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The geological and geophysical interpretation of the sub-Carpathian autochthonous gas-bearing Devonian structures of Lachowice–Stryszawa

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The problem of searching for oil and gas in Devonian carbonate reservoirs under autochthonous Miocene molasse and Carpathian flysch fold-thrust cover has been presented on the example of Lachowice–Stryszawa structure (western segment of Polish Carpathians). The structure of Carpathian autochthonous substratum as interpreted from vertical Lachowice 7 well and directional Stryszawa 1K well profiles showed the occurrence of inversional strike-slip fault separating blocks of different tectonic development. The misleading seismic wave diffraction effect generated by narrow fault-framed trough closing up Stryszawa gas-productive anticline has been proved with theoretical modelling of the wave-field using 1D and 2D seismogeological models. The seismic lines as interpreted with the use of LANDMARK workstation and software allowed to establish the reflection boundaries not only from Carpathian overthrust and autochthonous Miocene but also from Devonian substratum and deeper basement. As a result, the time-structure map of the top of autochthonous Palaeozoic substratum has been presented. This suggests the occurrence of mostly longitudinal pairs of strike-slip faults and fault-related structures of the substratum. The faults originally developed under tensional regime were rejuvenated into compressional ones due to Carpathian fold-thrust movements.

INTRODUCTION

During the last decades the front of exploration in Polish Outer Carpathians (Flysch Carpathians) moved from traditional Central Carpathian Depression (Krosno–Jasło–Sanok) in the east to western segment of Polish Carpathian fold-and-thrust belt, including the area of Nowy Sącz–Rabka–Sucha Beskidzka–Żywiec i.e. generally 20–50 km south of Kraków–Żywiec (Fig. 1).

Initially, the exploration drillings were aimed mainly to penetrate folded flysch of Dukla–Grybów unit covered with Magura nappe. There, a few oil and gas fields were discovered in Eocene-Oligocene flysch sand beds. However, the low fracture-type porosity of flysch turbidite sand reservoirs, strictly confined to fault and thrust zones, resulted in rapid pressure and production depletion (T. Lenk, 1983; E. Jawor, 1984, 1989).

Some deeper drillings reached the autochthonous substratum of flatly thrusted western segment of Polish Carpathians (Fig. 1). A number of gas deposits that had been already discovered at the front and directly below the frontal part of Carpathian overthrust opened new perspectives to explore the southern extent of autochthonous Miocene molasse under the folded flysch thrust plane. Also, the southern continuation of autochthonous Palaeozoic substratum at a distance of 20–40 km under West Carpathians has been confirmed by the results of Potrójna IG 1, Sucha IG 1, Lachowice 1 and Zawoja 1 deep wells (E. Jawor, 1984; A. Ślączka, 1985; P. Karnkowski, 1986).

Potrójna IG 1 well located about 7 km south of Carpathian frontal thrust went through folded flysch at 1641 m b.s.l. depth and Badenian Dębowiec Formation autochthonous Miocene conglomerate 82 m in thickness. Lower in the profile, the well penetrated Upper Carboniferous (Namurian A, Westphalian A+B) sands, muds, shales and coals 569 m thick and Lower Carboniferous (Visean) Culm facies 141 m thick, consisting of mud, shale with sand intercalations and detritic limestone at the bottom. More than 700 m thick interval of Carboniferous strata drilled in Potrójna IG 1 well proved the continuation of Upper Silesian Carboniferous Basin with its

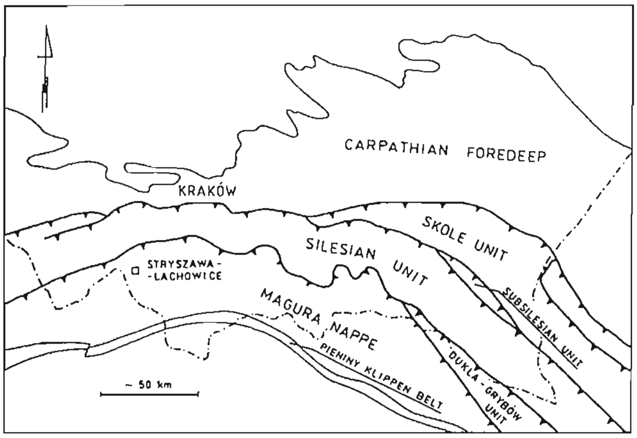

Fig. 1. Localization of Lachowice–Stryszawa area on the base of generalized map of Carpathians

Lokalizacja obszaru Lachowice–Stryszawa na tle zgeneralizowanej mapy Karpat

productive coal seams under the cover of thrusted and folded Carpathian flysch and autochthonous Miocene.

Some gas shows were observed there at the Devonian/Carboniferous boundary. Devonian sequence in Potrójna IG 1 well consisted of Lower Devonian shales (6 m thick), Middle Devonian dolomite (Eifelian-Givetian?) 115 m thick and of 364 m thick Upper Devonian (Frasnian-Famennian) limestone and fractured cavernous dolomite, the latter representing potential reservoir rock.

The Devonian strata rest unconformably upon 158 m thick series of light grey, thick bedded sands of favourable reservoir properties which are assumed to be of Cambrian age (A. Ślączka, 1985; E. Turnau, 1974). The well penetrated also Eocambrian variegated conglomerate 27.5 m thick entering, siliceous shales and quartzitic sands of Precambrian down to the final depth of 3700 m (3311 m b.s.l.).

About 16 km more to the south in Zawoja 1 well the oil and gas shows were observed in shale-silt Early Miocene (Karpatian) sandy reservoirs enriched in flysch-derived grains and fragments. However, in the same well the petroleum shows were also noted in Upper Carboniferous coal-bearing sand-shale-conglomerate strata that had been reached in 4852–5023 m depth interval (E. Jawor, 1989). These proved the existence of southern extension of Upper Silesian coal-bearing Carboniferous formations under the autochthonous Miocene and Carpathian flysch nappes.

Numerous petroleum shows have been noted not only in Carboniferous (e.g. Marklowice gas field) but also in Devonian strata near the frontal thrust of Polish West Carpathians in Bielsko-Biała–Andrychów–Wadowice area. The Lachowice structure of autochthonous substratum was the first gas field encountered in Devonian under the West Carpathian fold-and-thrust belt (E. Jawor, 1984). Flat and long range overthrust of folded Carpathian flysch provides efficient tectonic seal for both gas traps in autochthonous Miocene and possible oil and gas reservoirs in deeper Carboniferous and Devonian substratum. Here, the seismic survey is extremely important tool for location of promising structures of autochthonous Miocene and Palaeozoic substratum hidden under the folded flysch cover reaching there 2000–3000 m in thickness.

In the last decade the development of seismic methods and techniques, specifically the advanced reprocessing and 3D seismic survey, allowed to recognize some important boundaries such as Carpathian thrust plane, the bottom of autochthonous Miocene and a few reflections from Palaeozoic substratum. These could be followed at a considerable distance southward under the Carpathians (C. Nowotarski, 1987; C. Nowotarski, S. Przybyło, 1989). Still the seismic record from Carpathian autochthonous substratum is neither fully reliable nor geologically readable. Having this in mind, the modelling of seismic wave field has been applied to reprocess early acquired seismic data and help their geological interpretation. This allowed to separate the useful waves from disturbing ones in the seismic record. Such modelling was applied by POGC, Geophysical Division, Kraków concurrently with routine work of seismic groups. However, those models had to be verified and transformed into seismogeological ones considering both geological and geophysical data to show the most reliable concept of geologic structure of a given area.

The first successful exploratory well Lachowice 1 (Figs. 1, 2) located at a distance of about several tens kilometres south from Carpathian thrust front went through 3200 m of folded flysch and 750 m of autochthonous Miocene to encounter the gas flow from Devonian carbonates (E. Jawor, 1984).

The discovery of Lachowice gas field gave a prompt to penetrate the neighbouring Stryszawa elevation with Lachowice 7 well drilled about 4 km to NW towards Sucha Beskidzka (Fig. 2). That well discovered the second gas field entrapped in Devonian carbonates at 2254 m b.s.l. depth (U. Baran *et al.*, 1995).

In 1995 the directional drilling Stryszawa 1K started at 900 m depth from Lachowice 7 well, went inclined to WNW and reached the top of Devonian reservoir limestone which appeared to be barren 900 m apart from and 155 m deeper than in Lachowice 7 vertical well (Fig. 2). The combined geological and geophysical interpretation as adopted to resolve this exploration problem has made a good opportunity to present more general concept of geological structure of Carpathian autochthonous substratum in Lachowice–Stryszawa zone.

The concept is based upon geophysical and geological data derived from geological drilling and well-log reports (POGC Exploration and Drilling Division, Kraków, 1995; Geophysical Division, Kraków, 1976, 1986, 1987,1989, 1991). The well log records were used to determine the lithology, porosity and saturation coefficients of the beds encountered in Carpathian autochthonous substratum. The interpretation of dipmeter data appeared to be extremely useful to restore the lithostratigraphy and tectonics of sub-Carpathian cross-section in Lachowice 7–Stryszawa 1K segment (Fig. 3). Detailed study of sonic and density logs allowed to estimate the interval velocity and bulk density values necessary to establish the reflection coefficients. The lithologic-velocity model created the basis for synthetic seismogram prepared for Lachowice 7–Stryszawa 1K segment and allowed to determine the criteria for seismic wave field interpretation.

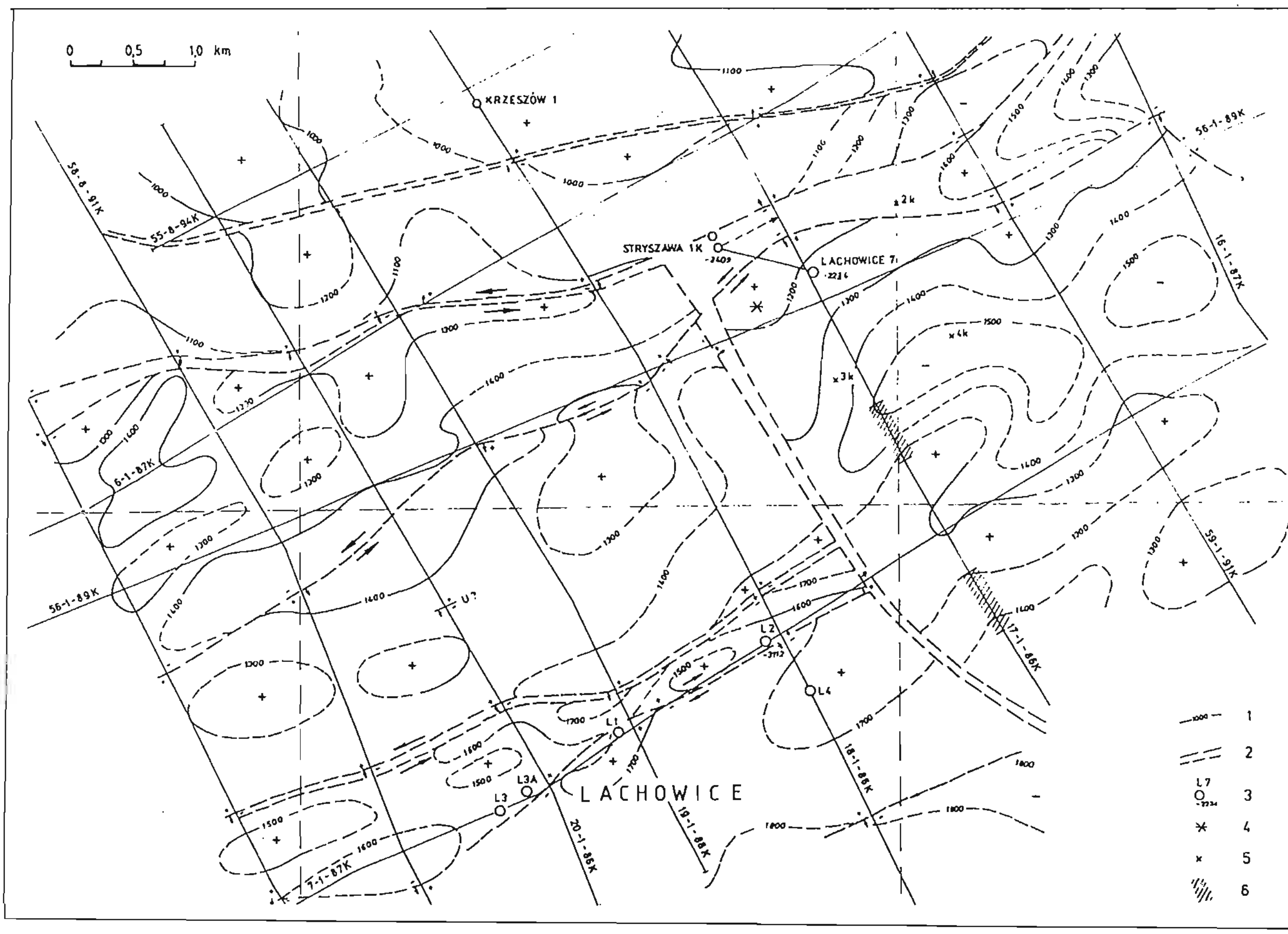

Fig. 2. Time-structure map of the top of Palaeozoic (Carpathian substratum), Lachowice–Stryszawa area
1 — isochrone (ms), 2 —fault, 3 — borehole, 4 — planned directional well, 5 — other planned wells, 6 — lack of data

Szkic czasowej mapy sejsmicznej stropu podkarpackiego podłoża paleozoicznego w rejonie Lachowic–Stryszawy
1 — izochrony (ms), 2 — uskok, 3 — otwór wiertniczy, 4 — planowany otwór kierunkowy, 5 — inne planowane otwory, 6 — brak danych

GEOLOGICAL STRUCTURE AND PETROLEUM EXPLORATION OF PALAEOZOIC SUBSTRATUM IN WESTERN POLISH FLYSCH CARPATHIANS

Lachowice–Stryszawa area is situated near Sucha Beskidzka by the front of Magura thrust in the western part of Polish Flysch Carpathians (Figs. 1 and 2). Considering the gas accumulations discovered here in the sub-Carpathian Devonian reservoirs (Lachowice field discovered by Lachowice 1 well and Stryszawa field discovered by Lachowice 7 well) the geological-geophysical interpretation presented here concentrates mainly on the tectonic structure and petroleum perspectives of platform Palaeozoic strata sealed up by sub-Carpathian autochthonous Miocene and covered by Carpathian folded flysch formations 2500–3200 m in thickness. Palaeozoic substratum of western part of Polish Carpathians is the remote southeastern continuation of the Upper Silesian Coal Basin (GZW) with its Lower Precambrian-Early Caledonian basement (W. Pożaryski *et al.*, 1992) and erosionally reduced, relatively flat, cover of Variscan stage. Post-Caledonian palaeoelevations active as uplifted blocks in Variscan epoch still persisted during Permian and Triassic until their final extinction in Jurassic period (P. Karnkowski, 1993).

In the western part of Carpathian Foredeep, the palaeorivers distributary system with its incised channels and valleys trending and deepening to SE under the Carpathians is preserved at the bottom of Miocene surface. This variable palaeomorphology controlled the sand-shale ratio of the lower part of the Miocene strata. Sandy Miocene molasse filled river channels thus creating the possibility of the occurrence of stratigraphic gas traps (E. Jawor, 1982). It is not exactly known, how far such a system would extend to the south. In general, however, the reservoir properties of the Miocene formation decrease under Carpathians so that in Zawoja–Lachowice–Sucha Beskidzka area it acts rather as sealing cover to Palaeozoic reservoirs. Here the bottom of the Miocene still

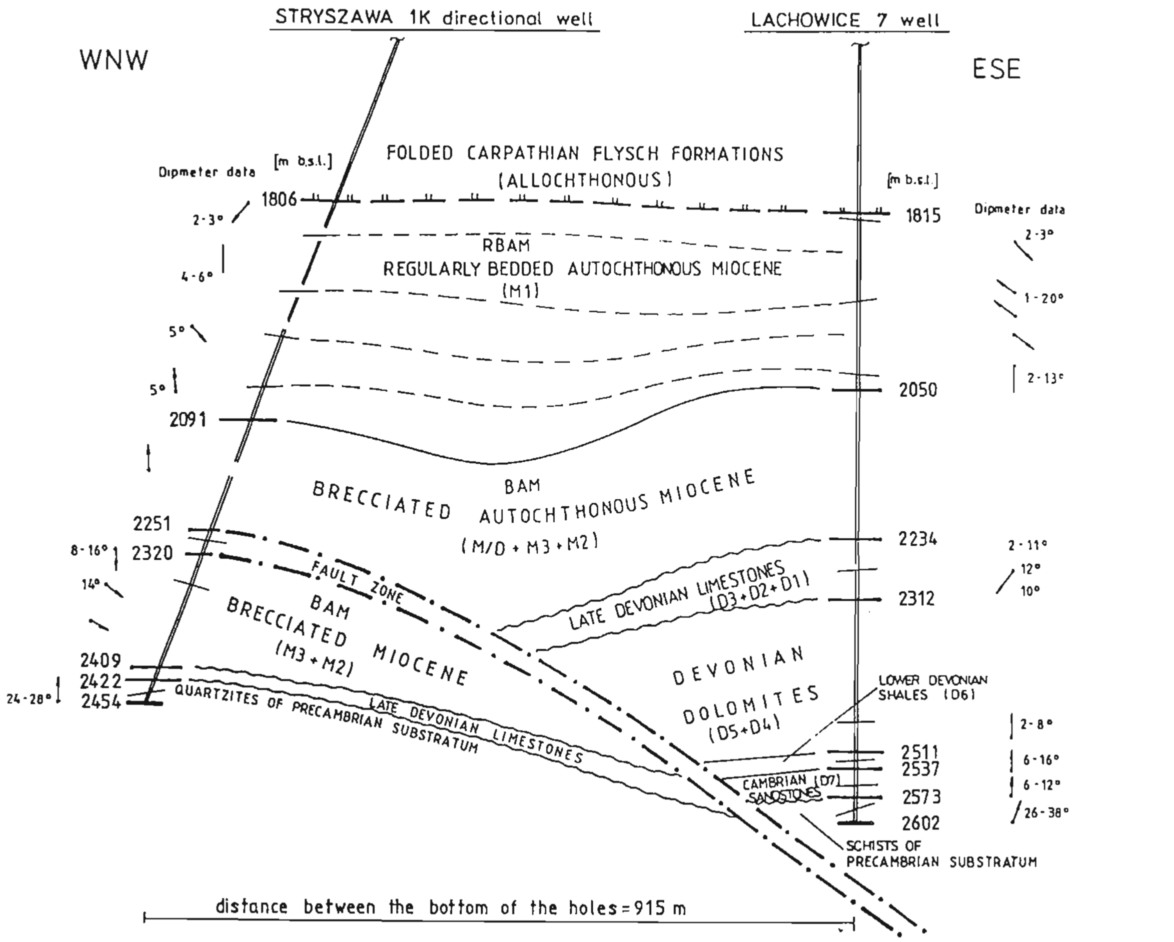

Fig. 3. Geological cross-section of autochthonous Carpathian substratum between Lachowice 7 (vertical) and Stryszawa 1K (directional) well profiles
Along each well profile the depth to the sea level and prevailing direction and dip angles are indicated

Przekrój geologiczny autochtonicznego podłoża Karpat między pionowym otworem Lachowice 7 a kierunkowym otworem Stryszawa 1K
Wzdłuż każdego profilu zaznaczono głębokość w stosunku do poziomu morza oraz przeważające kierunki i kąty upadu

forms quite diversified morphotectonic surface whereas the top is truncated by nearly horizontal plane of Carpathian overthrust. Therefore, the identification of Miocene boundaries, although seismically difficult, is important to follow its thickness variations and locate promising structural elevations in Palaeozoic substratum.

Variscan stage consists of Devonian and Carboniferous formations in which numerous gas and oil shows have been observed in Bielsko-Biała–Andrychów–Wysoka area (K. Konior, 1963, 1965*a*, *b*, 1969, 1974; K. Konior, E. Turnau, 1973). Devonian formations rest directly upon Precambrian basement or upon post-erosional fragments of earlier Palaeozoic. The dip of Devonian strata, mostly less than a few degrees, rise up to several tens degrees in fault zones.

Devonian rock sequence is bipartite. In Lower Devonian the variegated sandstone and red shales of Oldred facies, from several tens to 100–200 m thick, dominate (K. Konior, 1965*a*, *b*, 1969; K. Konior, E. Turnau, 1973; A. Ślączka, 1976, 1985; E. Turnau, 1974). The Middle and Upper Devonian consist mostly of carbonates.

In Middle Devonian (transgression starting from Eifelian) hard crystalline dolomite and dolomitic limestone up to 200 m in thickness occurs. On the calcite fine-grained matrix background there are observed irregular transitions into dolomite resulting from metasomatic dolomitization. It has been suggested (L. Górska *et al.*, 1978) that the degree of dolomitization increases southward with increase in depth. Pronounced post-diagenetic metamorphose caused the pore space to be considerably filled with successive generations of dolomite and anhydrite, the latter as an end member. The shale content seems to increase both towards the bottom and the top of the formation.

Upper Devonian rock profile (Frasnian-Famennian) consists of dolomite, limestone and marls. West of Kraków meridian the distinct increase in thickness of Middle and Upper Devonian formations is observed (S. Sas-Korczyński, 1989). The bioherm and biostrome Frasnian limestones occur over the shallowings and pass into the shaly carbonate facies, that predominate within palaeodepressions. In Famennian the fine-grained marly limestone occurs along with dolomite and some subordinate sands at the top (A. Ślączka, 1985).

In Carpathian substratum of Lachowice–Żywiec–Bielsko-Biała zone the Carboniferous is almost entirely eroded so that practically only Devonian is directly covered and sealed up by sub-Carpathian autochthonous Miocene. Carboniferous formations occur mainly in palaeodepressions, i.e. to SWW from Bielsko-Biała (Cieszyn–Ustronie–Wisła) and east from Bielsko-Biała–Lachowice area (U. Baran *et al.*, 1995). The Mesozoic of sub-Carpathian platform cover occurs still farther to the east from Spytkowice–Kalwaria Zebrzydowska–Mszana Dolna), within the so-called Rzeszotary tectonic block.

In Lachowice 1 (4525 m) discovery well (Lachowice gas field — Fig. 2) the Middle and Upper Devonian carbonates 185 m thick, were reached in 3950–4135 m depth interval. These are covered by autochthonous Miocene and folded flysch strata 3200 m thick. After perforation and acidizing in Upper Devonian 3450–4060 m depth interval, the gas and condensate flow of Vp = 115 m^3/min was observed from microfractured limestone and dolomite at reservoir pressure of Pd = 0.84 MPa (E. Jawor, 1984, 1992). Still deeper, down to the depth of 4136 m the Lower Devonian sandstones and mudstones, then Silurian and Upper Precambrian formations were drilled (P. Karnkowki, 1989).

In the neighbouring Lachowice 2 well (Fig. 2) below Carpathian overthrust surface at 3005 m depth the autochthonous Miocene molasse (3597 m depth), probably Upper Devonian-Lower Carboniferous (?) limestone (3612 m depth) and Devonian carbonates were drilled,' all of them of the similar thickness as in Lachowice 1 well profile. The reservoir limestone, in spite of reaching it about 350 m shallower, than in Lachowice 1 well appeared to be water saturated. The trap of Lachowice appeared to be more complicated than it had been assumed previously (E. Jawor, 1989). Actually it is considered to be a combined structural-tectonic and stratigraphic trap, associated with post-erosional surface and fractured fault zone closed up on the southern wall of longitudinal fault. The pay zone area is of about 10 km^2, the field more than 100 m high is estimated to be of 5–10 Mm^3 gas reserves (E. Jawor, 1992; P. Karnkowski, 1993).

In Carpathian Foredeep the Lower Carboniferous formations extend from Rzeszów in the east to Andrychów–Bielsko-Biała in the west. In western part of the foredeep the extension of the Upper Silesian Basin is characterized by almost continuous shallow platform deposition from Late Devonian to Tournaisian-Middle Visean. Tournaisian is there represented by detrital limestone with cavernous limestone interbeddings of the total thickness of 90 m. The Lower Visean consists of cavernous micrites 68 m thick, covered with dark claystone, mudstone and thin sandstones developed as Culm facies (R. Zając, 1995).

The most indicative for the geology of autochthonous substratum in Lachowice–Stryszawa–Zawoja–Sucha Beskidzka zone is the profile of Potrójna IG 1 well located 10 km north of Stryszawa (A. Ślączka, 1985). There, the Lower Carboniferous (Visean ca. 140 m thick) consists of detritic limestone grading up into marls and shales with sands interbeddings representing Culm facies. It has not been clear if there is any stratigraphic gap between Devonian and Carboniferous. However, that boundary seemed to be readily recognizable from well log record. Also, the boundary between Visean and Upper Carboniferous (Namurian A) has been

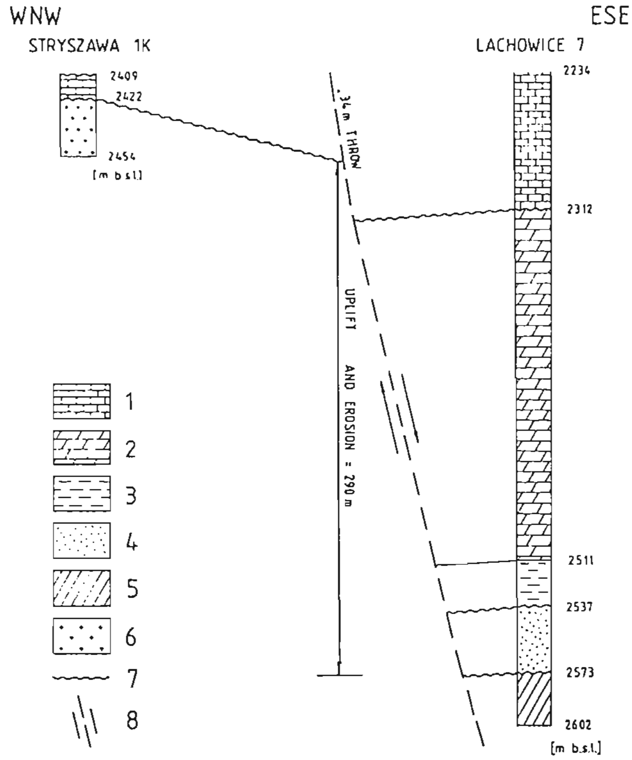

Fig. 4. Normal fault disturbing Stryszawa structure as restored at Early Variscan stage during Famennian

1 — Late Devonian limestone; 2 — Middle-Late? Devonian dolomite; 3 — Devonian shales; 4 — Cambrian sandstones; 5 — Precambrian (Eocambrian?) schists; 6 — quartzites of Precambrian substratum; 7 — suggested erosional unconformity; 8 — fault plane

Rekonstrukcja równoleżnikowego uskoku normalnego zamykającego strukturę Stryszawy z początkiem ery waryscyjskiej w famanie

1 — wapienie późnego dewonu; 2 — dolomity środkowego-późnego dewonu; 3 — łupki dewonu; 4 — piaskowce kambru; 5 — łupki prekambru (eokambru?); 6 — kwarcyty podłoża prekambryjskiego; 7 — niezgodność erozyjna; 8 — płaszczyzna uskoku

established arbitrarily by the turn of marine into brackish fossils. Namurian A — 246 m thick in Potrójna IG 1 well profile — is represented by fine-grained sandstone followed by shales and muds interbedded with sapropelic shales and coals. Apparently, there is a gap between Namurian A and Westphalian A (108 m thick) composed of grey muds and shales with coal beds and subordinate sands. In the uppermost part of Carboniferous profile (Westphalian B — ca. 115 m thick) the sandstones of Orzesz and Łazice Formations prevail. These are interbedded with mudstones and coal beds, the latter being best developed at the top of the sequence.

The top of Carboniferous marks the erosional surface (weathered down to 34 m) covered directly with autochthonous Miocene conglomerate. The Upper Carboniferous sandstones form potential reservoir. In Potrójna IG 1 well profile their porosity reaches 14% (A. Ślączka, 1985). About 16 km more to the south in Zawoja 1 well under 800 m thick cover of sub-Carpathian autochthonous Miocene molasse, at the depth of 4858 m the oil and gas shows were observed from Upper Carboniferous horizons (E. Jawor, 1989).

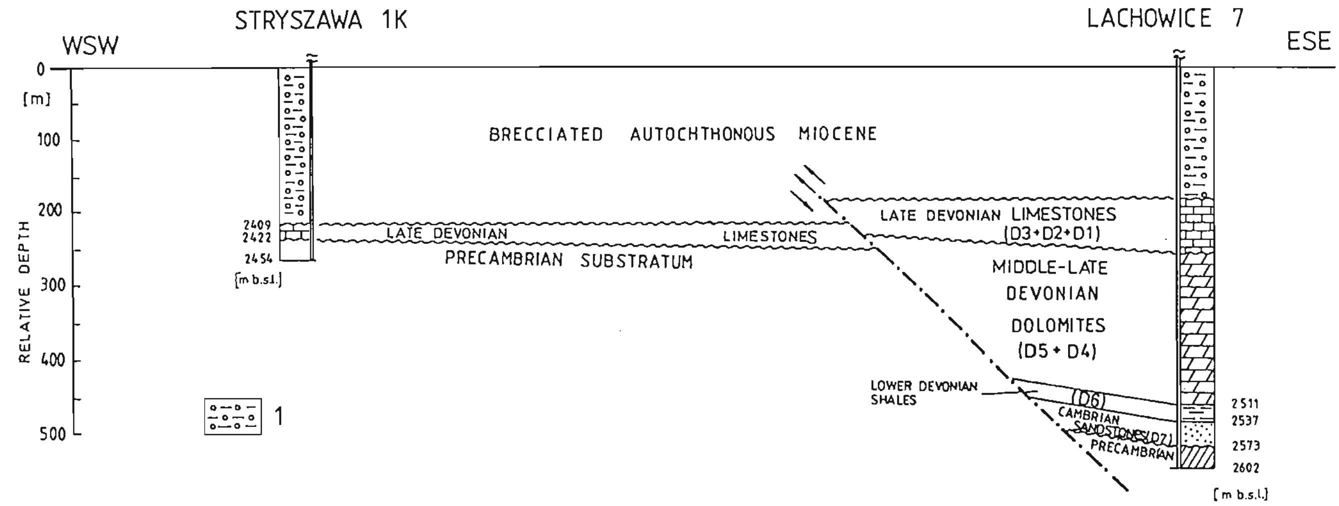

Fig. 5. The reverse fault of Stryszawa structure as developed in the Early Miocene (Carpathian fold-and-thrust compression) stage of tectonic inversion
The palaeostructure cross-section is related to the top of brecciated (autochthonous) Miocene (BAM) taken as a datum level; 1 — brecciated (autochthonous) Miocene (BAM); for other explanations see Fig. 4

Rekonstrukcja równoleżnikowego uskoku zamykającego strukturę Stryszawy, przekształconego inwersyjnie w uskok odwrócony w dolnym miocenie
Przekrój paleotektoniczny wyrównany do stropu zbrekcjowanego (autochtonicznego) miocenu (BAM); 1 — zbrekcjowany miocen (autochtoniczny) (BAM); pozostałe objaśnienia jak na fig. 4

RESTORATION OF GEOLOGICAL STRUCTURE OF AUTOCHTHONOUS SUBSTRATUM

After the development of Lachowice gas field the next gas deposit Stryszawa was discovered with Lachowice 7 well. There the platform Palaeozoic substratum was reached at the depth 2759 m (2234 m b.s.l.) after drilling through 2340 m of folded Carpathian flysch and about 235 m of autochthonous Miocene. According to U. Baran *et al.* (1995) the first 39 m of Palaeozoic substratum (2234 to 2273 m b.s.l. depth interval) represent Lower Carboniferous. This suggestion was rejected due to the recent opinions (M. Narkiewicz, 1996) that no Carboniferous strata occur in Lachowice 7 profile. Therefore the interval under discussion has been included into Upper Devonian limestones, so that their total thickness is 78 m (2234 to 2312 m b.s.l. depth interval). The Devonian dolomite complex 199 m thick (2312 to 2511 m b.s.l. depth interval) was recognized below. From the limestone reservoir and the uppermost part of dolomites (2245 to 2325 m b.s.l. depth interval) the gas flow of 88.54 m^3/min at formation pressure of 26.46 MPa (2854 m depth) was observed after perforation and acidizing (U. Baran *et al.*, 1995). Considerable content of higher hydrocarbons (C_{3+} = 66,8 g/m^3 up to C_7) shows that possible Devonian source rock may have reached the wet gas stage. The claystone bed 26 m thick (2511 to 2537 m b.s.l. depth interval) that occurs below the dolomites has been also included into Devonian. This is underlain by 36 m thick sandstone showing very good reservoir properties, which belong most likely to the Cambrian. The sandstone rests directly upon the schists of the Precambrian (Eocambrian?) basement.

Assuming initially that the tectonically undisturbed crest of Stryszawa anticline was situated NW from Lachowice 7 well the Stryszawa 1K directional borehole (azimuth 291°) was drilled. It was deviated from the vertical at a distance of 911 m (Figs. 2, 3). It reached the Carpathian overthrust plane nearly at the same depth of 2091 m b.s.l., went through 50 m thicker autochthonous Miocene molasse (285 m in thickness) and only 13 m thick water saturated Devonian limestone resting at the depth of 2422 m b.s.l. upon the quartzites of Precambrian substratum (Fig. 3). Thus the top of Devonian in Stryszawa 1K well occurred unexpectedly 175 m deeper than in Lachowice 7 well profile and the Devonian reservoir limestone appeared to be dry and reduced in thickness by 327 m. To explain such great variations, observed at a distance of only 900 m, the attempt to correlate the sub-Carpathian intervals from both well profiles was taken considering the results of well log interpretation, prepared by Well Logging Centre of Geophysical Division, Kraków. These results are presented in Table 1. For directional Stryszawa 1K well the true vertical depth was indicated together with well log and the relative depth values (Table 1), used to construct the sub-Carpathian geological cross-section showed in Figure 3.

The Lachowice 7 well profile was used as a basis to construct the seismic model. The interval velocities from acoustic curves and bulk density values from density log were recognized. These were used to calculate the reflection coefficients for substantial rock boundaries. These reflection horizons recognizable from seismic sections at the top of individual Miocene and Devonian strata are indicated in Table 1.

The results of dipmeter record were analyzed to verify the strata boundaries and locate possible unconformities and position of fault planes. Azimuth and angle of dips, recalculated to apparent dip values, are indicated on geological cross-section along Lachowice 7 and Stryszawa 1K well profiles (Fig. 1). In Lachowice 7 well profile the Eocambrian schists of significant dip (26–38°NE) are discordantly covered with D7

Table 1

Results of well log interpretation according to the data from Well Logging Centre of Geophysical Division, Kraków

Lachowice 7							Stryszawa 1K					
No.	Formation	*H0* [m]	*H1* [m b.s.l.]	*h* [m]	*V* [m/s]	SB	*H0* [m]	*H1* [m b.s.l.]	*H0r* [m]	*h* [m]	Formation	No.
1	Quaternary	5		5			5		5	5	Quaternary	1
2	Folded Carpathian flysch	2340	1815	2335	2404	v	2445	1806	2331	2326	Folded Carpathian flysch	2
3	Miocene RBAM M1	2575	2050	235	3835	v	2750	2091	2616	285	Miocene RBAM M1	3
4	Miocene BAM M2 M3 M/D	2759	2234	184	4486 5056 4692	v	3092	2409	2934	318	Miocene BAM M2 M3 –	4
5	Upper Devonian limestones D1 D2 D3	2837	2312	78	5049 4090 5774		3106	2422	2947	13	Upper Devonian limestones – D2 D3	5
6	Middle-Upper Devonian dolomites D4 D5	3036	2511	199	5738 5853							
7	Lower Devonian shales D6	3062	2537	26	6387							
8	Cambrian sandstones D7	3098	2573	36	4989	v						
9	Precambrian basement	3127	2603	29	5093						Precambrian basement	6

H0 — geophysical depth (from surface to bottom of the horizon); *H1* — absolute depth; *H0r* — true vertical depth; *h* — thickness; *V* — interval velocity; SB — seismic boundaries resulting from interpretation

sandstone, most probably of Cambrian age (Table 1). The sandstones together with overlying Lower Devonian claystones D6 reveal the similar stratification with dips 6–16° directed to NE. This could advocate for Early Devonian age of sandstones (Oldred?), however, recently they are commonly agreed to belong to Cambrian (Z. Buła, 1994; A. Kotas, 1982*a*, *b*; A. Ślączka, 1982; M. Jachowicz, W. Moryc, 1995). The same northern dip at a lower angle of 2–8° characterises the lower part of probably Middle Devonian dolomites (D5). The higher part of Devonian dolomites (D4) would represent Middle-Upper Devonian (by analogy to Potrójna IG 1 well; A. Ślączka, 1985). These reveal a great scatter of dips resulting most probably from the development of sub-erosional-cavernous and fractured weathering zone. The dipmeter records suggest the occurrence of erosional boundary between the dolomites (D5+D4) and limestones (D3+D2+D1) (Table 1, Fig. 3). In such a case the cavernous-fractured weathering zone in dolomites below the erosional surface as well as the secondary porosity developed in limestone just above the erosional unconformity D4/D3, could have played an essential role for the formation of gas reservoir in Stryszawa.

Between the lower interval of Devonian dolomites (D5) and their higher cavernous-fractured part (D4) there occurs the seismic boundary. The lowermost part of Devonian limestone (D3) resting upon erosional surface of dolomites and limy dolomites (D4) also reveal increased porosity. The limestone complex (D3+D2+D1) shows the upward increase of shale content passing into shales and marls (D1) at the very top of the sequence. The dips in limestones, ranging between 2–12° and directed to SW, are apparently different from those of underlying dolomites. Lithology of (D3+D2+D1) limestones by analogy to Potrójna IG 1 well profile (A. Ślączka, 1985) suggests their Late Famennian-Etroeungtian(?) age. In that case the erosional and overlap relation between the (Middle-Upper? Devonian) dolomites (D5+D4) and (Famennian-Etroeungtian(?) limestones (D3+D2+D1) could be related to Early Bretonian (Svalbardian?) phase.

Apparently the equivalents of lower and middle part of Devonian limestone (D3+D2) (Table 1) of only 13 m in thickness are found in Stryszawa 1K directional well profile. There, they rest directly upon the quartzites of Precambrian substratum dipping at 24–25°N. The absence of the highest part of shale-marl layer of this complex (D1) is significant. Also, the complete absence of lower part of Devonian formation (D6–D4) and the fact that the bottom of Devonian limestone is lying deeper than in Lachowice 7 well profile — prove the occurrence of two different tectonic blocks, that are

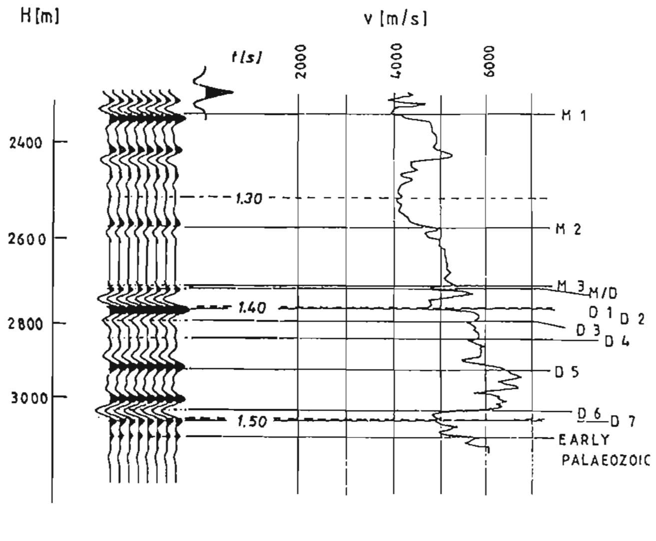

Fig. 6. Synthetic seismogram for Lachowice 7 well profile and acoustic velocity curve from the top of autochthonous Miocene down to Early Palaeozoic; for correlation with lithostratigraphic members see Table 1

Sejsmogram syntetyczny obliczony dla otworu Lachowice 7 zestawiony z krzywą prędkości akustycznych (strop miocenu-starszy paleozoik); dowiązanie litologiczno-stratygraficzne warstw podano w tab. 1

separated with fault, disturbing the Palaeozoic substratum. The fault would be reverse, thus causing the tectonic increase in Miocene thickness in Stryszawa 1K well profile (Fig. 3). According to E. Jawor (personal comment) it is possible that such a rise in thickness could result from pre-Miocene erosion of Palaeozoic surface. However, this would not explain the substantial difference in Palaeozoic between the two neighbouring well profiles neither in sequence nor in the character of its substratum.

Within autochthonous Miocene resting directly upon Palaeozoic substratum the two essential members, named Brecciated Autochthonous Miocene (BAM = M2+M3+M/D — Table 1) and Regularly Bedded Autochthonous Miocene (RBAM = M1) have been recognized. The RBAM (235–285 m thick), occurring just under thrusted Carpathian flysch folds, consists of regularly stratified shale-sand beds showing low dips of 1–5° (Fig. 3). Below, there occurs clastic sand-conglomerate mixture or breccia of the lower part of Miocene deposits — the BAM. These contain considerable amount of limestone clasts, apparently derived from eroded Devonian substratum. This is especially the case by the bottom of Miocene in the so-called transitional zone (M/D), representing most probably the Miocene basal conglomerate in Lachowice 7 well profile. It is to be noted that the equivalent of that member is absent in Stryszawa 1K well profile. Within the BAM in Stryszawa 1K profile the most probable fault zone marked by rapid rise of dip angle and change in azimuth was recognized within 2251 to 2320 m b.s.l. depth interval. Accordingly, it has been found that the reverse fault separating Stryszawa 1K from Lachowice 7 block tilted southward at an angle of 16°, throws its northern wall. In the geologic cross-section (Fig. 3) the apparent dip angle of the fault plane has been considered and its course interpreted due to the planar intersection with hanging (ESE) and foot (WNW) wall of the Carpathian substratum. The fault which has been recorded from seismic line 17-1-86K data interpretation, disturbs the top of Devonian at a distance of 480 m north-west from Lachowice 7 well and its reverse character makes the BAM thickness to be doubled in Stryszawa 1K well profile. The fault could be of early origin, then being rejuvenated due to Variscan tension and finally reversed due to compression coming from Carpathian fold-thrust movements (see below). The fault is of strike-slip character which may explain the difference in geology of the substratum on its opposite walls.

As it results from palaeogeologic reconstruction presented in Figure 4 the fault was normal (tensional) at the beginning of Variscan movements throwing its southern wall (ESE) whereas its northern wall (WNW) was uplifted and eroded at least at 290 m. Principal displacement along the fault plane and extensive erosion of its northern wall could have taken place as early as during Famennian (Svalbardian phase) and later differentiation of the fault blocks (additional throw amounting 34 m) continued due to subsequent phases of Variscan movements.

Obviously it is difficult to restore the geological events during the period of the large gap, embracing Late Palaeozoic, Mesozoic and Early Tertiary. It may be assumed only that in the Early Miocene the tensional stress, responsible for displacement of normal faults from Palaeozoic times has been replaced by compression due to Carpathian fold-thrust movements. As long as the Stryszawa fault was normal the transitional (M/D) breccia (basal conglomerate) was deposited at the bottom of the Miocene by the southern wall of the fault (Lachowice 7). Beginning with that time the fault, rejuvenated by Carpathian fold-thrust movements, was subject to inversion and evolved as a reverse fault. The restored Early Miocene inversional phase of fault movement is presented in Figure 5. The cross-section related to the top of the BAM taken as horizontal datum level shows original position of the fault walls. This was the growth fault syndepositional in relation to brecciated BAM sediments, thus uplifting the southern wall and throwing the northern one.

The period of BAM sedimentation (Karpatian-Early Badenian?) marks the beginning of rejuvenated reverse fault activity. With farther folding and thrusting of Western Carpathians over autochthonous Miocene substratum, the faulting has continued in the form of post-depositional tectonic fracture tilted more flatly, piercing the Carpathian thrust plane and coming up to a certain height among folded flysch. Most probably, these inverted faults, i.e. normal and tensional since Palaeozoic then compressional and transformed into reverse faults starting from Early Miocene (Karpatian) are typical of the majority of tectonic lineaments disturbing the autochthonous Carpathian substratum in the area under study. The inversional faulting due to compression, coming from Carpathian fold-thrust movements, formed structural-tectonic trap for gas accumulation in Stryszawa, sealed up by Miocene molasse both from the top and by juxtaposition across the fault plane. The strike-slip character of the faults (Fig. 2) favoured the sealing conditions of the tectonic traps.

GEOLOGICAL CONCEPT VERIFIED BY SEISMIC MODELLING

The wave pattern in seismic sections from Stryszawa structure zone (Fig. 8) is typical of the Carpathians (K. Pietsch, 1992). Seismic sections are characterized by the lack of continuous long range correlation of seismic boundaries and their various arrangement in the lower and upper complexes. The upper complex, with its most variable position of seismic boundaries, corresponds to allochthonous folded flysch formations. The lower complex that corresponds to autochthonous Miocene and Palaeozoic substratum is distinctive of relatively smooth and low tilted seismic boundaries.

The resulting seismic record is strictly controlled by the geological structure of the area, notably by:

— the presence of folded flysch formations, more than 2000 m thick, composed of turbidite sand-shale alternations;

— the fold-thrust tectonics of Flysch Carpathians and the fault-block structure of their autochthonous basement.

Intricate seismic model of the area makes the recorded wave field ambiguous and difficult to geologic interpretation. Since the reflection boundaries within autochthonous Miocene and its top are indistinct, and the tectonics of folded flysch and its faulted substratum is complex, the seismic record is of interferential character. Reflected waves interfere with intense diffracted waves and side ones.

Geological interpretation of such seismic record is possible only if all the parameters of the wave field have been determined and the role played by individual structural elements of geologic structure has been defined (K. Pietsch, 1988). Such a problem may be resolved by modelling the propagation of seismic waves for a given seismogeologic model that shows the geologic structure in the subsurface. The application of the theoretical seismic record analysis (e.g. 1D modelling) makes it possible to estimate the significance of individual geologic boundaries and rock series in generating a given wave field. The correlation of synthetic wave field (2D modelling) with recorded field allows to restore the real arrangement of seismic boundaries also those which are important for petroleum exploration. 1D and 2D seismogeological models were used for modelling the synthetic seismic wave field of Stryszawa structure. The construction of 1D model was based upon well-log data (sonic logs and density logs for the Lachowice 7 well). The 2D model has been inferred from geologic cross-section of Lachowice 7–Stryszawa 1K segment (Figs. 3, 5) resulting from well-log data (Table 1), and the rough interpretation of seismic time section 17-1-86K.

For one-dimensional modelling of seismic waves propagation the method of synthetic seismograms was adopted using the LOGM program of GMA system (Geophysical Micro Computer Application Ltd.). The theoretical Ricker's signal with dominant frequency of 40 Hz and the parameters close to a signal generated along the traces of 17-1-86K line were applied.

When analysing the theoretical wave field special attention has been paid to Miocene, Devonian and earlier Palaeozoic formations of Carpathian substratum since the distribution of their seismic boundaries is most important for petroleum prospects of the area. The example of synthetic seismogram is presented in Figure 6 together with a sonic log of seismogeological model for Lachowice 7 well. The following velocity intervals has been distinguished in sonic log: M1, M2, M3 and M/D within autochthonous Miocene and D1, D2, D3, D4, D5 and D6 in Devonian. These velocity intervals were related to lithostratigraphic profile considering previously analyzed well-log data (Table 1).

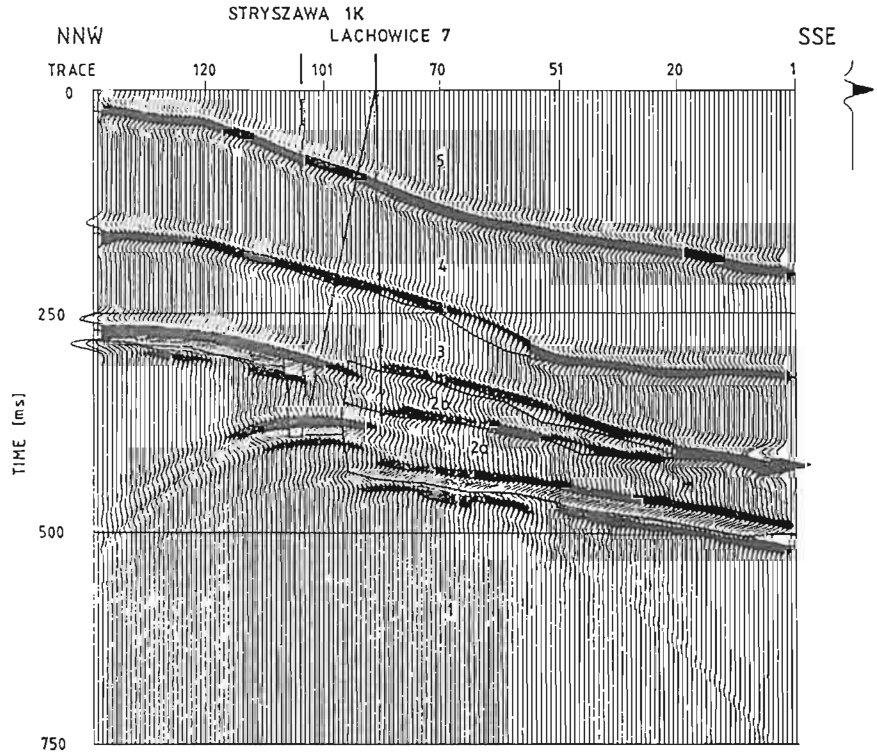

Fig. 7. Seismogeologic model and synthetized seismic cross-section along 17-1-86K line

1 — Precambrian-Early Palaeozoic (Cambrian); 2a — Devonian dolomites; 2b — Devonian limestones; 3 — lower brecciated part of autochthonous Miocene; 4 — upper sandy-shale regularly bedded part of autochthonous Miocene; 5 — folded Carpathian flysch

Model sejsmogeologiczny i syntetyczny przekrój sejsmiczny wzdłuż profilu 17-1-86K

1 — prekambr-starszy paleozoik (kambr); 2a — dolomity dewonu; 2b — wapienie dewonu; 3 — dolna zbrekcjowana część miocenu autochtonicznego; 4 — górna piaszczysto-łupkowa regularnie warstwowana część miocenu autochtonicznego; 5 — sfałdowany flisz karpacki

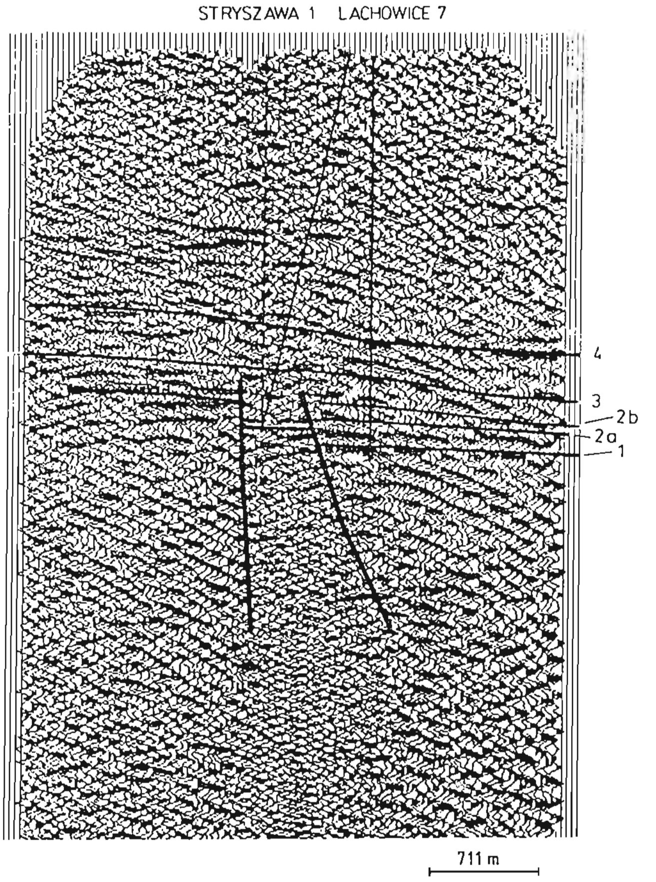

Fig. 8. Reprocessed seismic cross-section 17-1-86K line; the horizons related to the top of Lower Palaeozoic (Cambrian) (1), Devonian dolomite (2a), Devonian limestone (2b), autochthonous Miocene breccia (3), autochthonous Miocene along Carpathian overthrust (4)

Zinterpretowany przekrój sejsmiczny 17-1-86K; poziomy do stropu dolnego paleozoiku (kambru) (1), dolomitów dewonu (2a), wapieni dewonu (2b), autochtonicznej brekcji mioceńskiej (3), miocenu autochtonicznego wzdłuż nasunięcia karpackiego (4)

The lithologic boundaries are readily recognizable from synthetic seismograms. Reflection boundaries of the greatest dynamics correspond to the top of: Miocene (M1), Devonian limestone (D1), and Devonian dolomite (D5), as well as to the interference reflection related to Lower Devonian shales (D6) and the upper part of earlier Palaeozoic.

The bipartite subdivision of autochthonous Miocene into upper regularly bedded sand-shale (RBAM = M1) and the lower brecciated part abundant in carbonate debris (M2, M3, M/D) is readily distinguishable from seismic reflections distribution. Theoretical seismic record of Devonian substratum differs greatly from that of relatively homogeneous autochthonous Miocene.

The synthetic seismograms show that the wave field distribution recorded over Stryszawa structure should reflect the arrangement of seismic boundaries related to the structure of Carpathian autochthonous substratum. The most important for petroleum exploration is to receive the reflection boundaries from the top of Devonian (D1) and the boundary between Upper Devonian limestone (D+D2+D3) and Middle-Upper Devonian dolomite (D5+D6). As mentioned above the dolomite/limestone boundary is decisive for the location and distribution of Devonian limestone reservoir which has appeared to be gas productive in Lachowice 7 well.

The complicated tectonics of the Flysch Carpathians makes it necessary to apply not only 1D but also 2D seismogeological modelling. The seismogeological model used to compute the synthetic seismic cross-section is shown in Figure 7. Apparently it is simplified in comparison to real geological structure but it takes into consideration all the boundaries important for petroleum prospection (see also Table 1). The first main boundary is the thrust plane between overthrusted flysch formations (5) (greatly reduced for modelling) and sand-shale regularly bedded upper part of autochthonous Miocene (4). The second important boundary is that between the upper part of Miocene (4) and its lower brecciated beds (3). Other boundaries taken into consideration are the top of Devonian limestones (2b), and the boundary between Devonian limestones (2b) and dolomites (2a) underlying them. The top of the earlier Palaeozoic and Precambrian (1) at the bottom of 2a is the deepest recognized boundary. The structure of 2a/2b and 2b/3 surfaces shows the position of Devonian gas reservoir carbonates. The trap is closed by the fault from NNW and from SSE being limited by erosional sub-Miocene surface, that truncates Devonian reservoir limestone (Fig. 7).

The synthetic seismic profile (Fig. 7) prepared with the use of STRUCT GMA program is completed with seismogeological model. The two upper seismic boundaries reflect parallel run of gently tilted top Miocene surface (4/5) and intra-Miocene boundary (3/4). Lower brecciated part of Miocene molasse within the narrow fault-framed graben with its 13 m thick Devonian carbonate floor (Stryszawa 1K well profile, Figs. 3, 5, Table 1) is the source of numerous diffracted waves confusing the pattern of the useful ones reflected from intra-Devonian boundary (2a/2b) and the top of Devonian (2b/3). The interference of reflected and diffracted waves distort considerably the image of the structure. The graben structure becomes almost indistinguishable from synthetic seismic record (Fig. 7). It has been obliterated by diffraction waves generated on its northern hanging wall. Those waves interfere with reflected waves, thus creating illusive anticlinal pattern of seismic boundaries that do not correspond to the actual structure. The same effect may occur on time sections record the more that the diffraction waves are not the only disturbing agent. Then, also the wave pattern itself is less clear. The position of Lachowice 7 well and Stryszawa 1K drilling deviated from it as indicated on synthetic seismic profile (Fig. 7) shows that the deviated well has been designed as based on such misleading seismic record.

Also, the results of the above modelling indicate the usefulness of theoretical wave field analysis to be completed before geologic interpretation of seismic data acquired from complex sub-Carpathian structure is made. The modelling of seismic wave field allows to define geological premises for the subsurface interpretation of seismic record.

SEISMOGEOLOGICAL INTERPRETATION OF CARPATHIAN AUTOCHTHONOUS SUBSTRATUM

The results of seismic modelling for 1D and 2D seismogeological models describing the structure of Carpathians in Stryszawa area reveal high complexity of the wave field. Nevertheless these also proved it possible to contour the structure of autochthonous substratum of Carpathian orogen.

To determine the structural arrangement of the sub-Carpathian boundaries in Stryszawa zone, the seismic-and-geological interpretation of seismic data has been performed with the use of the SEIS WORK 2D program in LANDMARK workstation.

First stage of interpretation work was to construct the time-depth model in well profile using SYN TOOL program on LANDMARK workstation. This allowed to define the relationship between the depth interval in a well profile and the time scale of seismic record. With this aim the sonic log and lithostratigraphy of well profile together with seismic records from 17-1-86K line were used as input data. The general correspondence of reflections pattern as simulated on synthetic seismogram (correlated with lithostratigraphic boundaries) with those recognizable in seismic time section, proves the possibility of geological matching the seismic horizons.

As a second step of interpretation resulting from synthetic profiles already prepared (Fig. 7) the seismic horizons were correlated in the seismic sections shot in the area under study. Additionally, the migrated time sections with majority of diffraction waves being removed were also used. Geological adjustment of reflections on the 17-1-86K line in the vicinity of Lachowice 7 well created the basis for geological fitting of seismic horizons in time sections. This fitting is quite reliable in the zones of good correlation of reflections only within the same side of a given fault. In different zones separated by faults the correlation is only probable. It is also presumable in zones where the quality of available seismic data is low.

Figure 8 shows the example of the interpretation of seismic profile 17-1-86K. There, the seismic boundaries correspond successively to the top surfaces of the same lithostratigraphic members as those recognized in synthetic seismic profile (Fig. 7, Table 1).

Major faults disturbing Palaeozoic and Miocene of autochthonous substratum up to the lowermost part of folded flysch were also identified in the seismic profiles. The faults delimit blocks in the Palaeozoic basement. Their position proves the occurrence of a tectonic graben, best seen in 17-1-86K seismic line (Fig. 8). As results from our interpretation, the Stryszawa 1K well went into the central part of this graben. The most promising part of Stryszawa structure trap seems to be bordered by the tectonic graben on NNW (Figs. 2, 8), and by meridional fault (Fig. 2) on WSW, whereas to SSE the reservoir is truncated by sub-Miocene erosional surface (Figs. 2, 8).

The authors reinterpreted the seismic sections, shot in 1986–1991 (half of them being reprocessed by POGC, Geophysical Division, Kraków, 1995) and contoured the time-structural map of the top of Palaeozoic substratum in Lachowice–Stryszawa area (Fig. 2). The density of seismic lines shot in the area is rather low and equals merely to 1.1 km/km^2, which makes difficult to locate the sub-Carpathian structures, the area of which can be as small as 1–3 km^2. Therefore the proposed version of the structure map presented here may only be taken as a sketch, resulting from the efforts of contouring the coherent scheme of tectonic structure and prospective zones of petroleum accumulation.

The system of nearly latitudinal faults striking from ENE to WSW at a distance of at least 6–10 km (azimuth about 250°) is apparently the most distinctive structural element of Carpathian substratum in the area under study. The distance between neighbouring longitudinal faults may occasionally decrease to 0.3–1.1 km and then they frame relatively narrow tectonic grabens or horsts. Within larger intervals, where parallel faults run apart at a distance 2.2–3.7 km the structure of Palaeozoic surface is relatively gentle. Longitudinal faults forming the southern frame of narrow grabens are usually the reverse faults. They may have originated due to Variscan tension, being then transformed into reverse faults as a result of Carpathian fold-thrust compression. Longitudinal faults that frame grabens from northern side are usually normal or vertical, though they may also happen to be reverse compressional ones. Both types of longitudinal faults are characterized by slightly sinuous, divergent and convergent course, variable amount and direction of throw, which speaks for their strike-slip (oblique-slip) character. The majority of longitudinal fault planes are inclined southward. Many of them find their continuation in flatly tilted thrust fault planes disturbing the main Carpathian thrust and continuing up to a certain height within the folded flysch.

The longitudinal faults are accompanied by relatively narrow peri-fault structures. They are shifted across the fault plane or just alternately placed along opposite walls of the fault, which also points to their displacement along the wrench fault.

The structures confined to or framed by closely spaced pairs of strike-slip faults are elongate in shape and small in size. Such a system of small fault-confined structures is observed along a pair of wrench longitudinal faults disturbing the Lachowice elevation (Fig. 2) i.e. Lachowice 3–Lachowice 1–Lachowice 2 wells. Among these only Lachowice 1 well encountered gas from Devonian reservoir. The Lachowice gas field entrapped on a downthrown wall in fault-confined structure is sealed up by longitudinal strike-slip fault and separated from hanging wall where other wells appeared to be dry.

Having in mind the above concept of strike-slip fault and peri-fault tectonics the attempt was made to extrapolate in a coherent way the structure contours of Palaeozoic substratum over the remaining part of the area. This allowed to locate possible position of other elevations within unexplored zone north from Lachowice towards Krzeszów. The structures marked with cross on a map show the position of possible local elevations (Fig. 2).

The only transverse fault of sub-meridional orientation that could be contoured on the map (Fig. 2) is the fault running roughly NW–SE starting from Stryszawa 1K well. In the northern part the fault is reverse, whereas more to the south it changes probably into the normal one. The fact that only one meridional fault has been recognized in the area may result from actually lower frequency of transversal tectonic fractures or from sparseness of seismic data in east-west direction. Structural-tectonic pattern of consolidated basement and Palaeozoic substratum of western frontal section of Polish Carpathians in Cieszyn–Bielsko-Biała area also proves that latitudinal orientation of tectonic lineaments prevail (S. Szafran, R. Nowak, 1984).

The sub-meridionally oriented transcurrent fault separates the Lachowice structure in SW from Stryszawa elevation in NE (Fig. 2). The latter forms fault confined anticline bordered from the north by reverse longitudinal fault (which makes a frame to 300–500 m wide tectonic graben) and from the west bounded by transcurrent fault. The crest of the anticline is situated by the juncture of above mentioned faults. It is possible that the fault junction and the narrow graben had been reflected in palaeomorphological depression which became wider as a result of pre-Miocene erosion. Presumably, the Stryszawa structure may continue eastwards at a distance of 2 km along latitudinal fault and southwards at about 1 km along meridional fault. It is also probable that southern segment of Stryszawa Anticline finds its northeastern continuation on the opposite northern wall of longitudinal fault. South from Stryszawa (Lachowice 7 well) beyond relatively broad and gentle syncline, one may expect the occurrence of northeastern continuation of Lachowice structure connected with the next pair of longitudinal, strike-slip faults. This narrow bifurcated zone has been contoured with 1300 ms isochrone. However, farther reconnaissance of these local structures needs more detailed 2D or 3D seismic surveys.

CONCLUSIONS

Combined interpretation of geological, seismic and well log data allowed to postulate the following conclusions on the concept of geological structure and petroleum perspectives of sub-Carpathian autochthonous substratum in Lachowice–Stryszawa zone:

1. Analysis of geological and well log data, including dipmeter record, makes it possible to restore the structure of Carpathian autochthonous substratum in Stryszawa area. In such a way the presence of inversional reverse fault, closing up the gas trap anticline from the north, was confirmed. The correlation of Lachowice 7 and Stryszawa 1K wells together with restoration of the fault evolutionary stages suggests the presence of erosional unconformity between Middle-Late Devonian dolomite and Late Devonian limestone, which may have enhanced the development of fractures and secondary porosity in carbonate reservoirs. The geological and well log interpretation was the basis for seismic modelling, necessary to establish the criteria for geological interpretation of seismic data.

2. Seismic modelling (one- or two-dimensional) confirmed the difference between seismic record characteristic of folded flysch formations and its autochthonous substratum, which allowed to delineate the top surface of autochthonous Miocene. It has been possible to recognize seismically the lower part of brecciated autochthonous Miocene (BAM) from its upper regularly bedded interval (RBAM). Also, the top Devonian boundary and some other velocity boundaries within Palaeozoic substratum appeared to be traceable with seismics. The top of Devonian interface and the recording of the seismic boundary between Devonian dolomite and limestone are of special importance for petroleum exploration since they enable to contour gas trap structures and reservoir beds such as those of Stryszawa.

3. The absence of distinct reflection boundaries within Miocene formation and the complicated tectonics of folded Carpathian flysch and fault-block Palaeozoic substratum is the source of interference of seismic waves. The geological interpretation needs modelling of seismic waves propagation accomplished for assumed models that approximate the geologic structure. Two-dimensional modelling proved the occurrence of the narrow fault-framed tectonic grabens disturbing Palaeozoic substratum and filled with autochthonous Miocene molasse. These are the source of numerous diffraction waves, distorting the image of seismic interfaces from Devonian and deeper substratum. The interference of these seismic waves makes narrow tectonic grabens hardly detectable and an illusive record of non existing anticlines appears instead. This phenomenon may partly be eliminated by applying migration procedures.

4. The tectonic lineaments of sub-latitudinal orientation forming pairs of closely spaced strike-slip (oblique-slip) faults are predominant feature of fault-block tectonics in sub-Carpathian autochthonous substratum. These longitudinal faults frame narrow horst-grabens (sometimes only 0.3–0.9 km in width). The structures occurring within larger fault-blocks (2–4 km in width) are broader and more gentle. The transversal faults of sub-meridional orientation probably also of strike-slip character are less frequent. Pre-Miocene erosion enhanced the effect of fault-block differentiation of the substratum.

5. Fault-block tectonics of Carpathian substratum shows inversional character. Longitudinal normal faults of sub-latitudinal orientation developed under tensional regime during Variscan epoch and have been later transformed into reverse ones (starting from Early Miocene, Karpatian/Badenian) as a result of compression due to Carpathian fold-thrust tectonics. At the beginning of tectonic inversion the reverse growth faults evolved syndepositionally with Early Miocene BAM molasse. Later, they developed as low tilted thrust faults disturbing the main plane of Carpathian thrust and continued

up to a certain height within folded flysch. As a result of such tectonic evolution the thickness of Devonian in presently uplifted blocks of Carpathian substratum may be larger then on the downthrown wall of the faults.

6. Gas accumulations in Carpathian autochthonous substratum (Lachowice–Stryszawa area) are confined to fractured, cavernous zones of weathering in Devonian dolomite and diagenetically alternated part of Famennian limestone which occur respectively below and above the erosional surface separating them. This erosional boundary may be related to Early Bretonian (Svalbardian) movements in the Late Famennian. The gas traps are represented by small fault-confined anticlines sealed off by longitudinal strike-slip faults or sometimes by the junction of latitudinally and meridionally oriented faults (e.g. Stryszawa). The gas deposits may occur both on downthrown (Lachowice) or upthrown wall of the fault (Stryszawa). These traps sealed off by impermeable autochthonous Miocene are of structural, tectonic and stratigraphic character (pre-Miocene erosion).

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INTERPRETACJA GEOLOGICZNA I GEOFIZYCZNA PODKARPACKICH STRUKTUR GAZONOŚNEGO DEWONU AUTOCHTONICZNEGO W REJONIE LACHOWIC–STRYSZAWY

Streszczenie

Ropo- i gazonośność podłoża południowo-zachodniej części polskich Karpat fliszowych, zarówno w obrębie południowego przedłużenia miocenu autochtonicznego, jak i platformowych utworów dewonu i karbonu (potwierdzona wynikami wierceń Sucha IG 1, Lachowice 1, Zawoja 1), dały asumpt do penetracji kolejnych struktur podkarpackich w tym rejonie.

Szczególną rolę w poszukiwaniu struktur w podłożu Karpat odgrywają badania sejsmiczne, których dynamiczny rozwój w ostatnich latach stworzył możliwość uzyskania odbić od powierzchni nasunięcia sfałdowanego fliszu, spągu miocenu autochtonicznego oraz platformowego podłoża paleozoicznego. Interpretacja geofizyczno-geologiczna materiałów sejsmicznych z Karpat i ich podłoża pozostaje wciąż niejednoznaczna. Metodą wspomagającą interpretację są modelowania sejsmiczne, które mogą stanowić podstawę do identyfikacji fal użytecznych i zakłócających oraz geologicznego dowiązania śledzonych granic sejsmicznych.

Obiektem badań jest wyniesienie podłoża w rejonie Stryszawy (ok. 4 km na NE w kierunku Suchej Beskidzkiej), na którym otworem Lachowice 7 odkryto złoże gazu w utworach węglanowych dewonu. Otwór kierunkowy Stryszawa 1K natomiast, prowadzony z tego samego miejsca i odchodzący 900 m na WNW, nawiercił strop dewonu 155 m niżej, wchodząc w strefę pozazłożową.

Pierwszym etapem badań była interpretacja budowy geologicznej podłoża autochtonicznego i na jej podstawie konstrukcja modelu sejsmogeologicznego. Rozkład granic sejsmicznych oraz parametry sejsmiczne warstw opracowano, posługując się interpretacją litologiczną profilowań geofizyki wiertniczej, wykonaną przez Ośrodek Interpretacji i Metodyki Geofizyki Wiertniczej Zakładu „Geofizyka" — Kraków, profilowaniami upadu warstw dla otworów Lachowice 7 i Stryszawa 1K (weryfikacja wydzieleń oraz lokalizacja niezgodności i uskoków), wstępną interpretacją danych sejsmicznych zarejestrowanych przez Zakład „Geofizyka" — Kraków, jak również informacjami geologicznymi o budowie i wynikach poszukiwań naftowych w badanym rejonie.

W układzie warstw i kompleksów tworzących model sejsmogeologiczny podłoża autochtonicznego Karpat w rejonie Stryszawy, bezpośrednio pod sfałdowanym i nasuniętym fliszem występują utwory miocenu — w górnej części osady piaszczysto-ilaste regularnie uwarstwione, niżej utwory piaszczysto-ilaste, zaburzone z udziałem brekcji i zlepieńców oraz fragmentów skał węglanowych. Podłoże (od góry) zbudowane jest z wapieni, dolomitów i iłowców dewonu oraz piaskowców, najprawdopodobniej, kambryjskich, zalegających na łupkach eokambru (Lachowice 7). W profilu otworu kierunkowego Stryszawa 1K wapienie dewońskie spoczywają bezpośrednio na kwarcytach podłoża prekambryjskiego.

Redukcja miąższości węglanowych utworów wyższego dewonu, całkowity brak starszych utworów dewonu oraz obniżenie o 110 m położenia spągu wapieni dewonu w otworze Stryszawa 1K w stosunku do otworu Lachowice 7 zinterpretowano jako wskaźnik istnienia dwóch różnych bloków tektonicznych podłoża paleozoicznego. Rozdzielający je uskok zinterpretowano jako odwrócony o rozwoju inwersyjnym. Mechanizm rozwoju uskoku sugeruje istnienie niezgodności erozyjnej między wapieniami i dolomitami dewonu, która mogła mieć wpływ na rozwój szczelinowatości i wtórnej porowatości w obrębie gazonośnego horyzontu zbiornikowego.

Drugi etap badań to konstrukcja teoretycznych pól falowych dla oceny roli poszczególnych granic sejsmicznych modelu w formowaniu pola falowego, czyli identyfikacja warstw, które mogą być kartowane sejsmicznie oraz rozpoznanie ich przestrzennego ułożenia.

Pierwsze z zadań rozwiązano drogą modelowań jednowymiarowych, czyli drogą konstrukcji sejsmogramów syntetycznych, drugie — za pomocą modelowań dwuwymiarowych, w wyniku których uzyskano syntetyczne profile sejsmiczne.

Modelowania sejsmiczne zostały wykonane w systemie GMA (Geophysical Micro Computer Application Ltd.), pracującym na komputerze PC 486, programami LOG M i STRUCT.

Sejsmogramy syntetyczne wskazują, że w polu falowym odwzorowana jest duża część granic litostratygraficznych, które zostały wyznaczone w modelu sejsmogeologicznym. Są to kolejno: strop miocenu autochtonicznego, granica między warstwowanym miocenem piaszczysto-ilastym a zaburzonym układem utworów mioceńskich z udziałem węglanów, granica między utworami miocenu a węglanowymi utworami dewonu, a także między wapiennymi i dolomitycznymi utworami dewonu oraz granica odpowiadająca stropowi starszego paleozoiku. Szczególnie istotna dla poszukiwań naftowych jest możliwość identyfikacji granicy między dolomitami i wapieniami dewonu oraz granicy stropu dewonu, określających gazonośną strefę Lachowic i Stryszawy.

Zaangażowanie tektoniczne podłoża Karpat fliszowych powoduje, że rejestrowane pole falowe jest polem silnie interferencyjnym, w którym na odbicia pochodzące od zidentyfikowanych wyżej granic sejsmicznych nakładają się fale zakłócające, przede wszystkim fale dyfrakcyjne towarzyszące uskokom. Do ich identyfikacji wykorzystano syntetyczne profile sejsmiczne obliczone dla opracowanego modelu sejsmogeologicznego.

Analiza profilu syntetycznego wskazuje, że w zapisie odwzorowany jest jednoznacznie strop utworów miocenu i granica wewnątrzmioceńska. Założony w modelu niewielki międzyuskokowy rów tektoniczny, wypełniony utworami miocenu, jest źródłem licznych fal dyfrakcyjnych, które zakłócają obraz fal odbitych od stropu starszego paleozoiku, granicy wewnątrzdewońskiej oraz stropu dewonu. W syntetycznym zapisie sejsmicznym rów ten staje się w zasadzie niewidoczny. Jest on zamaskowany falami dyfrakcyjnymi powstającymi na krawędziach rowu, które interferując z falami odbitymi tworzą pozorny obraz antyklinalnego ułożenia warstw. Przyjęcie obrazu zinterferowanego jako rzeczywistego odwzorowania struktur może prowadzić do błędnej lokalizacji otworów wiertniczych.

Kolejny etap badań obejmuje interpretację sejsmiczno-geologiczną zarejestrowanych przekrojów na stacji roboczej LANDMARK (z wykorzystaniem programów SYN TOOL i SEIS WORK 2D) w celu określenia układu strukturalnego granic podfliszowych. Geologiczne dowiązanie refleksów, wykonane na profilu 17-1-86K w strefie lokalizacji otworu Lachowice 7, stanowiło podstawę do geologicznego dowiązania horyzontów sejsmicznych na przekrojach czasowych. Na przekrojach zidentyfikowano również, wyko-

rzystując wnioski wynikające z interpretacji profilu syntetycznego, uskoki naruszające podłoże paleozoiczne, osady mioceńskie oraz spągową część fliszu. Ich wzajemne ułożenie wskazuje na istnienie rowu tektonicznego ograniczającego od północy strukturę Stryszawy. Według przedstawionej interpretacji otwór Stryszawa 1K wszedł w środkową część tego rowu. Perspektywiczna pod względem złożowym część struktury Stryszawy wydaje się być ograniczona od NNW rowem tektonicznym, od WSW uskokiem, a od SSE skrzydłowym obniżeniem powierzchni podmioceńskiej.

Końcowym wynikiem interpetacji było opracowanie strukturalnego szkicu czasowego granicy stropu podłoża paleozoicznego rejonu Lachowic–Stryszawy. Budowa strukturalna zdominowana jest tu tektoniką dysjunktywną, obejmującą przede wszystkim odwrócone dyslokacje równoleżnikowe, tworzące pary blisko leżących uskoków przesuwczych, ograniczających wąskie zrębo-rowy. Uskoki południkowe występują rzadziej. Akumulację gazu w podłożu można wiązać z niewielkimi antyklinami przyuskokowymi, zamkniętymi przede wszystkim uskokami równoleżnikowymi. Pułapki uszczelnione miocenem autochtonicznym mają charakter strukturalno-tektoniczno-stratygraficzny. Uskoki pierwotne naruszające podłoże paleozoiczne powstały w reżimie tensyjnym, po czym, jako uskoki potomne, uległy inwersji wskutek kompresji jaka towarzyszyła ruchom fałdowo-nasunięciowym Karpat fliszowych.

Zamiarem autorów było wykazanie przydatności kompleksowego podejścia geologiczno-geofizycznego do problematyki poszukiwań naftowych w obrębie podłoża autochtonicznego zachodniej części polskich Karpat fliszowych.