes within the upper mantle. A deep-rooted fault zone reaching down to the Moho or even upper mantle, which probably corresponds to the Trans-European Fault (TEF) (Figs. 2 and 5), has been distinguished in profile GB-2B-96. The TEF is also marked in the refraction profile LT7, as well as a few kilometres south of the boreholes Piła IG 1 and Szubin IG 1. The TEF marks the southwestern boundary of the rift in the uppermost Rotliegend and the deepest part of the Mid-Polish Trough in the Zechstein and Mesozoic. This suggests that subsidence of the area was controlled by the structure of the crystalline crust (Pokorski, 1995).

The Lower Palaeozoic (Caledonian structural complex) extends between the reflection horizon **SK** and the reflection boundary **Pz** which marks the base of the platform cover. This boundary has been drilled in two boreholes. In the Polskie Łąki PIG 1 borehole Ordovician deposits are overlain by the Middle Devonian at a depth of 4890 m. In the Bydgoszcz IG 1 borehole, Silurian(?) deposits underlying the Middle Devonian have been drilled at a depth of 5573 m. The reflection horizon **Pal** is not recorded in profile 25-III-82. Both the reflection horizons are locally drawn hypothetically in the southwestern part of the profile, although presumed fold structures and faults have been distinguished within the Caledonides in the Chodzież area. The Caledonian complex seems to attain a thickness of approximately 10 km in this part of the profile. The estimates are supported by profile LT-7 (Guterch *et al.*, 1994).

The platform cover is primarily characterized by a reflection horizon which coincides with the base of the Zechstein **Pz**. This divides the cover into two units: of upper Palaeozoic and upper Zechstein-Mesozoic age, respectively. Below the Zechstein anhydrites, though the Devonian, Carboniferous and Rotliegend deposits, cannot be separated on the profiles. This lower part of the platform cover is between 3 and 6 km thick. The upper Zechstein-Mesozoic succession is well known from many seismic sections and boreholes. Its thickness in the profile studied is about 6000 m in the extreme south-west. Towards the north-east the thickness decreases to 5000 m in the vicinity of Chodzież, and to approximately 3000 m in the Koszalin–Chojnice tectonic zone. Tectonic deformation has been observed within these rocks in the Szamotuły Zone, though these seem not to have affected the lower platform complex.

CONCLUSIONS

1. The obtained seismic materials, though, mostly of poor quality, have revealed a general picture crustal structure.

2. The TESZ is ~ 75 km wide along the profile. Crustal thickness is variable: from ~ 30 km within the Variscan Belt up to ~ 40 km within the TESZ.

3. Regional fault zones may exist — reaching down to the Moho surface — as deep fracture zones (Dolsk TEF).

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