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Zechstein reefs of the Main Dolomite in Poland and their seismic recognition

ABSTRACT: Seismic techniques provide facilities for tracing reflections from high--velocity anhydritic-carbonate sets sandwiched by low-velocity salts within the Zechstein deposits of Poland. Especially important for Zechstein deposits and most of all for the Main Dolomite (*Ca2*) is the slope of the Werra platform extending along the basin margin. During the Main Dolomite (*Ca2*) sedimentation, the slope of platform had separated the lagoon from the interior being then the starved basin. The barrier reef was coincident with the slope, and with rapid thickening of the overlying Stassfurt Salts. The carbonate buildups referred to as „the pinnacle reefs" and „the atoll reefs" were deposited in this very starved basin. The best hydrocarbon prospects are believed to be the pinnacle and atoll zones extending around the entire basin.

INTRODUCTION

The Central European Zechstein Basin ranks amongst the world's major evaporite basins. The easternmost part of the Basin is situated in the area of the Polish Lowland (Text-fig. 1). The Upper Carboniferous coal-bearing rocks, more than 4.000 m thick were deposited in parallic Variscan Foredeep and covered by the terrigenic Rotliegendes (Lower Permian) sediments constisting locally of excellent reservoir rocks. For many years these sediments were the most prospective sequence for hydrocarbon exploration in Europe. During the inundation by the Zechstein (Upper Permian) sea the foredeep evolved in to an epicontinental area. The sedimentation was developed in terms of four evaporite cycles, everyone of which was composed of a sequence of shale, carbonate, anhydrite and halite (Text-fig. 2). Three of the four cyclothemes contain carbonate members. The second cycle carbonates, the Main Dolomite (*Ca2*) is of the highest importance for oil and gas investigations.

During the last twenty years the Rotliegendes deposits proved to be the most promising for gas investigations, while the oil was found in

Ca2 only. There are 28 oil and gas fields in *Ca2*, generally small in size. The distribution of these fields is coincident with the lagoonal facies.

The present authors' study concentrated on the interpretation of reefs in *Ca2* from the geologic and seismic data. In accordance with a definition given by Heckel (1974), the term „reef" is used for a biildup that displays evidence of (*i*) potencial wave resistance, (*ii*) growth in turbulent water which implies wave resistance, and (*iii*) evidence of control

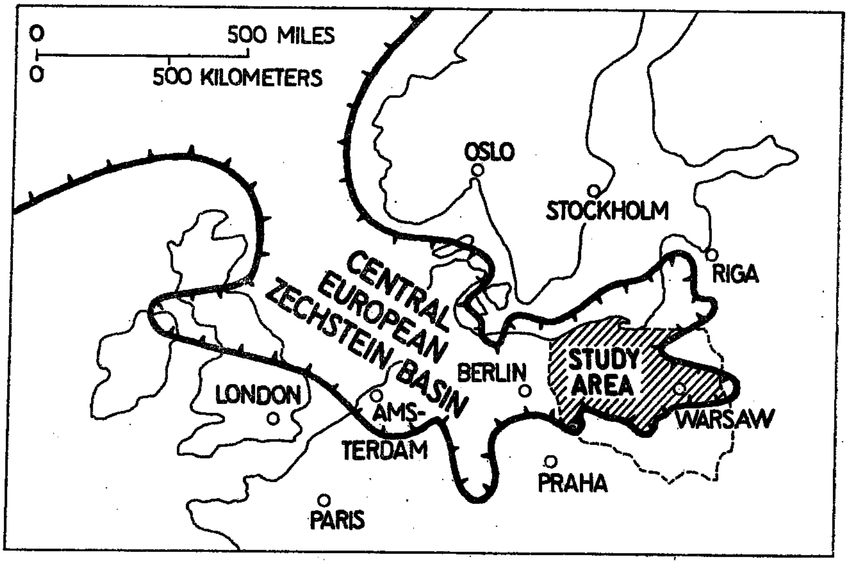


Fig. 1. Index-map showing relation of the study area to the Central European Zechstein Basin

over the surrounding environment. The authors drawn their conclusions from the analysis and interpretation of seismic data. The results compare well with lithofacies investigations (Bojarska & Rost 1974, Głowacki 1975, Czajor & Wagner 1973). The principles of this procedure were given ealier (*see* Antonowicz & Knieszner 1981), and presently this way is applied to the investigation of the Polish part of the Zechstein Basin. This paper includes also the results of research conducted by the oil industry in Poland (*see* Antonowicz & Knieszner 1977).

RESULTS OF THICKNESS ANALYSIS

The thickness analysis is based on about 10.000 data derived from over a thousand boreholes. Twelve thickness maps were designed for carbonate and for evaporite units of the Zechstein sequence as well as for the clastic deposits of the Rotliegendes (*see* Antonowicz & Knieszner 1977). During these investigations, there were recorded thick, up to 100 m and more, accumulations of the carbonates of the Zechstein Limestone (*Ca1*) along the margin of the Zechstein basin, and there appeared the interdependence between the increase of the Zechstein Limestone of (*Ca1*) thickness, and the zones of lack or considerable reduction of the sedimentary rocks of Rotliegendes.

Along the margin of the Werra basin, the sediments of this very cycle formed a wide and nearly flat platform, up to 400 m thick, basinward limited by a steep slope. Besides the reefal carbonates of the Zechstein Limestone (*Ca1*), the platform comprises the swells of *A1d* and *A1g* (Text-fig. 3). Because the filling of the basin by salts interrupted, the

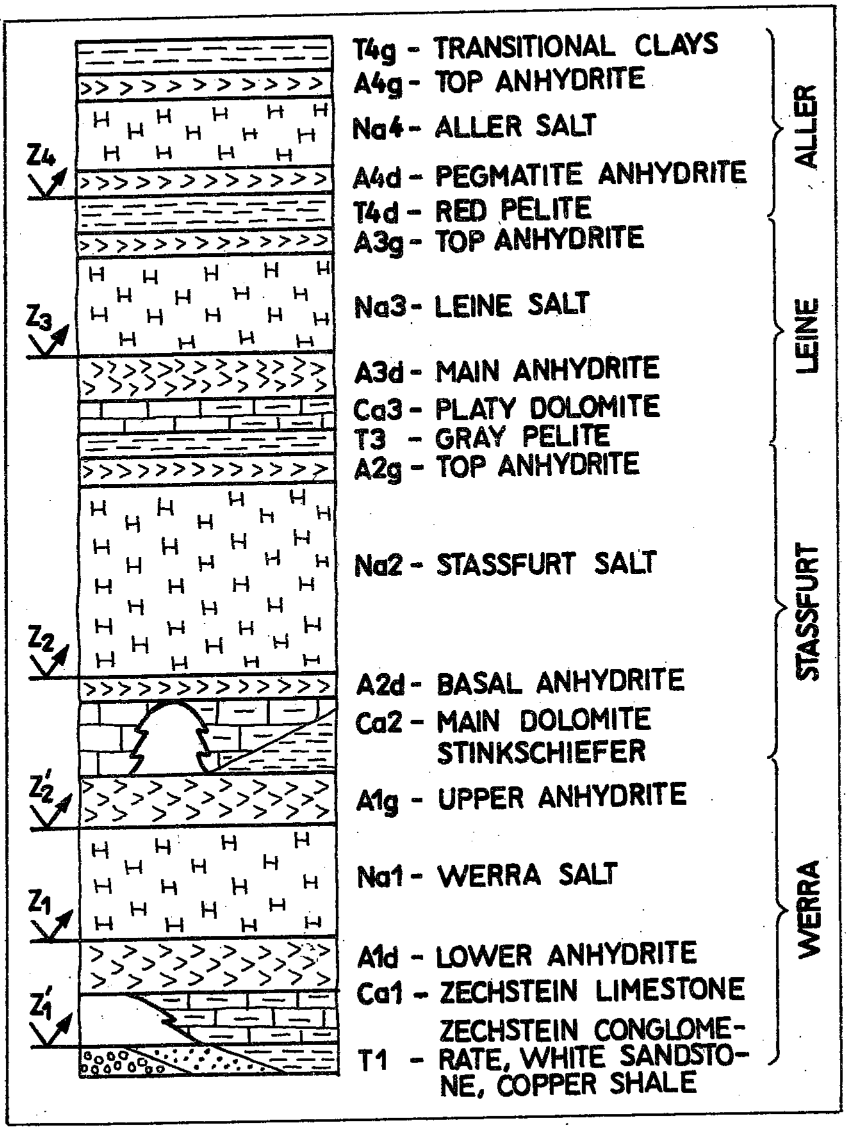


Fig. 2. Generalized stratigraphic column showing the studied sequence; Z'_1, Z_2, Z'_2, Z_3, Z_4 — Zechstein reflectors

Werra salts had not only compensated a deficiete of sediments in the centre of the basin but also the salts had reached their thickest development around the margin.

The existence of the platform determined the paleogeomorphology and influenced conditions of the *Ca2* sedimentation (Text-fig. 4). The most prolific sedimentation of carbonates was concentrated in the shallow, warm, and aerated waters on the platform. In the marginal zone of the Werra platform, the conditions for barrier reef development of the second cycle have existed. The thickness of *Ca2* carbonates in the zones of the barrier reef varies from 40 m up to 190 m. The barrier reefs are composed mainly of algal carbonates. On their steeply dipping flanks there occur brecciated dolomites which are regarded as a reef talus. Between the barrier and the margin of the basin, the lagoonal massive dolomites (in large measure algal) created wide, flat bank reefs which reached a thickness of above 60 m. The sediments of *Ca2* thin out basinawardly, off the platform edge, at a rather rapid rate. The carbonates that extend circumferentially around the basin are changing into marly carbonates and marly stinking shales deposited in a starved basin.

The reef facies developed also outside of the Werra platform in the area of the starved basin. Such reefs had grown on elevations of the sea bottom, igneous or erodible in origin. According to the size of elevations and of the facies pattern, two types of reefs are recognizable: the pinnacle reefs, and the atolls with lagoonal facies in their centre (*see* Text-fig. 3).

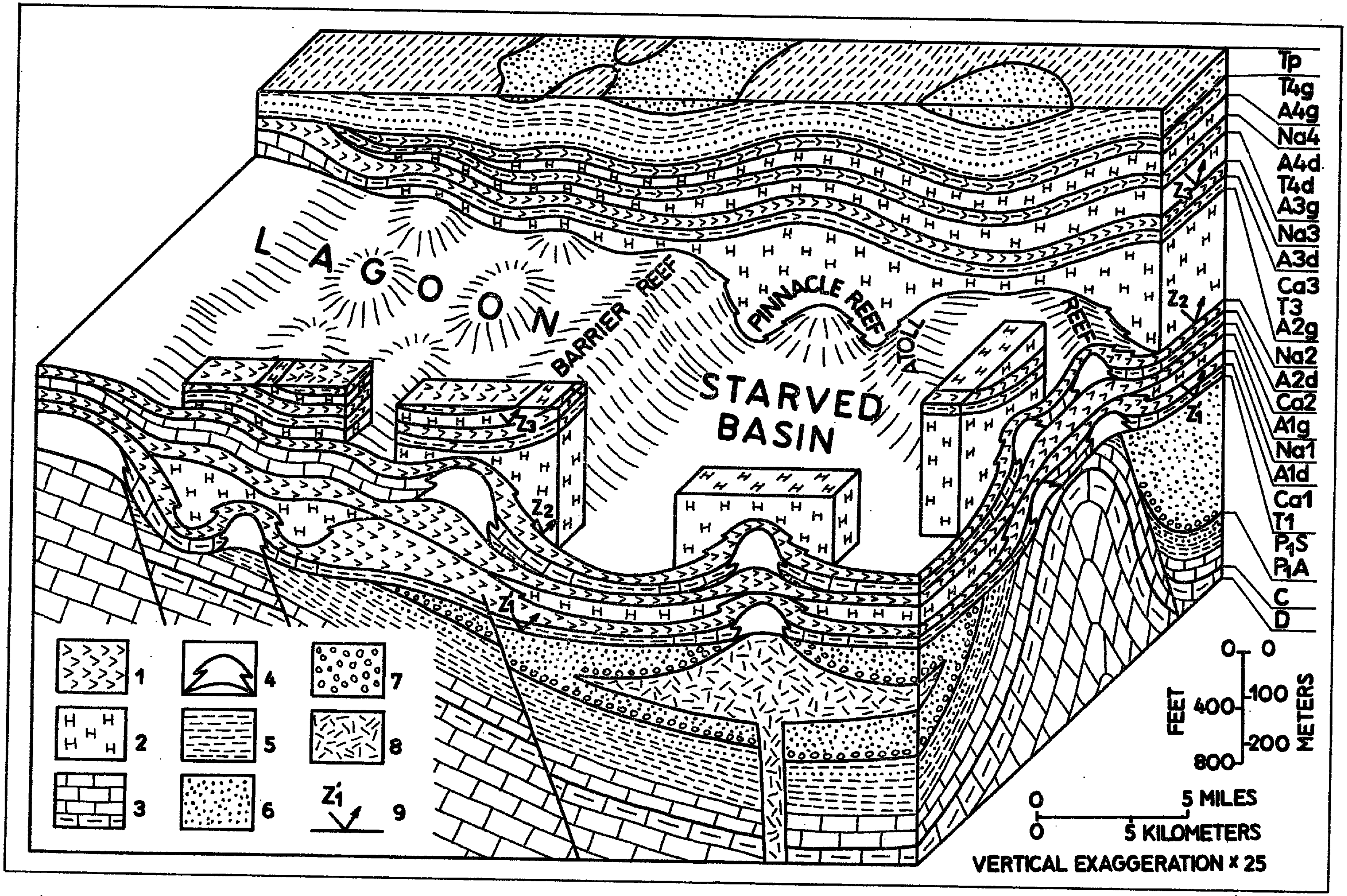
On the basinward slopes of the barrier as well as of pinnacles and atolls, there occurs an abrupt thickening od *A2d* up to 100 m, which forms thick lenses elongated along the slopes.

In the compensational phase of the Stassfurt cycle, the salts filled the basin. The primary salt thickness above the lagoonal facies of *Ca2* was as a rule less than 100 m. The rapid basinward thickening of these halite is coincident with the position of barrier reefs. A very high rate of sedimentation is supposed for the Zechstein salts, and according to Richter-Bernburg (1972) it was up to 10 cm annually.

In contradiction to the Werra cyclotheme, the Stassfurt sedimentation levelled the bottom of he Zechstein basin. This was the reason why during the carbonate deposition of the next cyclotheme (Leine) a platform did not exist and the paleogeography was simpler than during *Ca2* in spite of relatively broad extension of the sea of the Leine cycle. The majority of reef banks of the Platy Dolomite (*Ca3*) located on the nearshore shallows were then occasionally eroded. The facies pattern of sulphate and salt member of this cycle was however similar to that of the older ones.

In the Aller cycle there is no evidence of carbonate sedimentation. The dominated clastic material marked the change of previous conditions and finishing the Zechstein sedimentation.

Block-diagram, to show the facies and thickness relationships in marginal parts of the Central European Zechstein Basin in Poland



1 — anhydrites, 2 — salts, 3 — carbonates and clayey carbonates, 4 — reefs, 5 — clays, 6 — sandstones, 7 — conglomerates, 8 — effusives, 9 — reflectors

SEISMIC INTERPRETATION

The Zechstein sediments may be divided, for purposes of seismic analysis, into two groups:

(*i*) rocks with high acoustic impedence (high-velocity sets of anhydritic-carbonate sequences),

(*ii*) rocks with lower acoustic impedence (halites, potash salts and pelites).

The presented data of density and layer velocity relations (Table 1) were obtained from borehole velocity surveys. Within the Zechstein deposits, the four sets with high layer velocity may be distinguished, as follows: 1 — *Ca1* and *A1d*; 2 — *A1g*, *Ca2*, and *A2d*; 3 — *A2g*, *Ca3*, and *A3d*; 4 — *A3g* and *A4d*.

Table 1

Type of rock	Layer velocity m/sec.	Density G/cm^3
anhydrites	5800-6400	2.9
dolomites and dolomitic limestones	6200-6800	2.7
pelites	3300-3400	2.5
halites	4100-4700	2.2

In each cyclotheme, there appears a low-velocity pelitic member but its thickness (except the Red Pelite of the Aller) is up to few meters and therefore these horizons may be neglected. The cyclic sedimentation of the Zechstein caused intercalation of high-velocity sets and the salts characterized by low layer velocity. The seismic reflections are displayed on the boundaries between these groups of strata (Text-fig. 2; for the reflection coefficients see Table 2).

Table 2

Boundary	Reflection coefficient
Anhydrite/pelite	0.36
Dolomite/halite	0.28
Anhydrite/halite	0.27
Halite/pelite	0.06
Anhydrite/dolomite	0.03

The most intense reflections appear on contacts of salts and/or pelites with anhydrites and/or carbonates, while reflections on contacts of salts with pelites and anhydrites with carbonates are of insignificant intensivity (Table 2). Therefore, the reflections at the tops and bottoms of high-velocity sets are dominant. The model studies (Kniesźner, Poleszak &

Skalny 1975) demonstrate how the seismic reflections are formed and reciprocally interfered in the Zechstein sequences. This method helps also to define the limits of the thickness intervals of salt and anhydrytic--carbonate sets to occur the dividing of interferd reflections. For the salts, the dividing of reflections from the top and bottom of a layer is noticable when thickness is above 60 m, while for anhydritic-carbonate is above 80 m. On the seismic sections (see Text-figs 5—10), the following five reflectors are correlated:

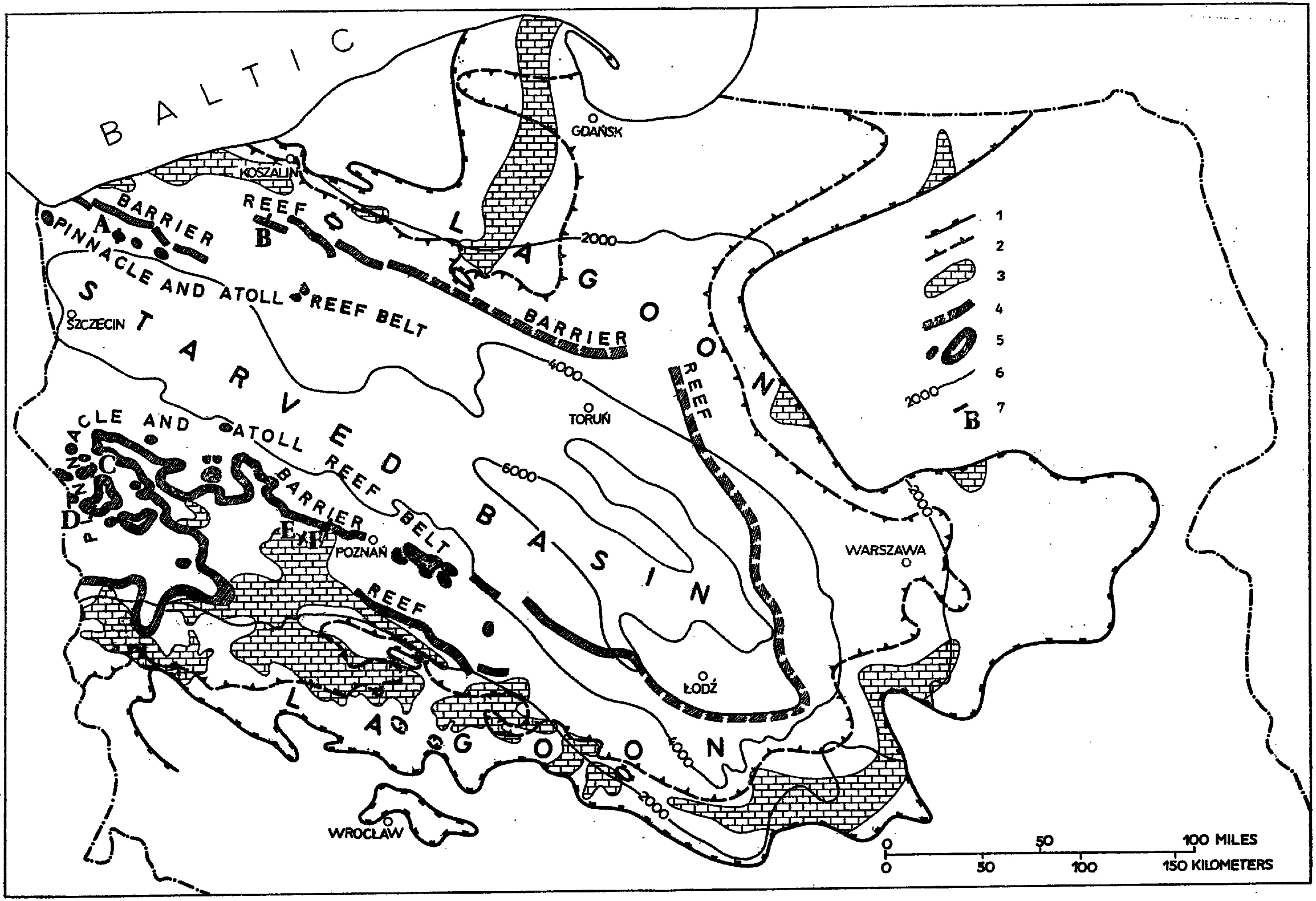
Z_4 — bottom of *A4d* or bottom of *Na4* / top of *A4d*
Z_3 — bottom of *Na3* / top of *A3d*
Z_2 — bottom od *Na2* / top of *A2d*
Z'_2 — bottom of *A1g* / top of *Na1*
Z'_1 — bottom of *A1d* or bottom of Ca1 / top of *T1* or of the pre--Zechstein substrate.

Comparing the position of the strongest Zechstein reflectors (Z_3, Z_2 and Z'_1), their different reciprocal setting in different areas attract the attention. In nearshore areas, dominated by lagoonal facies of *Ca2*, the reflections from anhydritic-carbonate sequence between *Na1* and *Na2* (reflector Z_2) and between *Na2* and *Na3* (reflector Z_3) are coextensive Text-fig. 9). In that way the interfered reflector Z_{3-2} is obtained. The division becomes recognizable when the thickness of *Na2* reaches 60 m. After crossing the outer slope of the Werra platform, together with the abrupt thhickening of *Na2*, the Z_2 reflector is rapidly moving away from Z_3 (Text-figs 6, 8, 10).

The reflector Z_2 (or Z_{2-3}) is separated from Z'_1 and Z_1 (Text-fig. 9) in the lagoonal area where the thickness of *Na1* is up to 300 m. Whereas the *Na1* unit is thin or absent (in a barrier zone) it is compensated by thickening of the Werra anhydrites. Along with reduction of *Na1*, the reflectors Z_1 and Z'_2 are vanishing.

Outside the platform, the reflector Z_2 draws near Z_1 as a result of basinward thinning of the Werra sediments, so that in the deeper parts of the basin only the interfered Z_{2-1} is observed. The transitional zone characteristic by the reflector Z_2 passing from Z_3 to Z'_1 marks the position of the barrier reefs located along the edge of the *Ca2* platform. This so--called „position change zone" appearing on many seismic sections had been plotted to form the map making interpolation and extrapolation of borehole data possible. As mentioned above, in the basin interior two types of reefs were present: the atolls and the pinnacle reefs. Their vertical reliefs of the Z_2 reflector are up to 200—300 m. The pattern of atoll reefs on the seismic sections (Text-fig. 8) is similar to that of the barriers in contradistinction to the pinnacle reefs in which the Z_2 reflector does not reach the Z_3 reflector (Text-fig. 7). These two reflectors above the pinnacle-reefs are separated by several hundreds meters of *Na2*.

Paleogeographic model for the Main Dolomite (*Ca2*) combined with the depth and range data



1 — present range of *Ca2*, 2 — present range of *Na2*, 3 — thickness of *Ca2* more than 40 meters (lagoonal banks), 4 — barrier reef, 5 — pinnacle and atoll reefs, 6 — present depth of burial at top of *Ca2* (contours in meters below sea level), 7 — lines of seismic sections *A-F* presented in Text-figs 5—10

Lowering of the basin bottom had taken place along the Variscan fracture lines approximately parallel to the basin longitudinal axis. The blocks enclosed between fracture lines had formed basinward steps sinking at a different rate (Text-figs 5—6). The Werra platform deposits connected with uplifted blocks and „position change zones" are roughly fitted to tectonic displacements limiting the blocks. Probably all the Werra anhydrites thickenings in the basin interior (beside the Werra platform) have their counterparts in uplifted blocks of the Variscan substrate.

The „position-change zone" is mainly manifested as an abrupt thickening of *Na2* and hence it outlined a boundary of halokinesis effects in the thickness changes of two upper cycles and changes of Mesozoic reflectors from continous to discontinous. Sometimes, there is a possibility to note the conection between the „position change zone" and the present-day morphology (especially courses of the rivers). None the less these dependences are often elusive and that active zone is only cleancut in two oldest cyclothemes.

SEISMIC DETECTION OF *CA2* REEFS

There is a number of elevations in the Z_2 reflectors along the „position change zone", the inclinations of which are gentle on the lagoon-side (up to 3—4°) and steep (up to 11—14°) on the basinward slope. The elevations are interpreted as culmination parts of the reefs which have formed a barrier.

Under elevations interpreted as reefs, there are usually observed elevations in the Z'_1 reflector (Text-figs 7 and 10). Their vertical reliefs are always smaller than that of the Z_2 reflector. Up to now it was not proved by boreholes, whether they are real elevations or velocity anamalies caused by the thickening of high velocity anhydrites of the Werra cyclotheme. In the lagoonal area, the majority of elevations of the Z_2 reflector correspond to the thickening of *Ca2* and to the depressions of the Z'_1 reflector. This effect is caused by a lens-type accumulation of the *Na1* salt (Text-fig. 9).

On the basinward steep flanks of the reef elevations there is commonly observed a weakening or complete disruption of the Z_2 reflector (Text--figs 7—8 and 10). It may be caused by the facies interfingering of *A2d* with *Na2* above the reef slopes which brings about the disperse of the energy. In other cases high inclination in the front of the reef is responsible for the lack of reflections.

As a rule, the Z'_1 reflector manifests a weaker zone beneath the *Ca2* reefs (Text-figs 7—8 and 10). The presumption is taken that the reason was a screening effect of the Z'_1 reflector by the rough surface of the

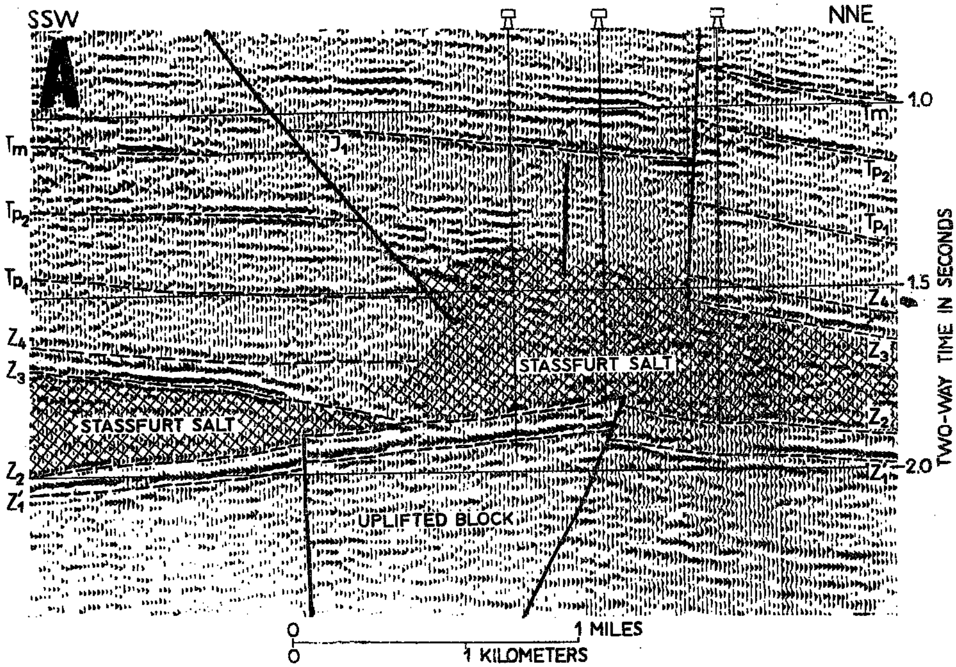


Fig. 5. Seismic section *A* (for location *see* Text-fig. 4); explanations in the text

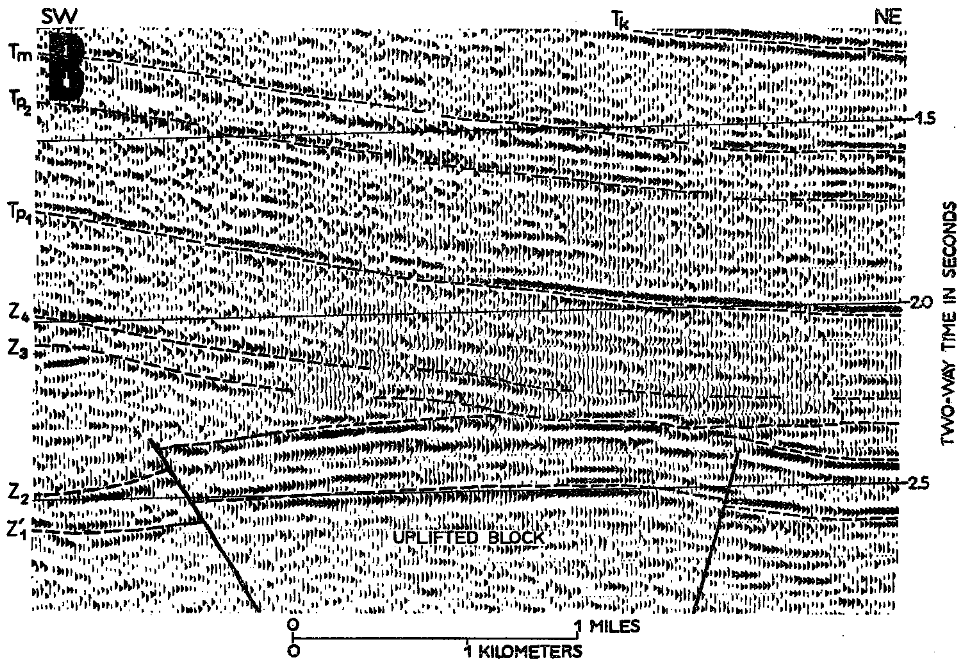


Fig. 6. Seismic section *B* (for location *see* Text-fig. 4); explanations in the text

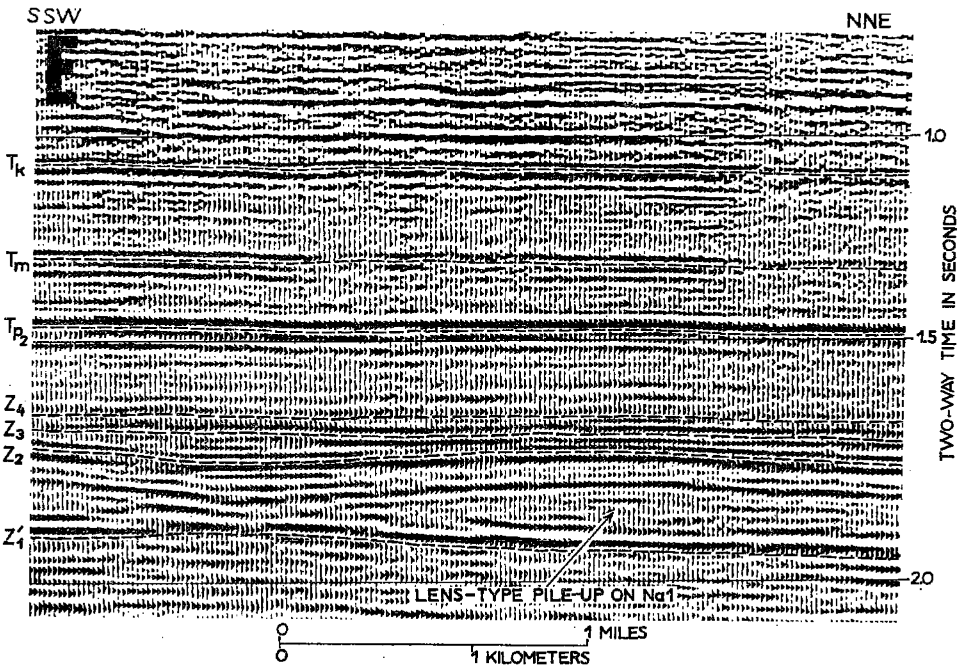


Fig. 9. Seismic section *E* (for location *see* Text-fig. 4); explanations in the text

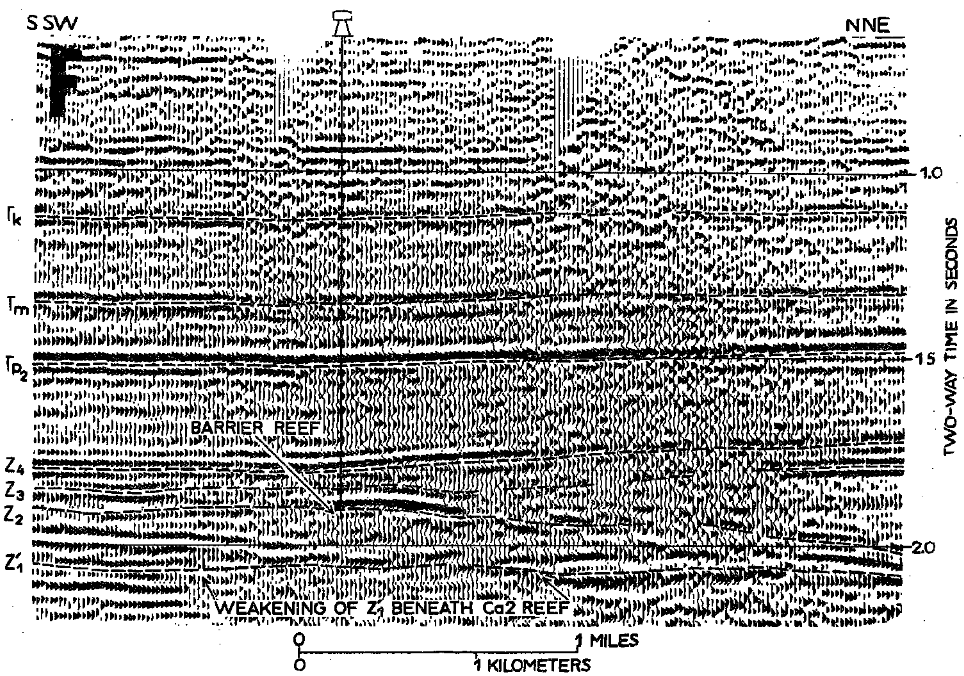


Fig. 10. Seismic section *F* (for location *see* Text-fig. 4); explanations in the text

top of the reef. The other reason may be the presence of tectonic faults or insignificant contrast of the acoustic impedence between the base of the Zechstein sequence and effusive rocks of the Rotliegendes forming the substrate of the thick Werra anhydrites and *Ca2* reefs. On some seismic lines the drape effect occurs over the *Ca2* reefs (Text-fig. 7). The other superincumbent reflectors in the Zechstein and Mesozoic deposits are displayed often by wide elevations occurring few miles basinward from the „position change zone". The origin of these elevations is probably connected with movements of *Na2* salts which crept down the reef slope (Text-fig. 10).

Almost all the elevations recognized by seismics in the *Ca2* and interpreted as reefs are associated with the positive, residual gravity anomalies (calculated by Griffin's method) ranging from 1 to 3.5 mg. The effect is presumbly caused not by a body of the reef but by massifs of heavy Werra anhydrites which formed the base for development of the reefs.

HYDROCARBON PROSPECTS

The commercial production of hydrocarbons from the lagoon zone of *Ca2* is practically limited to one field of oil of the average size. Almost all the boreholes which tested lagoonal carbonates commonly yielded traces of hydrocarbons but in less than commercial quantities.

Hydrocarbon potential of the barrier reef is far from being clear. The barrier reef zone has been pierced by drillings in a few points. Traces of hydrocarbons were found in all boreholes, but an oil production was obtained in two boreholes.

The pinnacle and atoll-reef belt extends around the entire Polish part of the Zechstein Basin (*see* Text-fig. 4). As the exploration is shifting basinward more and more pinnacles and atolls are recognized by seismic method, and recently some 25 such reefs were discovered. Considering the great dimensions of these reefs and perfect hydrocarbon seal provided by *Na2* salts which secured the priority of reefs in catching the hydrocarbons migrating from the centre of the basin, they have met all requirements of a trap, seal and source for the oil.

The seismic as well as geologic data led to the drilling on the six significant reef buildups from the basin interior and the existence of algal reefs was confirmed. Commercial production of oil was obtained (in case from the reef talus) in the three of them. In the three remaining reefs, an excess of the reservoir pressure was unexpectedly encountered and the boreholes were abandoned. Here, the gas had a high content of nitrogen with admixture of H_2S, but the heavy hydrocarbons occurrence indicates the possibility of the oil presence underneath.

Concerning the reservoir conditions, fissility is of great importance. Fissured dolmites extend along zones of intensive tectonic movements of Early and Late Cimmerian phases. These zones are readily interpreted from seismic data. The areas where they cross the reef trends are of the greatest potential for oil and gas prospection.

CONCLUSIONS

The reflection seismic method together with facies and thickness analysis provide an effective exploration tool for the recognition of reefs occurrence. The reefs of the Main Dolomite (*Ca2*) were devoloped in the marginal part of the Werra platform (barrier reef) as well as in the starved-basin interior (atoll and pinnacle reefs). Differentiated morphhology produced by pre-Zechstein tectonic and volcanic processes was responsible for development of the pinnacle and atoll reefs belt in the Zechstein Basin.

Except for paleogeomorphologic analysis, direct reflections from the tops of the reefs, changes from continous to discontinous within the Zechstein and Mesozoic strata, and presumed velocity anomalies should be used to guide drilling. The seismic detections performed for the Polish part of the Zechstein Basin display immediate application to oil and gas exploration and may be used also in other parts of this Central European Basin.

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CECHSZTYŃSKIE RAFY DOLOMITU GŁÓWNEGO W POLSCE I MOŻLIWOŚCI ICH ROZPOZNAWANIA METODĄ SEJSMICZNĄ

(Streszczenie)

W pracy przedstawiony został problem sejsmicznego rozpoznania osadów dolomitu głównego polskiej części basenu cechsztyńskiego (fig. 1). W wyniku analizy miąższości opartej na danych z około tysiąca otworów wiertniczych stwierdzono, iż warunki sedymentacji dolomitu głównego zdeterminowane były istnieniem platformy Werry okalającej cały basen. Na krawędzi tej platformy istniały warunki do tworzenia się rafy barierowej (fig. 3). W wyniku badań prowadzonych metodą sejsmiki refleksyjnej określono ułożenie granic cechsztyńskich związanych z pakietami węglanowo-anhydrytowymi (tab. 1—2, fig. 2, 5—10). Analiza rozkładu miąższości w powiązaniu z wynikami interpretacji materiałów sejsmicznych pozwoliła odtworzyć przebieg rafy barierowej dolomitu głównego (fig. 4). W centralnej części basenu, na lokalnych podniesieniach dna osadziły się anhydryty Werry o znacznej miąższości, na których rozwinęły się rafy atolowe i rafy typu wieżyczkowego (ang. *pinnacle reefs*). Zdaniem autorów najbardziej obiecujące, z punktu widzenia poszukiwań bituminów, są pojedyncze obiekty rafowe w centralnej części basenu.