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Tensional tectonics in the Pomeranian section of the T-T Zone and the implications for hydrocarbon exploration

The pattern of sub-Permian horizons correlated on seismic sections of the Pomeranian Swell and Pomeranian Trough suggests the existence of tilted blocks and half-grabens connected with the tensional nature of the tectonics of the T-T Zone. The tilted blocks and asymmetric half-grabens are believed to be significant for hydrocarbon exploration. The rollover anticline identified on seismic sections in the Koszalin area serves as an example.

INTRODUCTION

The Polish section of the large tectonic lineament called the Tornquist Zone (TZ) has been named the Teisseyre-Tornquist Zone (TTZ). It has been identified by A. Guterch (1968) and A. Guterch *et al.* (1986) as a deep tectonic trough, a Moho trough, with palaeorift properties. The width of the TZ ranges from 20 to 100 km, while the width of the Pomeranian section is about 50 km. The portion of the TZ north-west of TTZ has been defined as Sorgenfrei-Tornquist Zone (STZ). These two segments are offset near Bornholm Island (Fig. 1). The TZ was the zone of repeated rifting, compression and strike-slip movement and its activity started in the latest Precambrian. The marine reflection profiles in the area north-west of Bornholm Island (Scania, Kattegat, northern Denmark) show a mosaic of tilted, half-graben shaped blocks — the result of dextral wrench movements which dominated in the Late Palaeozoic (Fig. 2). Strike-slip movements were accompanied by intrusions of dikes in Scania. During Mesozoic times tensional stresses led to further subsidence of rifted basins which process was also accompanied by volcanic activity. Change of the stress field into transpression led to Cretaceous/Early Tertiary inversion. To the NW this inversion becomes less pronounced (*Babel Working Group*, 1991).

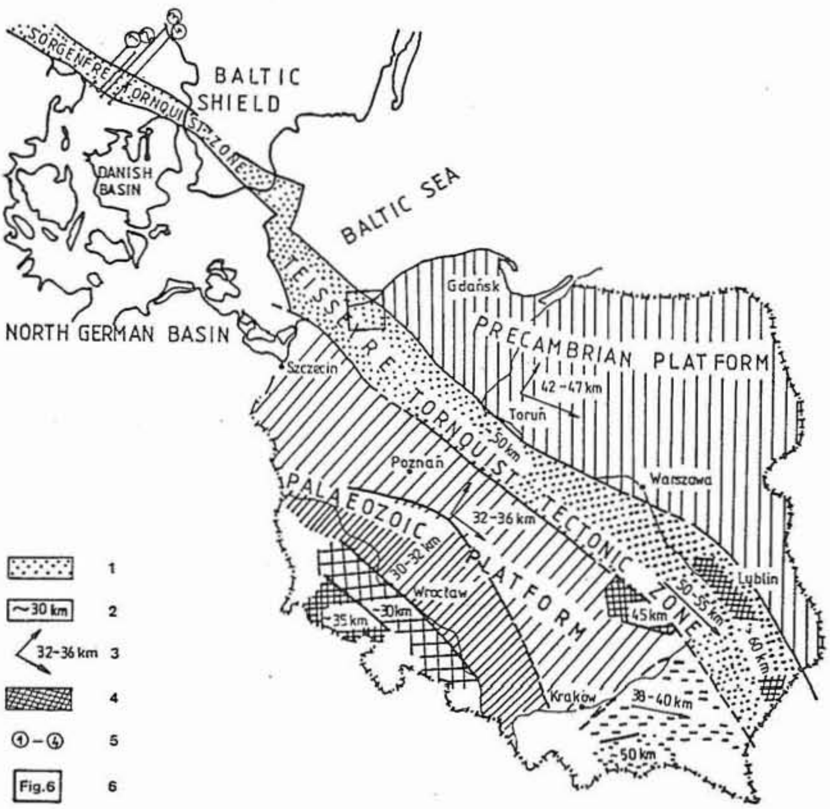

Fig. 1. The Tornquist Zone consists of two segments that are offset SW of Bornholm Island
1 — the Tornquist tectonic zone; 2 — depth to the Moho discontinuity; 3 — depth to the Moho discontinuity in kilometres and directions of increase of crustal thickness; 4 — anomalous zone in crustal structure in the T-T Zone (after *Babel Working Group*, 1991 and A. Guterch *et al.*, 1986); 5 — location of cross-sections in Fig. 2; 6 — location of map in Fig. 6

Strefa Tornquista, składająca się z dwóch części przesuniętych względem siebie na SW od Bornholmu
1 — strefa tektoniczna Tornquista; 2 — głębokość występowania niezgodności Moho; 3 — głębokość występowania niezgodności Moho i kierunki wzrostu miąższości skorupy; 4 — strefa anomalnej budowy skorupy w strefie T-T; 5 — lokalizacja przekroju z fig. 2; 6 — lokalizacja mapy z fig. 6

PREVIOUS STUDY

Geological data assembled in Poland during the eighties increasingly suggested a tensional nature of the tectonics in the Permian basin basement. Tensional movements were inferred, in part, from studies aimed at defining the distribution of the Main Dolomite barrier zones. As already noted in the late seventies (L. Antonowicz, L. Knieszner, 1981), the pattern of these zones defined by seismic methods (Fig. 3), is the result of tectonic activity. Drilling data revealed that the occurrence of Main Dolomite lagoonal sediments bounded

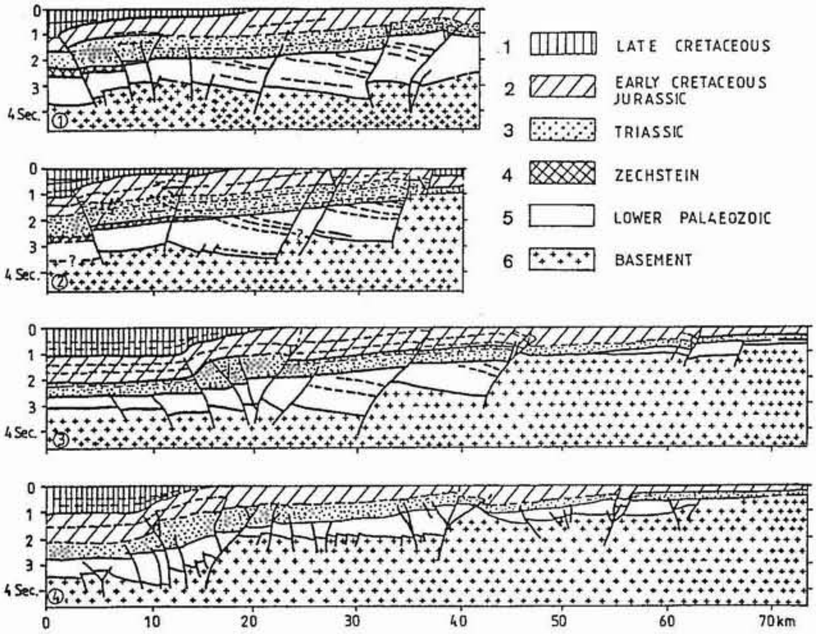

Fig. 2. Cross-sections based on seismic lines crossing Fennoscandian border zone in the area of Kattegat (location see Fig. 1) after P. A. Ziegler (1990)

Przekroje skonstruowane na podstawie interpretacji czasowej sekcji sejsmicznych przecinających granicę Fennoskandii w rejonie Kattegatu (lokalizacja na fig. 1) według P. A. Zieglera (1990)

1 — kreda górna; 2 — kreda dolna i jura; 3 — trias; 4 — cechsztyn; 5 — paleozoik dolny; 6 — podłoże

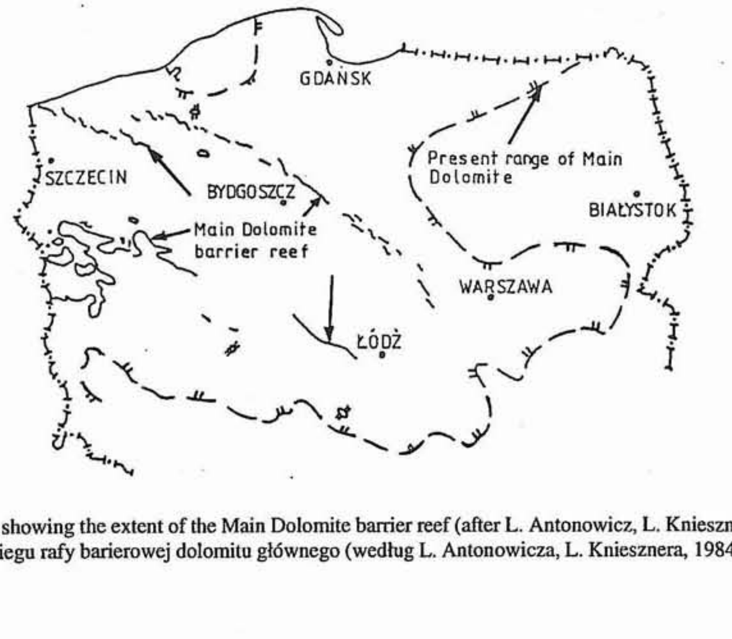

Fig. 3. Map showing the extent of the Main Dolomite barrier reef (after L. Antonowicz, L. Knieszner, 1984)

Mapa przebiegu rafy barierowej dolomitu głównego (według L. Antonowicza, L. Kniesznera, 1984)

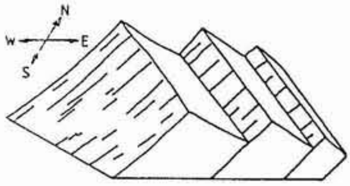

Fig. 4. Scheme showing the arrangement of the Permian basement blocks (after L. Antonowicz, S. Roman, 1986)
Schemat ułożenia bloków podłoża permu (według L. Antonowicza, S. Romana, 1986)

by barriers coincides with Permian palaeohighs. Therefore, barrier sediments in the Main Dolomite could be expected to follow the pattern of the elevated portions of the tilted blocks in the Permian basement. This, in turn, led to the opinion formulated by L. Antonowicz and S. Roman (1986) that "... the bottom configuration of the Permian basin in the area of the present Pomeranian Anticlinorium was controlled by faulting parallel to the Teisseyre-Tornquist line. This faulting produced step-like subsidence of blocks with their western margins higher than the eastern ones and upper surfaces dipping towards SE ...". This concept was illustrated by a block distribution model (Fig. 4). Likewise, J. Kutek (1980) envisaged a rotational nature of the displacements of many blocks in the deeper basement,

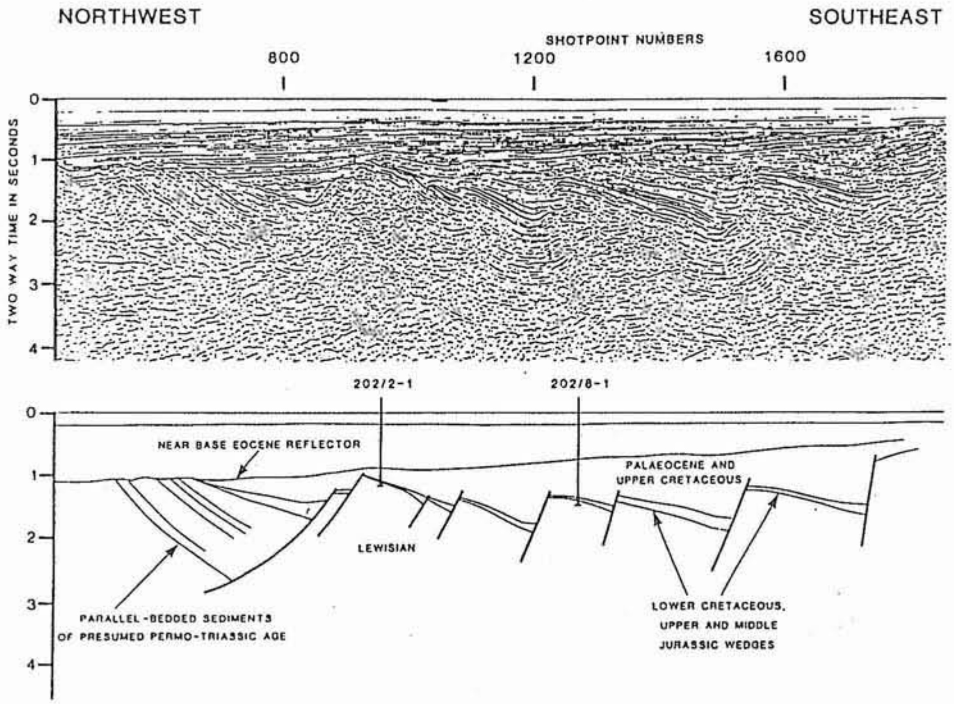

Fig. 5. Migrated time section of the northern shore of Scotland (after S. R. Kirton, K. Hitchen, 1987)
Zmigrowana czasowa sekcja sejsmiczna z rejonu na północ od wybrzeży Szkocji (według S. R. Kirtona, K. Hitchena, 1987)

Fig. 6. Structural map of the reflection horizon D3 of the Ustronie Morskie – Daszewo – Sarbinowo area
The large structure with the Carboniferous and upper portion of the Devonian truncated in the crestal part interpreted as rollover anticline; 1 – 4 — location of seismic profiles from Fig. 7; 1 — faults; 2 — the D3 horizon is not traceable beyond the serrate line; 3 — trend of the large fault separating the investigated block from NE (see Figs 7–9); 4 — isohypses in hectometres below sea level
Mapa strukturalna granicy refleksyjnej D3 z rejonu Ustronia Morskiego – Daszewa – Sarbinowa
Duża forma strukturalna ze ściętym w szczytowej partii karbonem i górną częścią dewonu interpretowana jest jako antyklina kompensacyjna; 1 – 4 — lokalizacja profili sejsmicznych z Fig. 7; 1 — uskoki; 2 — zasięg śledzenia horyzontu sejsmicznego D3; 3 — przebieg wielkiej dyslokacji ograniczającej badany blok od NE (patrz fig. 7–9); 4 — izohipsy w hektometrach poniżej poziomu morza

the presence of which in the Polish Lowlands is manifested by rapid thickness changes of the Mesozoic sediments.

In the section across the T-T Zone R. Dadlez (1974) shows a synthetic pattern of blocks and in a later section across the Kołobrzeg Block (R. Dadlez, 1993) the Middle Palaeozoic horizons in some segments are tilted towards NE, this latter section being already constructed from good quality seismic results.

To verify this reasoning based on analogies and indirect indications it is necessary to confirm on seismic profiles a distinctive arrangement of blocks similar to that known from northern Scotland (Fig. 5).

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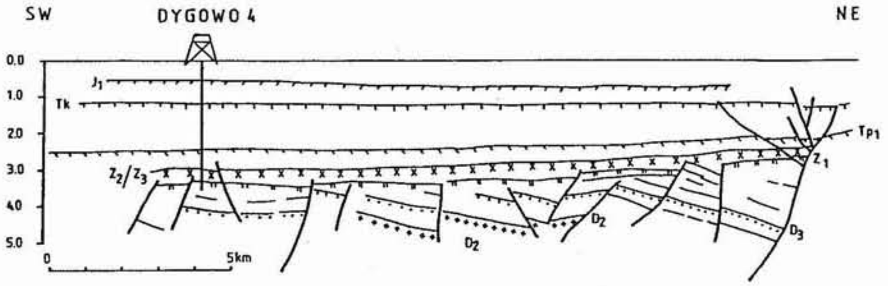
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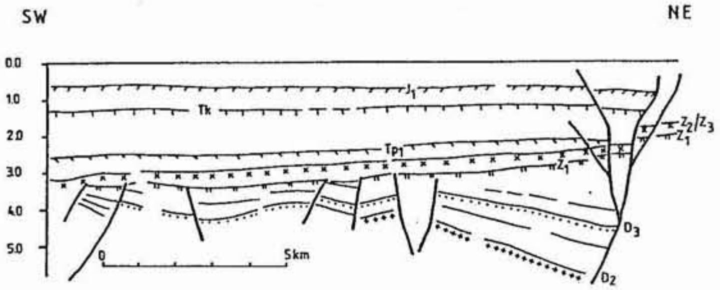
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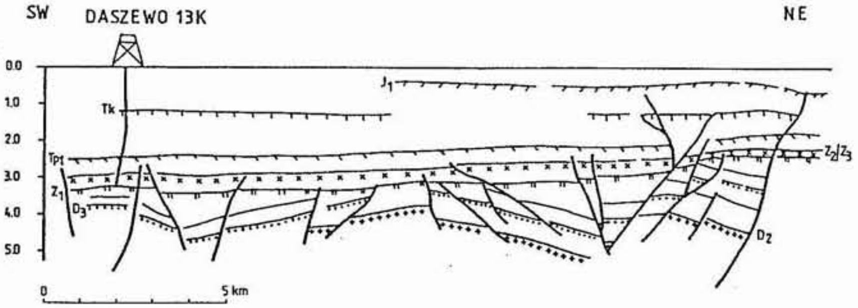
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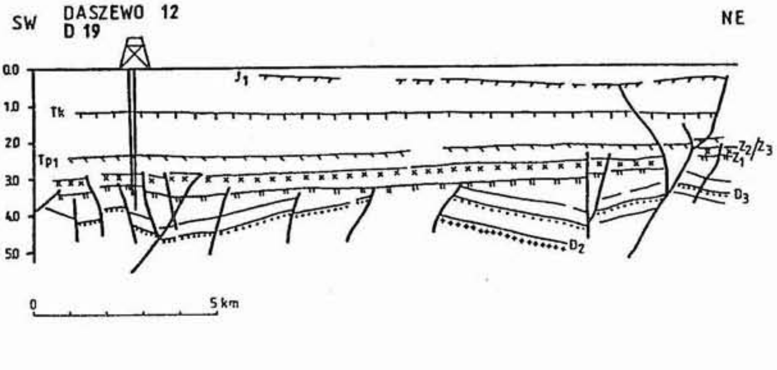
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SEISMIC DATA

The understanding of the tectonics of the Pomeranian section of the TTZ is greatly hindered by difficulties in obtaining seismic reflections from sub-Zechstein sequences due to unsufficient amounts of seismic energy penetrating formations older than Zechstein. In the Zechstein basin high-velocity anhydrite-carbonate sequences separating salts constitute excellent reflecting surfaces absorbing such large amounts of seismic energy, that the remaining energy is too low to penetrate underlying formations. Another obstacle is the low-velocity zone, exceptionally thick in the Pomerania region.

An additional reason for the failure to record seismic reflections in some areas is the geological structure itself. The extent of Variscan folding, still disputable, is also the northern boundary of the area where, with the present techniques, it is not possible to obtain and interpret reflections from sub-Permian formations. Consequently, interpretation of sub-Zechstein reflections in the Polish Lowlands is highly unreliable.

In search of record similar to that shown in Figure 5, all better quality seismic reports from the Pomerania area have been re-examined. The results permitted to set forth a hypothesis that the tectonic style in the Kołobrzeg area is determined by extensional stresses (L. Antonowicz *et al.*, 1993). Old results improved by reprocessing together with new better-quality seismic materials have supplied new information on the tectonics of the sub-Permian sediments in the Pomerania area.

Seismic profiles shot during the period of 1969–1986 in the Ustronie Morskie – Koszalin area have been reprocessed at the Computer Center, Geophysical Enterprise in Toruń including: (1) improvement of static and dynamic corrections permitting better summing up of the seismic signal, (2) selection, by tests, of appropriate filtration parameters substantially improving resolution of the seismic record by reducing the number of reflection phases and (3) new migration programme permitting a fairly reliable definition of true dip angles in the individual horizons. Due to this reprocessing the seismic results for the entire Palaeozoic-Mesozoic complex have been significantly improved enabling the distinction and interpretation of reflections from sub-Zechstein horizons.

Distinction of the sub-Permian seismic boundaries was based on their unconformable relationship with Mesozoic and Permian horizons which prevented correlational errors related to possible multiple reflections. Reflections from the Carboniferous and Devonian boundaries are mutually conformable and have a variable amplitude throughout the length of the profile line.

Fig. 7. Depth seismic profiles of the Ustronie Morskie – Daszewo – Sarbinowo area (location see Fig. 6)
The great fault in the NE is manifested in the Mesozoic formations as a graben inverted during syn-Alpine remodelling; the fault bordering the tilted block in the SW is poorly pronounced in the Mesozoic; in the middle — rollover anticline, a horst bounded by two grabens; D_2 — Middle Devonian, D_3 — Upper Devonian, Z_1, Z_2/Z_3 — Zechstein horizons, Tp_1 — top of the Lower Buntsandstein, T_k — Keuper, J_1 — Lower Jurassic

Głębokościowe profile sejsmiczne z rejonu Ustronia Morskiego – Daszewa – Sarbinowa (lokalizacja na fig. 6)
Wielki uskok na NE manifestuje się w utworach mezozoicznych jako rów wyniesiony inwersyjnie w czasie przebudowy syn–alpejskiej; uskok ograniczający pochyłony blok od SW w mezozoiku zaznacza się słabo; między nimi, ograniczony dwoma rowami zrąb — antyklina kompensacyjna; D_2 — dewon środkowy, D_3 — dewon górny, Z_1, Z_2/Z_3 — granice cechsztynu, Tp_1 — strop dolnego pstrego piaskowca, T_k — kajper, J_1 — jura dolna

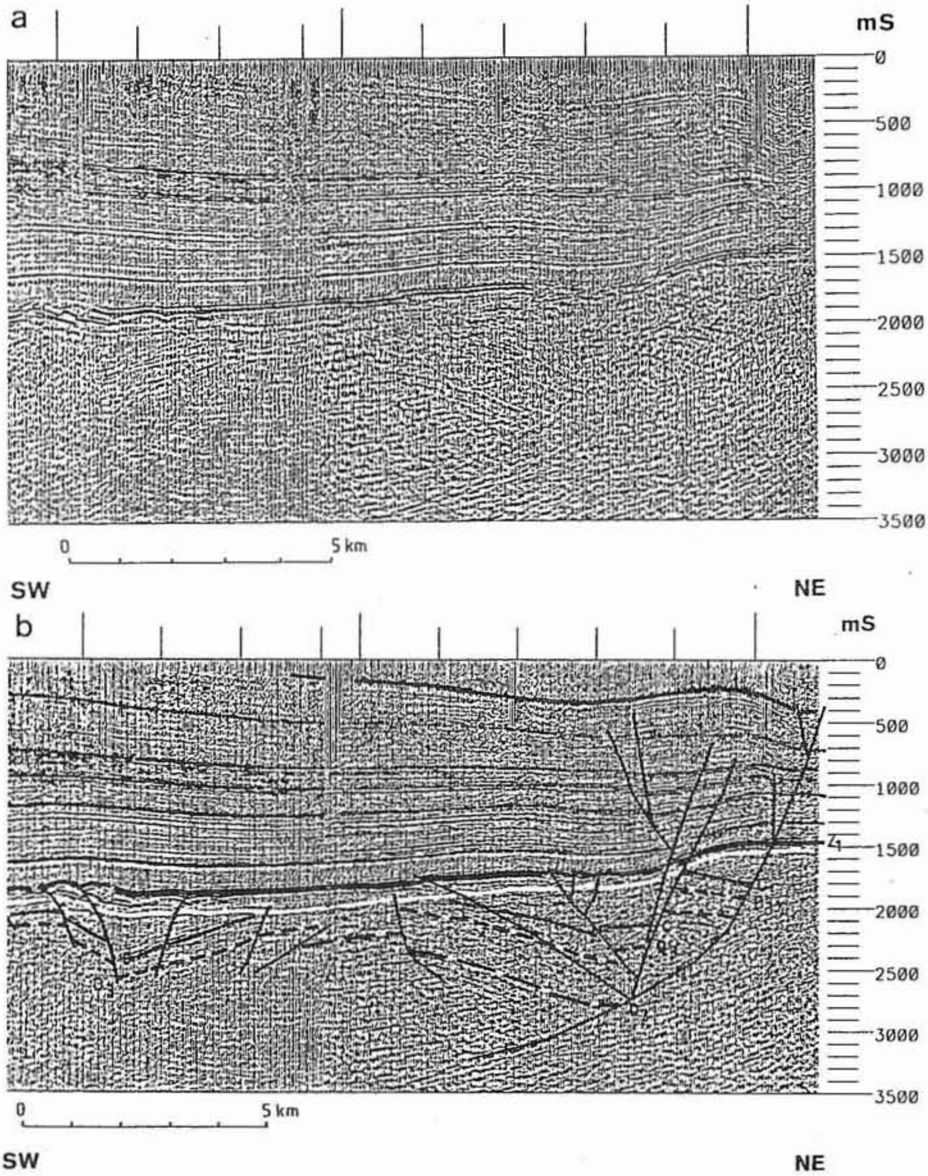

Fig. 8. Non-interpreted (a) and interpreted (b) version of time section (location see Fig. 6, depth version in Fig. 7 — seismic profile 4)

The non-interpreted time version (a) illustrates the quality of the original material interpreted for the Ustronie Morskie – Daszewo – Sarbinowo area; other explanations as in Fig. 7

Wersja niezinterpretowana (a) i zinterpretowana (b) przekroju czasowego (lokalizacja na fig. 6, wersja głębokościowa na fig. 7 — profil sejsmiczny 4)

Niezinterpretowana (a) wersja czasowa ilustruje jakość materiału wyjściowego, na którym oparto interpretację w rejonie Ustronia Morskiego – Daszewa – Sarbinowa; pozostałe objaśnienia jak na fig. 7

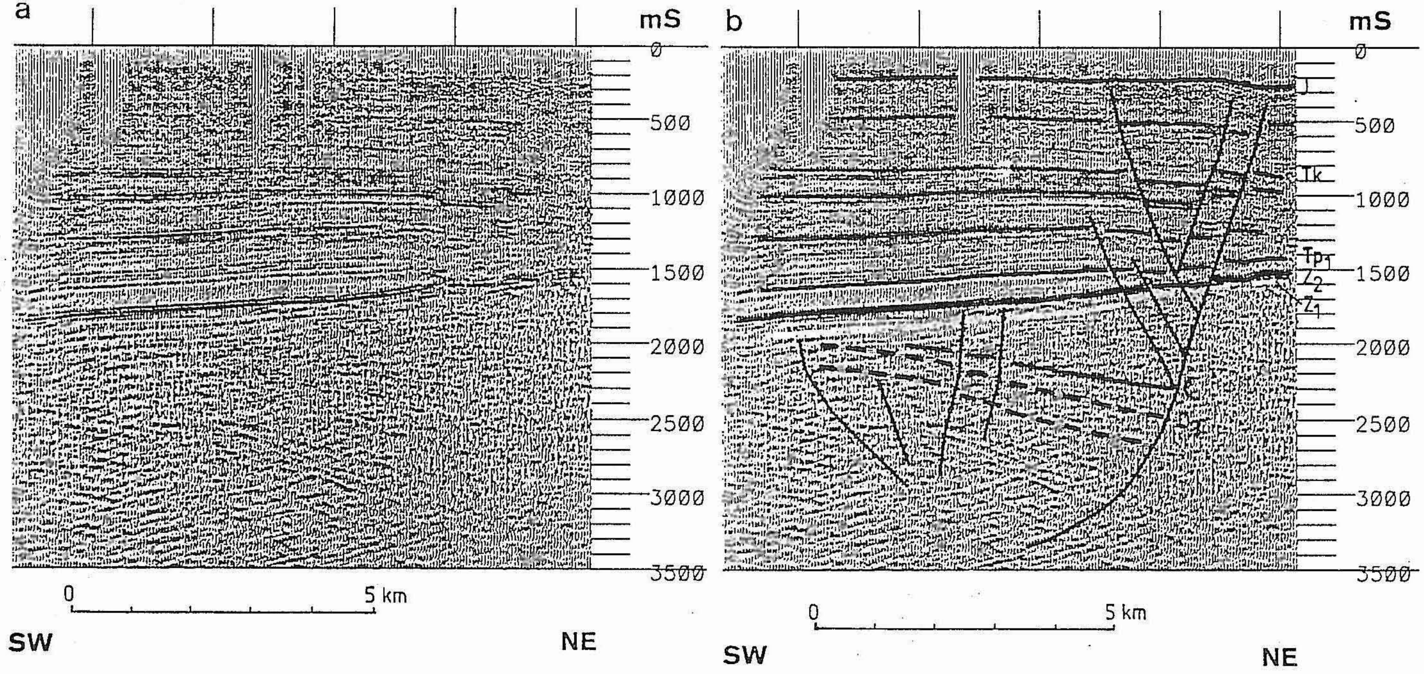

Fig. 9. Non-interpreted (a) and interpreted (b) version of time section from the Ustronie Morskie – Daszewo – Sarbinowo area illustrating the relationship between the Mesozoic graben and the Permian basement tectonics; the phenomenon is visible in Figs. 7 and 8 and described in the text

Explanations as in Fig. 7

Wersja niezinterpretowana (a) i zinterpretowana (b) przekroju czasowego z rejonu Ustronia Morskiego – Daszewa – Sarbinowa ilustrująca współzależność między rowem mezozoicznym a tektoniką podłoża permu; to samo zjawisko widoczne jest na fig. 7 i 8; omówienie w tekście

Objaśnienia jak na fig. 7

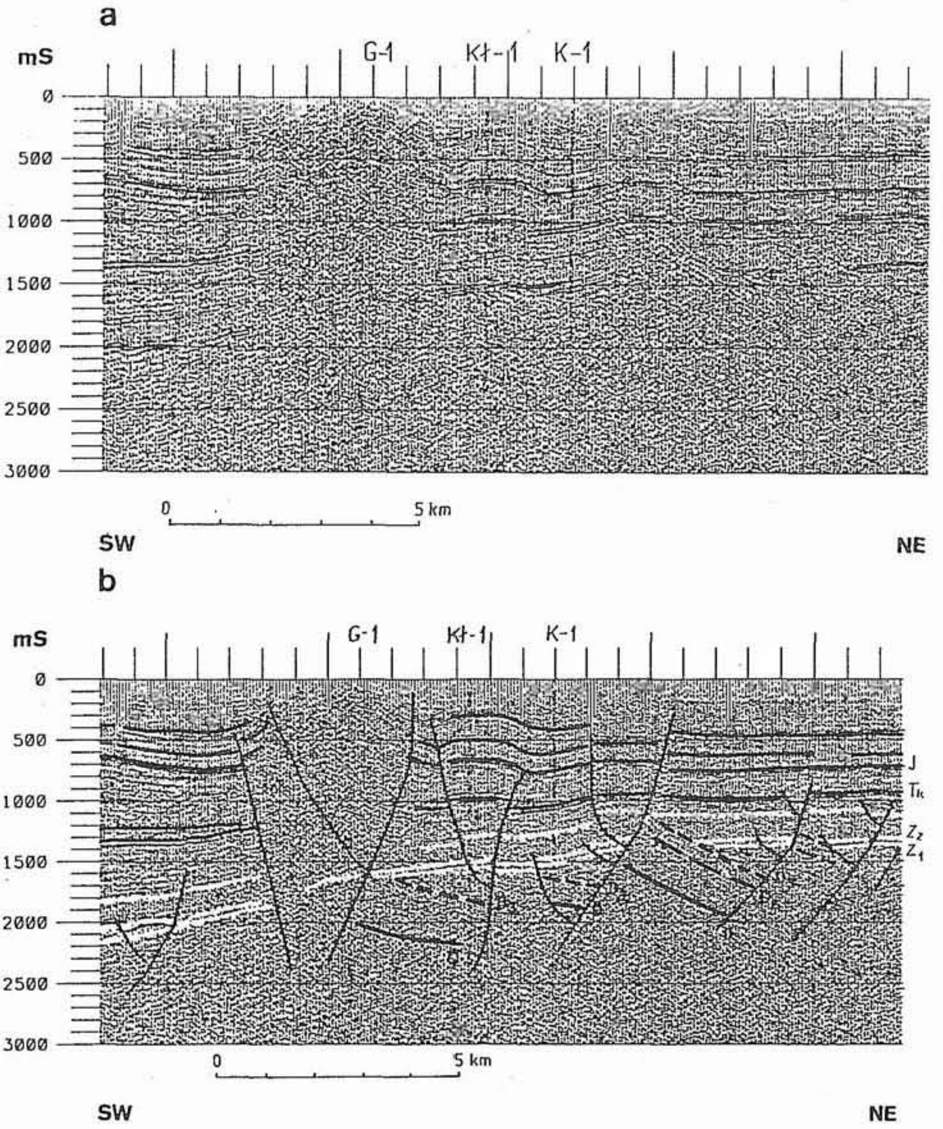

Fig. 10. Non-interpreted (a) and interpreted (b) time section across the boreholes Grzybnica IG 1 (G-1) – Kłanino 1 (Kł-1) – Karsina 1 (K-1)

NE of the borehole K-1 (Karsina 1) visible is the Devonian horst of Kościernica not covered by the Zechstein (the Kościernica 1 borehole is about 9 km from the profile line); a detailed image of this fragment of the profile is shown in Fig. 11; explanations as in Fig. 7

Niezinterpretowany (a) i zinterpretowany (b) przekrój czasowy przez otwory wiertnicze Grzybnica IG 1 (G-1) – Kłanino 1 (Kł-1) – Karsina 1 (K-1)

Na NE od otworu wiertniczego K-1 (Karsina 1) widoczny nieprzykryty cechsztynem zrąb dewoński Kościernicy (otwór wiertniczy Kościernica 1 znajduje się około 9 km od profilu); szczegółowy obraz tego fragmentu profilu przedstawiono na fig. 11; objaśnienia jak na fig. 7

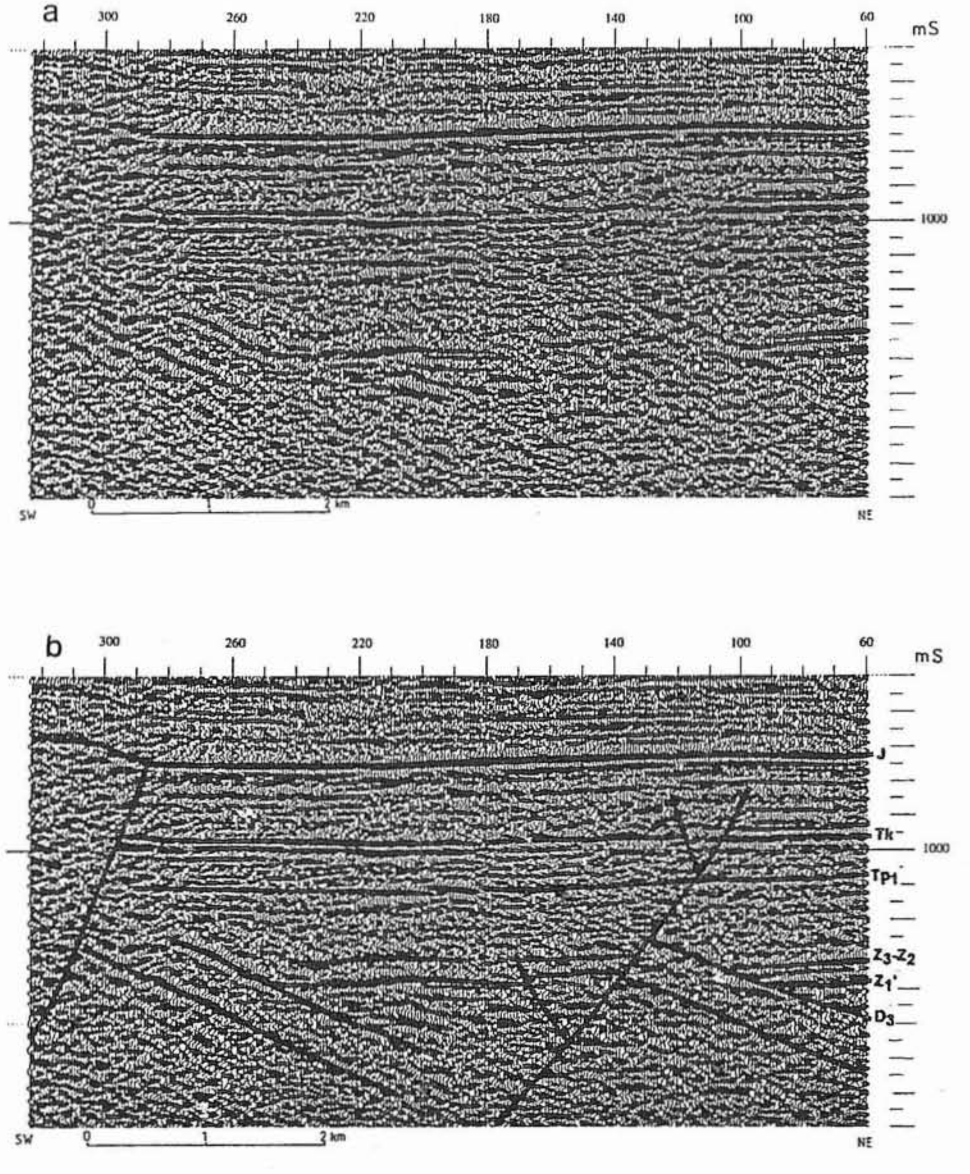

Fig. 11. Non-interpreted (a) and interpreted (b) fragment of the time section presented in Fig. 10
Visible is the Kościernica Horst and the subsequent minor Devonian horst; this arrangement illustrates the nature of the recent extent of the Devonian in this area; explanations as in Fig. 7
Niezinterpretowany (a) i zinterpretowany (b) fragment sekcji czasowej prezentowanej na fig. 10
Widoczny zrąb Kościernicy i następny mniejszy zrąb dewoński; układ ten ilustruje charakter współczesnej granicy zasięgu występowania utworów dewonu w tym rejonie; objaśnienia jak na fig. 7

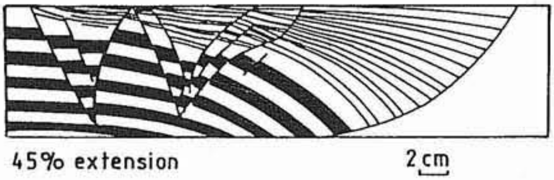

Fig. 12. Fault sequence diagram (after P. G. Ellis, K. R. McClay, 1988)
Pre-rift sediments black and white bands; other explanations see in the text
Diagram rozwoju uskoków (według P. G. Ellisa, K. R. McClaya, 1988)
Czarno-białe pasy — osady pre-ryftowe; pozostałe objaśnienia w tekście

These differences in the amplitude, numerous fault zones and lack of some Carboniferous and Devonian members impede the stratigraphic correlation of the individual boundaries and continuous identification of horizons across fault zones.

The interpretation given in Figure 6 is one of several possibilities and, given the present state of knowledge, considered by the present authors to be the most probable. The profiles presented in Figure 7 prove the tilted blocks to occur in the Permian basin with their upper parts levelled by erosion.

The extent of these structures is not quite clear, particularly in the remainder parts of the Pomeranian Trough and Pomeranian Swell. There are also uncertainties concerning the parts of the Permo-Mesozoic Basin where half-grabens filled with Rotliegendes sediments have been preserved, all of great significance for hydrocarbon exploration. The complex tectonic history — compression and transpression during Variscan time followed by Permo-Mesozoic tension and finally syn-Alpine remodelling — makes theoretical solutions extremely risky. In practice, only a concrete and reliable seismic record can serve as a basis for considerations on the arrangement of blocks in the Permian basement, the tectonic style of the basin and history of its evolution.

Difficulties in obtaining good quality seismic records have been encountered throughout the area. However, reliable information could have been obtained from some profiles (Figs. 8–10). Authors hope that from step-by-step accumulation of this information an increasingly accurate image will emerge.

The formation and development of large faults bordering the tilted blocks and cutting the entire upper part of the Earth's crust were accompanied by formation and development of secondary faults which form diversified systems and complicate the tectonic structure. Of particular significance is the rollover structure defined as hanging wall collapse in response to slip on listric normal faults (W. K. Hamblin, 1965; W. Crans *et al.*, 1980; N. J. White *et al.*, 1986; W. F. Dula, 1991; A. G. Nunns, 1991; H. Xiao, J. Suppe, 1992).

Figure 12 shows the results of one of the experiments on analogue models (60^{o} simple listric fault — homogenous sand) of hanging wall deformations in listric fault system. Sand model developed a large rollover anticline and two associated crestal collapsed grabens. The structures represented in Figures 6–11 have many features similar to those in the model shown in Figure 12. The present authors tend to believe that the structural form presented in Figure 6 constitutes a rollover anticline with two crestal collapse grabens.

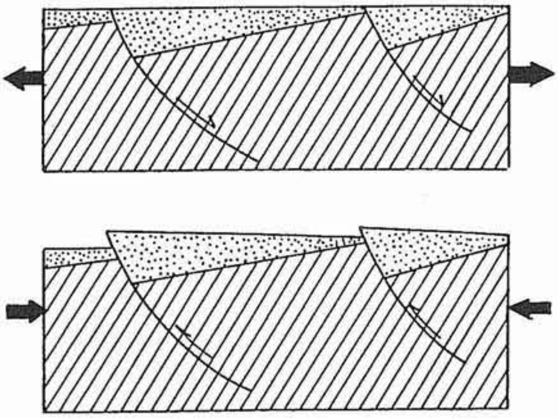

Fig. 13. The reactivation of extensional half-graben systems by subsequent compression and inversion
Reaktywacja systemu ekstensyjnych półrowów jako następstwo późniejszej kompresji i inwersji

In the Koszalin area the main fault bordering the block in the NE is accompanied by deformations not only in the sub-Permian but also in the Mesozoic (Figs. 8–10). This phenomenon is in vertical alignment with what is described in Polish literature as "Mesozoic grabens". These grabens are down-faulted only in the deeper part of the sequence, while upwards they change into flat elevations. Authors describing these structures (Z. Deczkowski, I. Gajewska, 1977; Z. Deczkowski, 1977; R. Urbański, T. Żołnierczuk, 1977; L. Knieszner *et al.*, 1983) envisaged a relationship between the faults which formed a Mesozoic graben and basement structures. They failed, however, to document and describe the nature of this relationship. Assuming the existence of tilted block and the accompanying rollover structures one can suspect that part of these grabens (in areas with low thicknesses of Zechstein salt) are continuations of faults bordering the tilted blocks in Palaeozoic formations. Due to compression this entire tectonic system was inverted during Cretaceous/Tertiary time. In this fashion elevations were created in the Jurassic and Cretaceous formations above the grabens. This explains the regularity with which Mesozoic grabens coincide with highs in the Zechstein basement. The mechanism of formation of such highs due to inversion is explained in Figure 13 and profiles in Figures 7–11 are concrete examples of inversion tectonics by re-activating listric normal faults.

EXPLORATORY IMPLICATIONS

Hydrocarbon exploration has revealed that tilted blocks and asymmetrical half-grabens are the most important expression of extensional tectonics.

Traps related to the hanging wall can be of essential significance for hydrocarbon accumulation in the Devonian and Carboniferous sediments as well as in the Rotliegendes

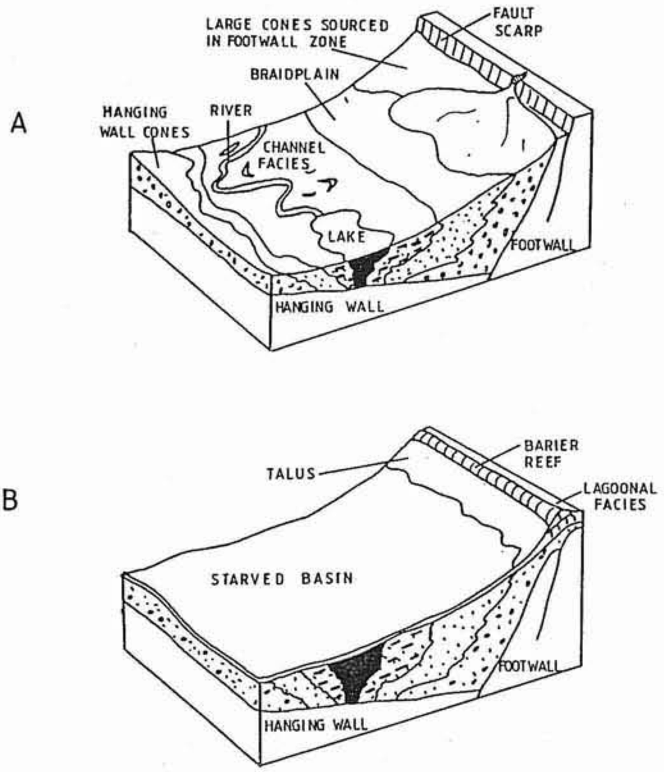

Fig. 14. A. Blockdiagram showing the main features of the development of the continental facies in the half-graben basin (i.e. Rotliegendes depositional conditions); the principal provenance area for the sediment is the footwall, although, due to the asymmetry of the basin, the material derived from the hanging wall can be transported further; periodical rejuvenation of the escarpment of the footwall is of serious consequences for the deposition in the basin B. Blockdiagram showing the main features of the development of the carbonate facies in half-graben basin (i.e. depositional conditions of the Zechstein carbonates); as the deposition and carbonate facies distribution are strongly dependent on the depth and tilt angle of the basement, significant contrasts are noted in the kind of sediments across the half-graben (M. R. Leeder, R. L. Gawthorpe, 1987)

The blockdiagrams show only the main listric fault bordering the basin; but in reality numerous anti- and synthetic as well as slip faults occur greatly complicating the tectonic structure and the reaction of depositional processes to the tilt of the block.

A. Blokdiagram ukazujący główne cechy rozwoju facji kontynentalnych w basenie półrowu (czyli warunki, w jakich odbywała się sedymentacja czerwonego spągowca); głównym źródłem osadów jest skrzydło spągowe (footwall), chociaż na skutek asymetrii basenu materiał pochodzący ze skrzydła stropowego może być przenoszony dalej; periodyczne odmładzanie skarpy skrzydła spągowego ma poważne konsekwencje dla sedymentacji w basenie B. Blokdiagram ukazujący główne cechy rozwoju facji węglanowych w basenie półrowu (czyli warunki, w jakich odbywała się sedymentacja węglanów cechsztyńskich); ponieważ sedymentacja i rozkład facji węglanowych są mocno uzależnione od głębokości i kąta nachylenia podłoża, występują znaczne kontrasty w typie osadów w poprzek półrowu (M. R. Leeder, R. L. Gawthorpe, 1987)

Na diagramach został ukazany tylko główny uskok szuflowy ograniczający basen; w każdym obrazie rzeczywistym występują liczne uskoki i to zarówno antytetyczne, jak i homotetyczne i przesuwcze, co niezmiernie komplikuje budowę tektoniczną i reakcje procesów sedymentacyjnych na pochylenie bloku formations draping these highs (T. P. Harding, A. C. Tuminas, 1989). In the case of the Rotliegendes the tilted block surface bordered by the hanging wall of the neighbouring block influences the lithology, facies and thickness (Fig. 14A). Also in the Zechstein carbonates, very sensitive to changes in the sea level, the depositional style is controlled by the tectonic system of tilted blocks (Fig. 14B).

One can suspect that in the Rotliegendes large blocks — a dozen to over 20 km wide — constituted separate subbasins, each of these basins being a separate problem and, by the same token, a separate exploration target.

If the existence of tilted blocks and half-grabens is accepted, the mosaic of separate Devonian and Carboniferous horizons of the sub-Permian surface, otherwise difficult to understand, can be logically explained.

The assumption that sub-Permian tectonics is coherent with the concept of tensional basin evolution influences further considerations on the development of sediments, formation and migration of hydrocarbons, seismic velocity, density, structural control and local tectonics — in practice, the overall approach to exploration.

CONCLUSIONS

1. Modern seismic techniques combined with proper modelling can provide information on the pre-Zechstein structure in the Polish Lowlands.

2. The tensional nature of the pre-Zechstein tectonics is in agreement with the rift nature of the TTZ.

3. The existence of tilted blocks and associated half-grabens is of major significance for hydrocarbon exploration.

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TEKTONIKA TENSYJNA NA POMORSKIM ODCINKU STREFY T-T I JEJ IMPLIKACJE DLA POSZUKIWAŃ NAFTOWYCH

Streszczenie

Analizę prowadzono na obszarze pomorskiego odcinka strefy Teisseyre'a-Tornquista rozumianej jako głęboki rów tektoniczny o cechach paleoryftu. Gromadzone w latach osiemdziesiątych dane geologiczne coraz wyraźniej wskazywały na tensyjny charakter tektoniki pre-permu na tym obszarze. Niestety trudności związane z uzyskaniem odbić sejsmicznych od granic podcechsztyńskich uniemożliwiały weryfikację tego poglądu. Zwrot nastąpił wraz z wprowadzeniem nowych procedur przetwarzania danych sejsmicznych. W artykule zaprezentowano profile sejsmiczne stanowiące, zdaniem autorów, dowód na obecność w podłożu permu pochylonych rotacyjnie bloków i towarzyszących im półrowów.

Poszukiwania naftowe prowadzone w wielu różnych basenach na całym świecie dowiodły, że pochylone bloki i asymetryczne półrowy, będące wyrazem tektoniki ekstensyjnej, mają zasadnicze znaczenie dla ogółu procesów prowadzących do powstania złóż bituminów. Szczególne znaczenie poszukiwawcze ma struktura zwana antykliną kompensacyjną, definiowana jako oberwanie się skrzydła wiszącego w rezultacie poślizgu wzdłuż szuflowego uskoku normalnego. W rejonie Koszalina udało się wydzielić dużą formę strukturalną, która jest antykliną kompensacyjną ograniczoną dwoma rowami zapadliskowymi.

Uwzględniając istnienie pochylonych rotacyjnie bloków i towarzyszącej im antykliny kompensacyjnej, można domniemywać, że część rowów mezozoicznych (w rejonach, gdzie miąższość soli jest niewielka) jest kontynuacją uskoków ograniczających pochylone bloki i przebudowanych inwersyjnie na przełomie kredy i trzeciorzędu.