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RESERVOIR CHARACTERIZATION OF THE WILCZE FIELD, FORE–SUDETIC MONOCLINE, WESTERN POLAND[1]

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ABSTRACT

The Permian Zechstein Formation of the fore-Sudetic monocline of western Poland is characterized by rapid lateral facies changes from dolomite to anhydrite or halite. The sharp velocity contrast related to these facies changes causes disruption of seismic horizons within both the Zechstein reservoir and the underlying Rotliegendes reservoir. Conventional seismic interpretation showed a three-way structurally closed anticlinal field, with questionable closure in the fourth direction. A reservoir characterization study was undertaken to determine the reservoir limits and to consider the possibility of a combined structural and stratigraphic trapping mechanism.

Seismic inversion was used to define the facies boundaries within the study area. Accurate modelling of the position and velocity of the salt facies resulted in a substantially different interpretation of the trapping mechanism and the field limits. The apparent faults in the seismic were healed and neither reservoir was found to be structurally closed. The reservoir characterization study has simplified the structural interpretation of both reservoirs in the field while complicating the stratigraphic interpretation of the Zechstein reservoir. Both reservoirs are interpreted to be substantially more extensive than previously mapped and a possible extension of the neighbouring Kargowa Field has also been identified.

INTRODUCTION

The Polish Oil and Gas Company (POGC) was uncertain of the extent and reserves of the Wilcze Field and wished to reexamine mapping of the field prior to determining whether to put it on production (Figure 1).

The reservoir characterization study had four objectives: 1) determine the field limits; 2) estimate the reserves in place; 3) train ten Polish geoscientists in the study methods; and 4) provide recommendations for future field development.

The project scope included poststack inversion processing and analysis of 50 km of seismic data and analysis of full log suites from six wells (Figure 2). The study produced a simplified structural interpretation but a more complex stratigraphic interpretation. The seismic inversion has removed substantial velocity distortions from the data, resulting in a significant increase in interpreted closure and estimated reserves.

REGIONAL GEOLOGY

The Wilcze Field is located in the fore-Sudetic monocline of western Poland. The northeast-dipping fore-Sudetic monocline area contains numerous oil and gas fields producing from Permian reservoirs. Gas production at Wilcze is obtained from the main dolomite of the Upper Permian Zechstein Formation and the underlying Lower Permian Rotliegendes sandstone. A gentle anticlinal structure oriented approximately NW-SE was originally interpreted as forming the trap for both units. This paper will demonstrate that the trapping mechanism is more likely a stratigraphic pinch-out. Figure 3 presents a diagramatic NW-SE cross-section of the Rotliegendes and Zechstein sections in the Wilcze area. Note the subdivision of the main dolomite into upper and lower units.

The main dolomite in the Wilcze area varies extremely in thickness, from a minimum of 36 m in the W2 well to a maximum of 160 m in the W7 well. No detailed lithologic description of the main dolomite in the field was provided; however, the unit is described in moderate detail from core of the Kargowa-7 well, a few kilometres to the northwest. Lithologic features such as the presence of oncolites, algal laminations, pellets in dolomite, accessory anhydrite and salt suggest a shallow subtidal depositional environment.

An erosional surface caps the basal 30 m of the cored section at the Kargowa-7 well, suggesting subaerial exposure, probably under supratidal conditions. Porosity types include cavities left by solution of oncolites, fractures and intercrystalline. Salt and anhydrite frequently occlude the original porosity.

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The seismic inversion process was performed using the *Seislog®* method. All figures and interpretations were produced using the *SEISLOG PLUS* workstation. *Seislog* and *SEISLOG PLUS* are registered tradenames of Teknica Petroleum Services Ltd. The authors would like to thank the Polish Oil and Gas Company for their kind permission to publish these study results, Mr. Stan Starczyk of the Reftek Group for organizing the project, and the World Bank for providing project funding. We would like to acknowledge the contribution of the ten Polish geoscientists, under the direction of Dr. Piotr Karnkowski. Our thanks to Arkadius Banach, Szymon Bujacz, Edward Czekanski, Elzbieta Dabrowska-Zurawik, Janusz Kazmarek, Katarzyna Kucharczyk, Theresa Kulaga, Jan Piatek, Elzbieta Wojcik and Joachim Wysocki.

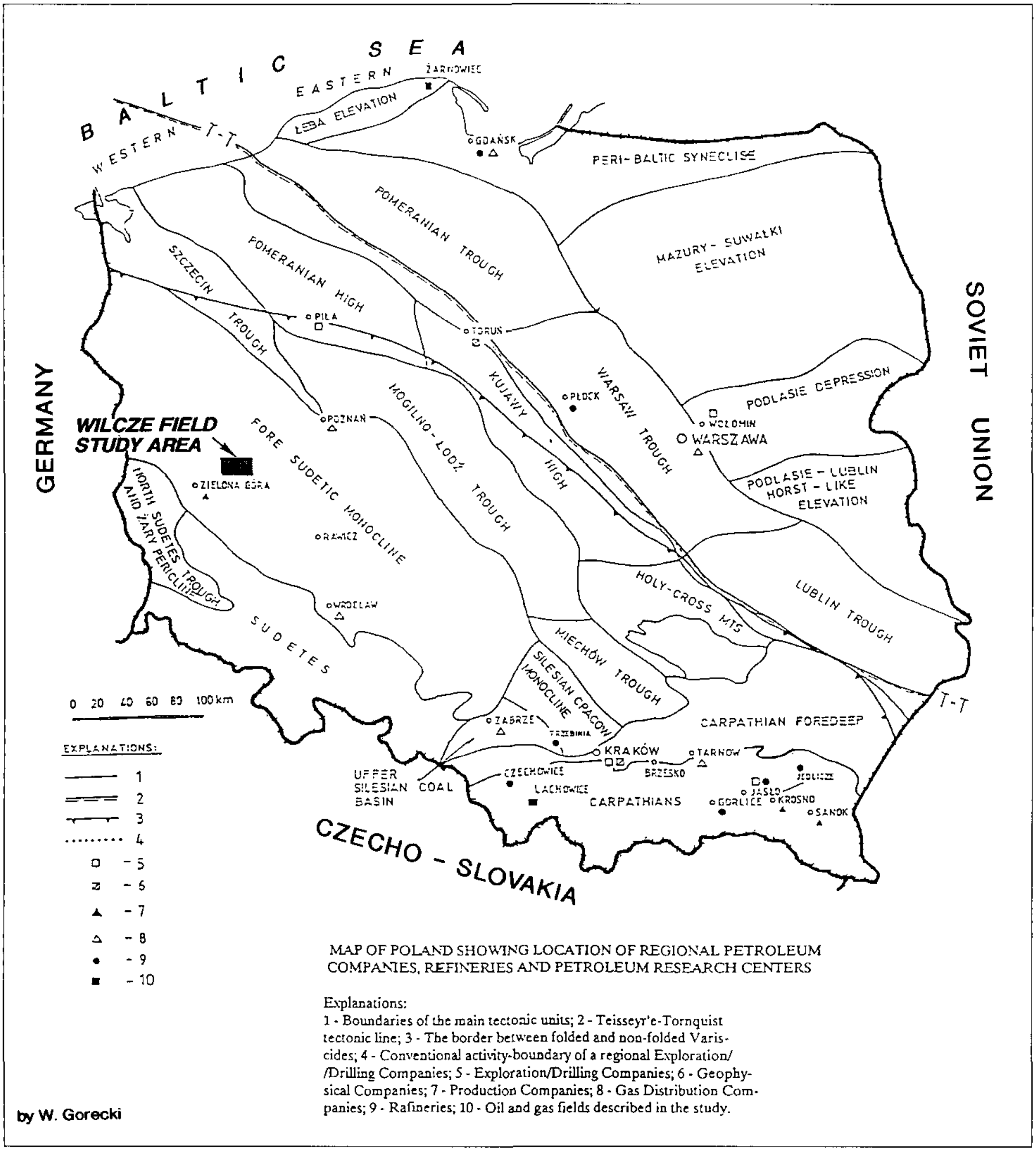

Fig. 1. Location of Wilcze study area, western Poland.

Consequently, we believe that extreme variations in the main dolomite thickness between wells is due to facies variations and not, as previously thought, abrupt thickening of the dolomite unit basinward of a shelf edge. The major facies change is from dolomite to anhydrite. The implication is that a physical disconformity may exist between the upper thin and the lower thick main dolomite sections.

The Rotliegendes sandstone in the field area is believed to be an overbank deposit of a fluvial system. This agrees well with regional interpretation that places the Wilcze area in a

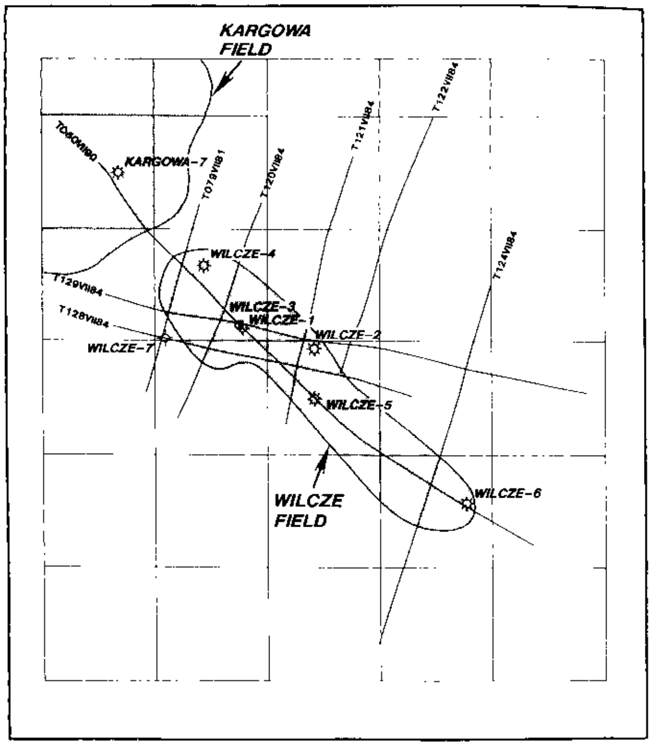

Fig. 2. Field outlines, well and seismic locations.

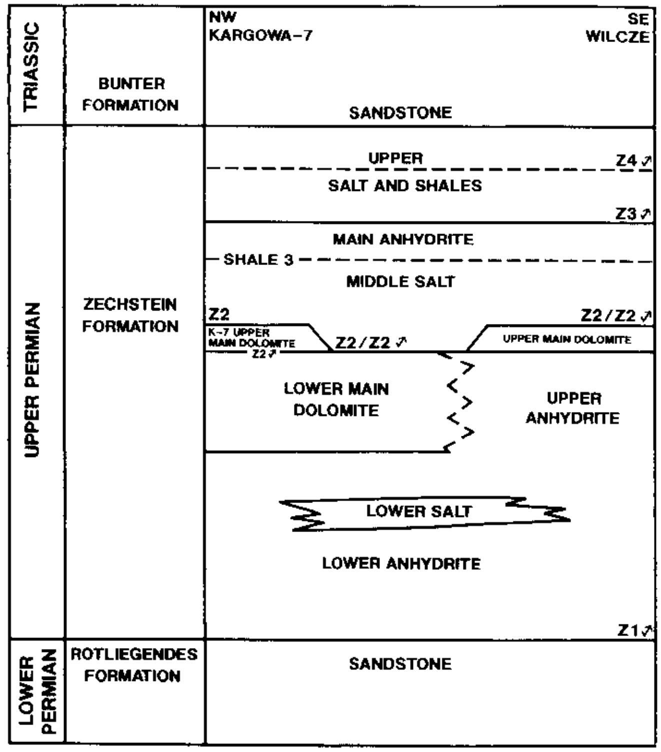

Fig. 3. Schematic cross-section and stratigraphic nomenclature. The ↗ symbol indicates seismic reflector.

continental setting during Late Lower Permian time (Ziegler, 1975; Ziegler, 1975; Polorski, 1976). At Wilcze, the sandstone is overlain by a thin limestone, suggesting a rapid initial incursion of fresh water at the beginning of Upper Permian Zechstein time. It is worth noting that this limestone may have served to protect the Rotliegendes sand from being saturated by fluids of the overlying Zechstein evaporites.

Lithologic information was obtained from thin sections. The Rotliegendes unit is a poorly sorted quartz sand containing minor amounts of chert, rock fragments and feldspars. Calcite, dolomite and anhydrite are variously present as cement. Significant amounts of detrital and authigenic clay matrix are also present. Maximum penetration of the Rotliegendes in the study area is 125 m. Although there are some similarities, well-by-well log correlations of the sand sequence are neither obvious nor convincing. This suggests that a high degree of facies variation is likely present in the Rotliegendes section.

Calcite, dolomite and anhydrite phases of cementation and the presence of clay minerals have served to reduce original porosity and permeability to low levels for a sandstone reservoir (Gaupp, 1993). As was the case for the main dolomite, effective porosity observed in thin section is considerably less than that measured from core.

Reservoir continuity in the Rotliegendes is good, with gas production being obtained from the W2, W4, W5 and W6 wells. Porosity development in all of these wells has the greatest continuity at the top of the section, suggesting a continuity of either lithologic or diagenetic facies that is not otherwise apparent.

The lithologic character of the Wilcze Rotliegendes sands suggests a high susceptibility to reservoir damage by drilling and/or completion fluids. This damage is confirmed by engineering pressure versus time plots which show a rapid pressure buildup, indicating extreme skin damage near the borehole. A partial solution to this type of problem would be to set casing at the base of the Zechstein and drill out the Rotliegendes with air. This possibility should be studied in greater detail prior to additional drilling.

Field Description

The field was previously interpreted as consisting of two stacked structurally trapped gas reservoirs. The overall structure was mapped as a low relief NW-SE-trending anticlinal feature with limited vertical closure, partially bounded by faults. The field contains hydrocarbons in both reservoirs (Dabrowska-Zurawik and Czekanski, 1990).

The cross-section shown in Figure 3 is a schematic representation of the constitution and the areal distribution of the Zechstein main dolomite in the study area. Gas is present in the upper main dolomite at Wilcze. The unit is overlain by silt and underlain by anhydrite and varies from 33.5 to 42.5 m thick. The Wilcze-4 well at the northwest end of the pool found the upper main dolomite absent and the anhydrite unit underlying it replaced by the lower main dolomite unit. At Wilcze-4 the lower main dolomite is 143.5 m thick. Hydraulic connection between the gas-bearing lower main dolomite of the W-4 well and the other wells in the Wilcze pool has not been established. At Kargowa-7 production is obtained from both the highly porous upper main dolomite and the lower main dolomite unit. The reservoir at Wilcze was originally mapped as having an average thickness of

11.5 m of 3.8% porosity over 11.7 square kilometres. The main dolomite is approximately 2000 m below sea level. The reservoir contains gas composed of 33% hydrocarbons, 66% nitrogen and small amounts of hydrogen sulphide and carbon dioxide. The water saturation is 35%.

The lower reservoir at Wilcze is in sandstones of the Lower Permian Rotliegendes Formation. The field was originally mapped with an average reservoir thickness of 7.2 m of 13.4% porosity over 7.6 square kilometres at a depth of 2400 m below sea level. Gas in the lower reservoir is composed of 29% hydrocarbons, 71% nitrogen and minor amounts of acid gases. The water saturation is 34%. Both the Zechstein dolomites and the Rotliegendes sandstones are widely spread reservoirs in western and northern Poland, Germany, Holland and the North Sea. The Kargowa Field, northwest of Wilcze, also contains gas in these Permian reservoirs.

Conventional Seismic Interpretation

Interpretation of conventional seismic displays shows a time low separating the Wilcze and Kargowa Fields and some faulting within the reservoir interval. Figure 4 presents a portion of line T050 which traverses the apparent structural crest of both fields and connects five of the study wells. The time separation between the two fields is visible near shotpoint 260, between the Kargowa-7 and Wilcze-4 wells.

The Z1 seismic reflector originating from near the top of the Lower Permian Rotliegendes sandstone is shown in blue. The top of the Zechstein main dolomite reservoir, originally interpreted as the Z2 seismic reflector, is shown in green colour. The Z3 seismic reflector originating from the top of the Z3 anhydrite is shown in blue. The previously interpreted depth structure maps of the Z1 and Z2 reflectors are illustrated in Figures 5 and 6.

Inversion Methodology

The seismic inversion process was performed following the *Seislog* method as described by Lindseth (1979). The inverted seismic displays are created in a three-step process:

1. The seismic traces are inverted using a relatively straightforward recursive mathematical operation, which

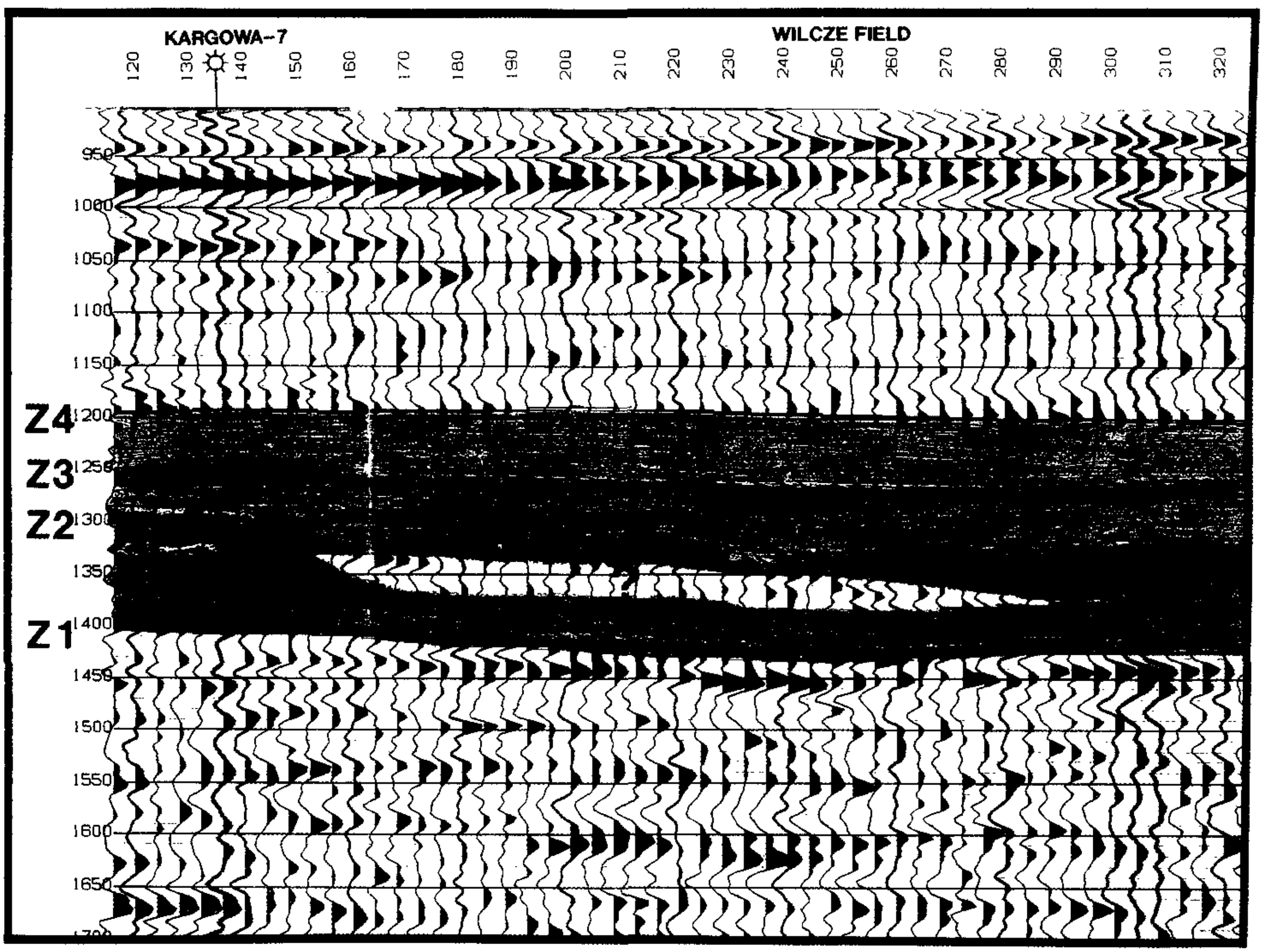

Fig. 4. Portion of line T050 V1190 running NW-SE, conventional seismic display.

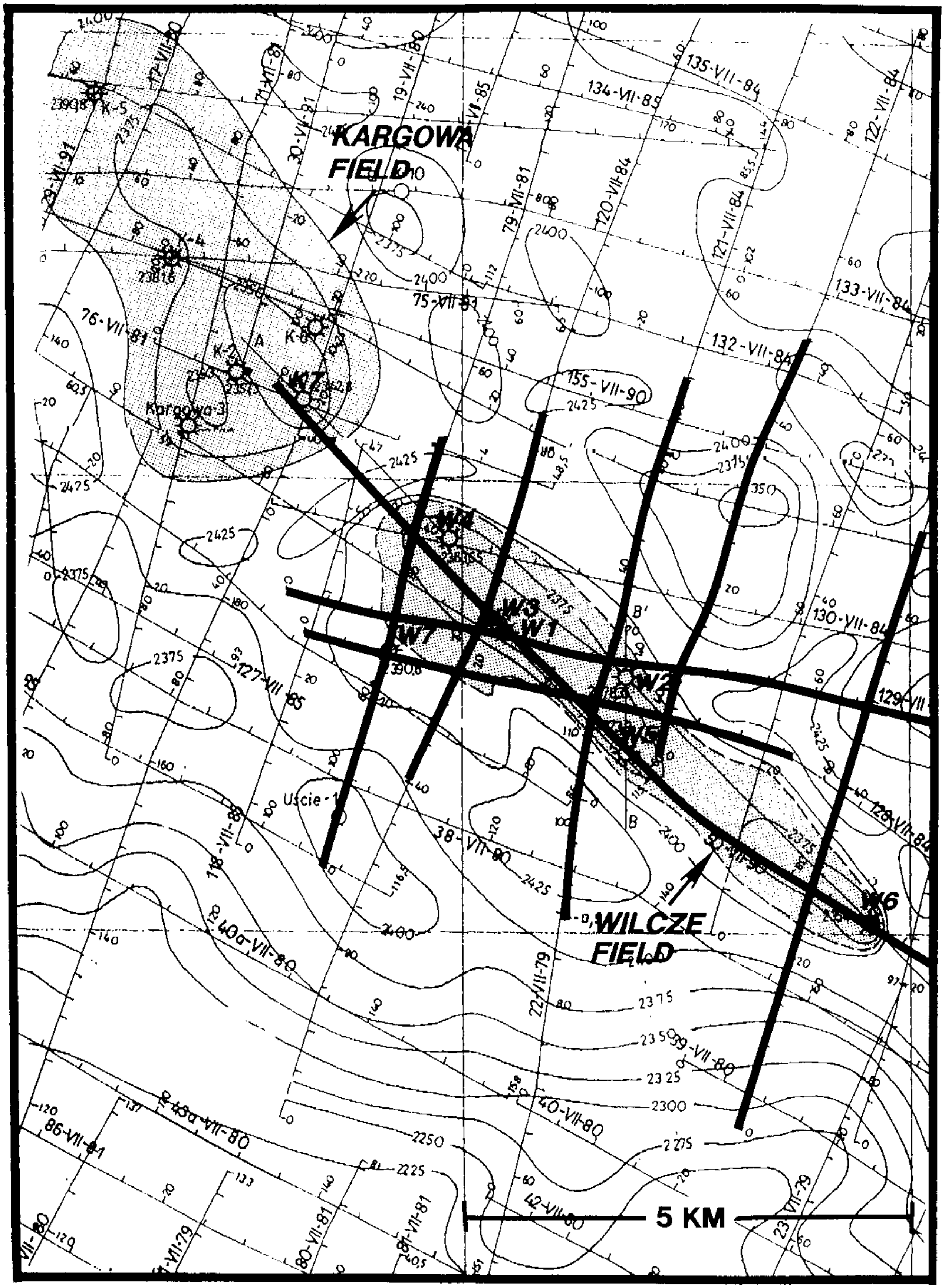

Fig. 5. Rotliegendes depth structure (POGC) (Z1).

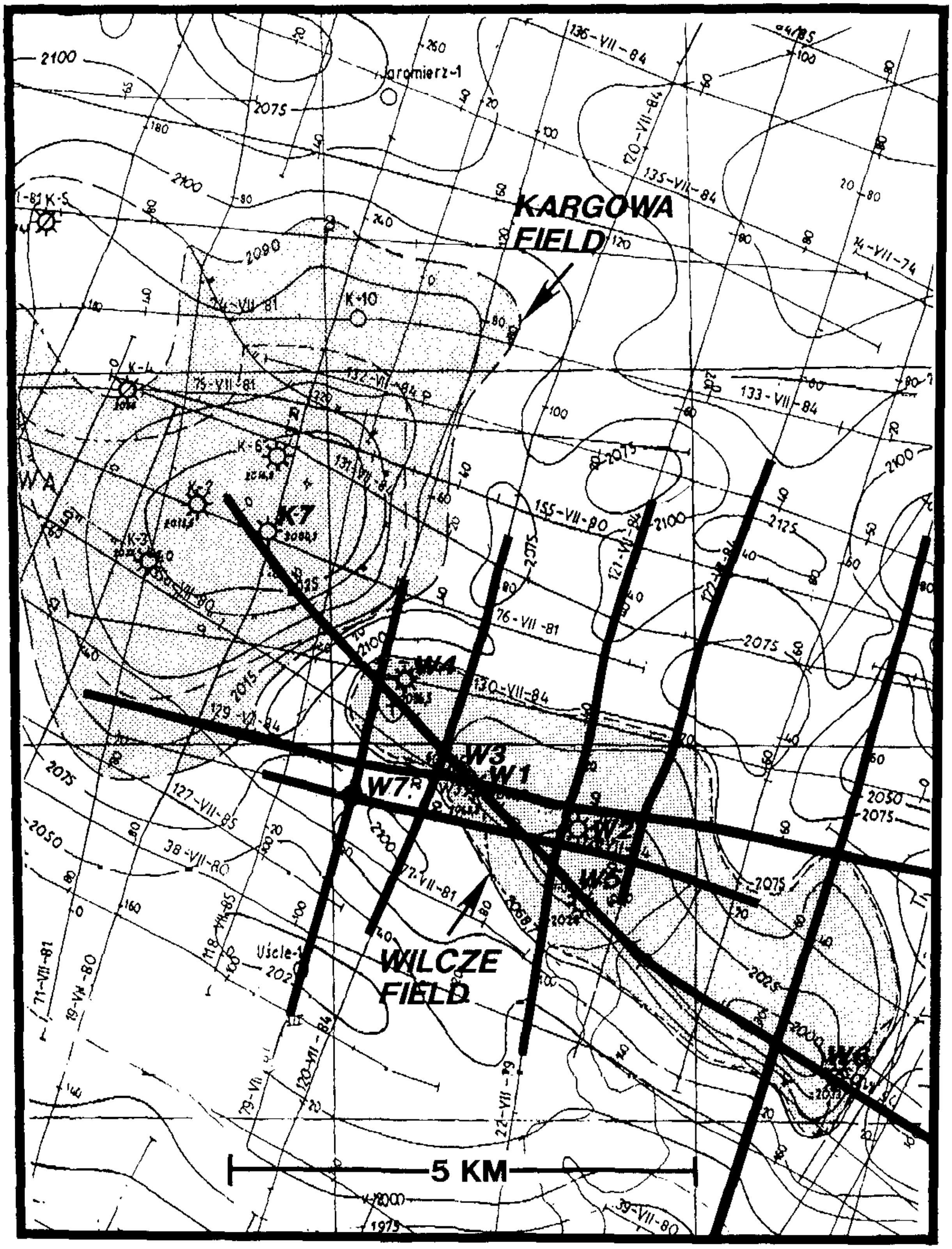

Fig. 6. Zechstein main dolomite depth structure (POGC) (Z2 ,*).

converts seismic reflection samples to the velocity domain of sonic logs. An inverted seismic trace at a well tie should very closely match the sonic log, if the sonic is filtered to the 10-70 Hz seismic bandwidth.

2. A low-frequency model is created; this is an interpretive process utilizing seismic horizons and interval velocity information from control wells to produce a 0-5 Hz curve at each seismic trace location.

3. The two components are added together to form composite traces.

The objective of seismic inversion is to display a section in velocity and depth, rather than amplitude and time. This is achieved by combining the acoustic impedance information from the seismic with velocity information from wells, or stacking velocities, or other sources. The inverted section consists of a series of velocity layers and interfaces.

The effects of density can be ignored by assuming that Gardner's linear relationship between velocity and acoustic impedance holds (Gardner et al., 1974). With this simplifying assumption, the inverted trace then represents an approximation of the velocity contrast at the rock interfaces.

In the case of a simple interface between two layers, let ΔV represent the velocity contrast and $\overline{V}$ represent the average velocity at the interface (Figure 7).

$$\Delta V = V_{i+1} - V_i ; \quad (1)$$

$$\overline{V} = \frac{V_{i+1} + V_i}{2} . \quad (2)$$

The composite trace is assembled by combining ΔV with $\overline{V}$ (Figure 7).

The velocity contrast component ΔV is calculated by inverting the seismic data. It will be subject to estimation errors caused by limited bandwidth (10-70 Hz), by seismic noise, and by assuming a linear relationship between velocity and acoustic impedance. These errors may effect the accuracy of lithology and porosity determination but should not effect the depth solution. The error caused by assuming linearity will be more significant in an evaporite sequence, where the crystalline structure alters the normal compressional relationship between density and velocity which exists in clastic rocks.

The formation depths are determined by the average velocity component $\overline{V}$ which comes from the low-frequency velocity model (0-5 Hz). The 10-70 Hz component from the seismic inversion has a zero mean, so it should not effect the overall length of the inverted trace. However, the combination of frequencies typically missing in the 5-10 Hz range, and errors introduced by the linearity assumption, may cause a cyclical error in the thickness of major isopachs. The resulting error in formation depths can be corrected by adjusting the low-frequency model.

The low-frequency component provides gross lithologic information, for example, where a thick clastic sequence grades to a higher velocity carbonate sequence. The inverted seismic component provides the detail: shale versus sand; salt versus anhydrite layers. The completed traces are displayed in depth and transit time, just like a sonic log. The inverted seismic section is coloured; the lower velocities are coloured yellow and orange, with higher velocities coloured blue and grey (Figures 8 and 11).

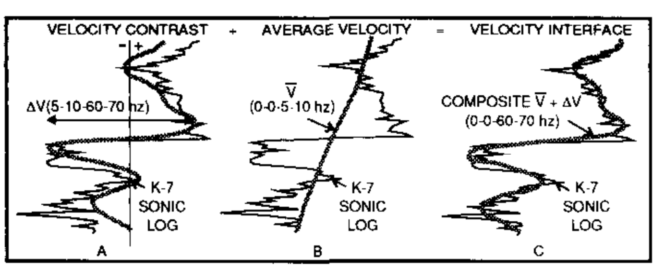

Fig. 7. The composite trace is assembled by combining ΔV and $\overline{V}$ (equations 1, 2).

Reservoir Characterization Study Results – Zechstein Formation

One of the key revelations of the study was the miscorrelation of the Z2 seismic reflector with the top of the K-7 main dolomite in the Kargowa-7 well. Figure 8 shows the seismic inversion display of line T050 from the K-7 well southeast towards the Wilcze-4 well.

Creating the inverted section requires a detailed correlation between seismic and well logs. This procedure led to the detection of the correlation error. The sonic log from Kargowa-7 is shown in Figure 8, filtered to the same frequency content as the inverted seismic section. Correlation of the major units is evident; however, note that the top of the high-velocity unit does not correlate with the top of the reservoir as originally interpreted. The top of the main dolomite in the K-7 well reservoir is seen to occur approximately 40 m above the Z2 seismic reflector.

Miscorrelation occurred because the upper part of the main dolomite exhibits extremely high porosity at Kargowa-7 compared with the Wilcze Field and the surrounding area. Average porosity in the unit in the Kargowa-7 well is over 11%, as compared with 4% in the Wilcze Field wells. The Z2 seismic reflector is continuous, but originates from the base of the best reservoir in K-7 (the upper dolomite unit) rather than from the top of the main dolomite. The transition can be seen by following the Z2 seismic reflector along the conventional seismic section, shown in Figure 4.

The inverted seismic display of line T050 shows several features of interest (Figure 8). The Kargowa-7 upper main dolomite reservoir appears to extend towards the Wilcze Field. The porous dolomite grades laterally into a lower velocity facies, which is interpreted to be salt. The salt is identified within the middle part of the Z3 unit in the Kargowa-7 well. Some debate remains as to the validity of a depositional model which has salt both above and below dolomite. It is possible that the lower velocity below the upper main dolomite relates to higher porosity dolomite,

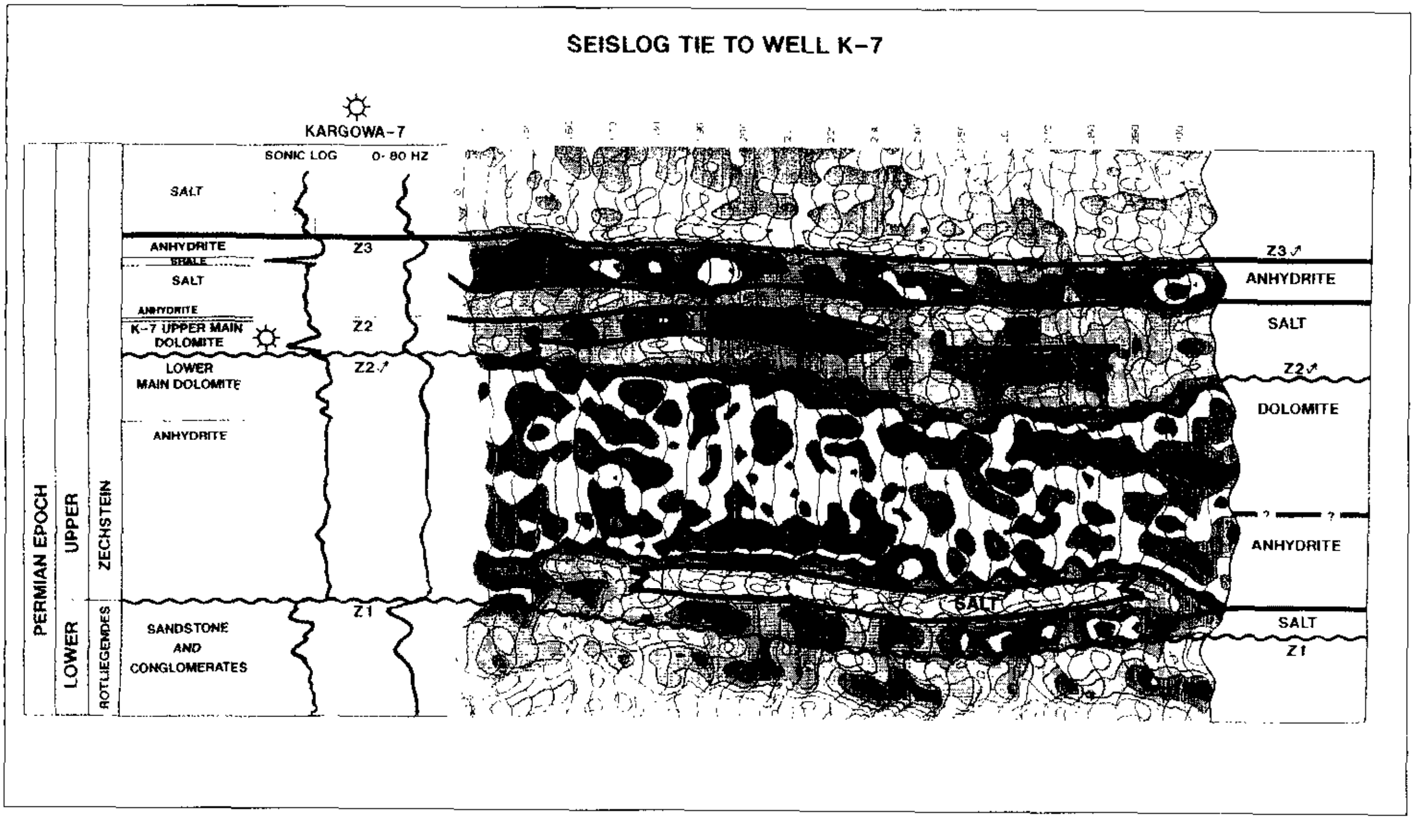

Fig. 8. *Seislog* tie to well K-7. Z1 and Z3 ties from well to *Seislog* display of seismic are obvious. Z2 geologic marker (top of K-7 upper main dolomite) is discontinuous and shallower than the seismic Z2 reflector.

rather than salt. The response may indicate salt, or it may be an erroneously low velocity caused by assuming a linear relationship between velocity and acoustic impedance.

One of the study objectives was to identify the separation between the dolomite and anhydrite facies within the Z1 to Z2 interval. It is evident from the inverted seismic display of line T050 that these facies are too similar in acoustic impedance to be reliably distinguished seismically. We also found that the very thin Rotliegendes sandstone units could not be directly detected seismically. However, it was possible to obtain useful structural information from the seismic inversion results.

The inverted seismic sections made it possible to interpret the areal distribution of the complex stratigraphy of the main dolomite unit. Once the complexity was understood, it was possible to identify the same features on the conventional seismic sections.

It is extremely difficult to produce accurate depth structural maps from the conventional seismic displays. The rapidly changing lithology creates rapid changes in depth conversion velocity functions. On the other hand, these changes can be very easily incorporated into inverted seismic display preparation. Displaying seismic traces as pseudo sonic logs makes lithology change observable and therefore believable. Displaying the composite traces in depth rather than time overcomes the "velocity distortions" and increases the accuracy of the reservoir depth structure maps. The depth structure map shown in Figure 9 was created by interpreting horizons on the inverted seismic depth displays. The depth map shows a reduced structural separation between the Kargowa and Wilcze Fields and a lack of structural closure of the Wilcze Field to the south.

It appears that a halo of salt and low-velocity dolomite exists on the flanks of the Wilcze Field, which contributes to the apparent time closure. Unfortunately, this halo created time lows on the conventional seismic time maps which discouraged stepout drilling to the northwest, in what is possibly the best developed reservoir in the area. Although the available grid of seismic data is not continuous, we interpret a possible extension of the upper main dolomite reservoir unit on lines T121, T122 and T123. A depth structure map showing the interpreted reservoir distribution is shown in Figure 10. Figure 11 shows the inverted seismic line T121, which illustrates the possible extension of the upper main dolomite reservoir above the lower main dolomite reservoir on the north flank of the Wilcze Field. The upper unit appears to be stratigraphically separated from the lower unit by a salt layer.

The interpreted distribution of the upper reservoir raises questions about the separation of the two fields. The Kargowa and Wilcze Fields have identical gas composition and only 6 m difference in their interpreted gas/water contact levels. Wilcze-4 was the only Wilcze Field well which encountered water and it appears that its lower main dolomite reservoir may be isolated stratigraphically from the other wells in the field. It was recommended that interference tests be performed once the wells are on production to confirm whether the reservoirs are separated.

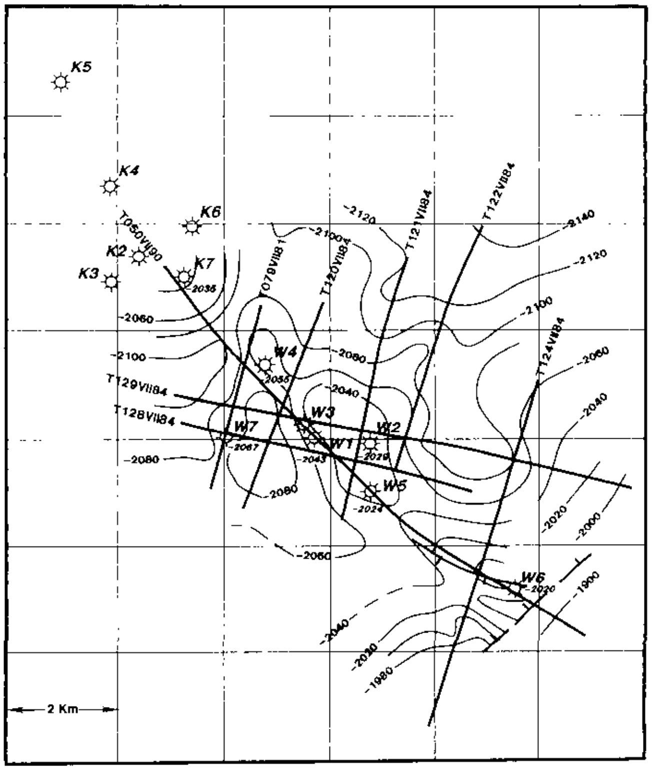

Fig. 9. Revised structure: Zechstein lower main dolomite (Z2 · ˙).

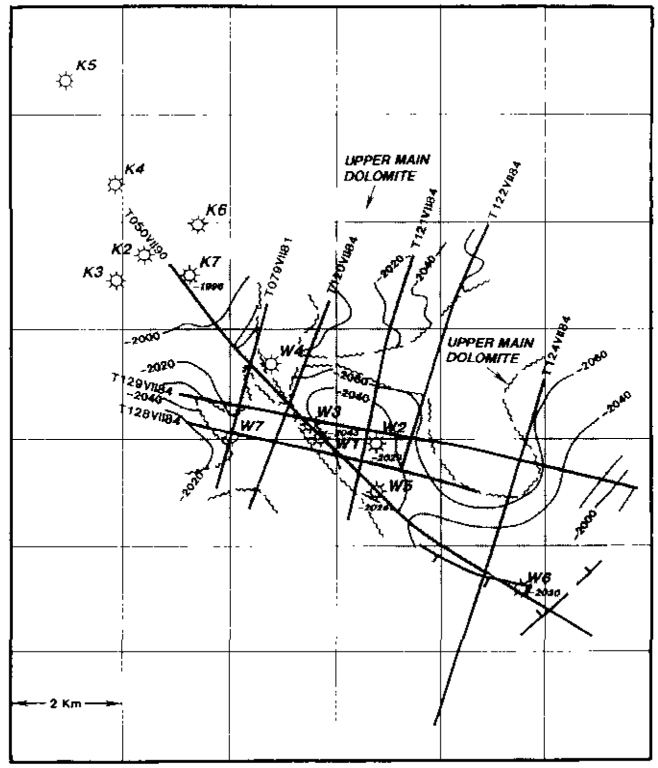

Fig. 10. Revised depth structure and areal distribution of the upper main dolomite reservoir.

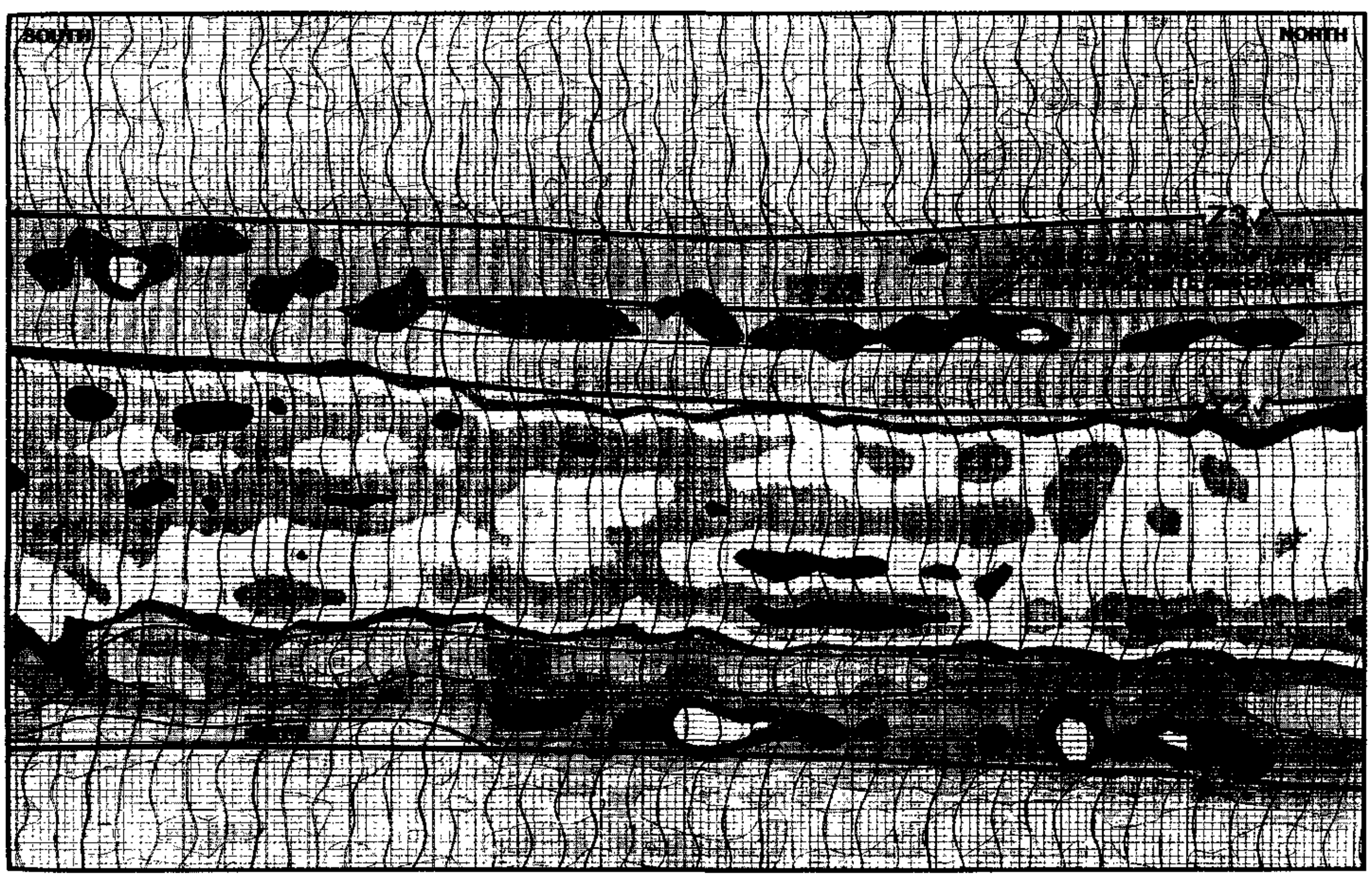

Fig. 11. *Seislog* section of line T121 V1184.

Seismic Inversion Interpretation Results – Rotliegendes Formation

The study showed that the Rotliegendes reservoir is generally not thick enough to be detected seismically. However, correcting for the velocity anomalies created by the rapid facies changes in the overlying Zechstein Formation has simplified the structural interpretation of the Rotliegendes Formation. The Rotliegendes Formation is shown to have very limited structural closure and appears open to the south and east of the Wilcze Field wells (Figure 12).

Faulting

Most of the originally interpreted faults were eliminated from the structural interpretation once the Zechstein velocities were properly corrected. Two interpreted faults remain near the southeast end of line T050. There was very limited data available for study in that area, so the fault orientation has not yet been confirmed by comparison with the surrounding lines. However, as drawn, it is consistent with major regional structural elements.

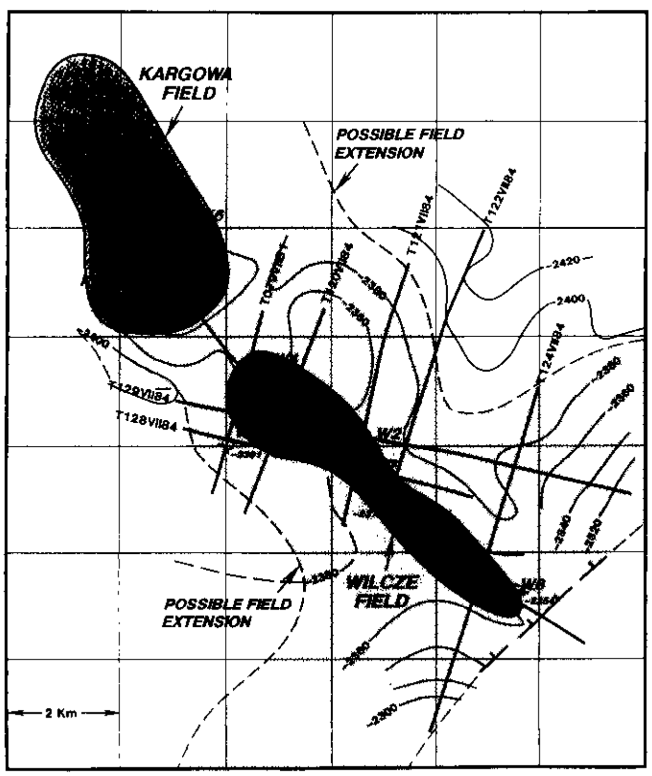

Fig. 12. Revised depth structure and possible field extension of the Rotliegendes sandstone reservoir (Z1 *).

Conclusions

In conclusion, the reservoir characterization study helped to better delineate the Wilcze Gas Field by identifying rapid lateral velocity changes originating from facies changes within the main dolomite interval. This simplified the structural interpretation of both reservoirs in the fields while complicating the stratigraphic interpretation of the Zechstein dolomite reservoir. The stratigraphic interpretation proposes that the seismic structural closure originally mapped in the Wilcze Field is largely due to local lateral termination of the upper main dolomite unit against the enclosing salt.

The main dolomite and Rotliegendes reservoirs are interpreted to extend well beyond the study area and a possible extension of the Kargowa Field was also identified. It has been indicated that the study will be extended prior to further drilling.

The original objectives included determining the field limits and estimating the reserves in place. The results indicate that both reservoirs could extend southward beyond the limits of the study area so neither the field limits nor the reserves could be determined. Several new areas with good potential for reservoir development were identified and should be considered in greater detail prior to further drilling.

In conclusion, the seismic inversion made it possible to interpret the complex areal distribution of lithologies within the Zechstein interval. Correctly interpreting those facies simplified the structural interpretation of both the Zechstein and the underlying Rotliegendes reservoirs.

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