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APPLICATION OF SEISMIC METHODS TO IDENTIFY POTENTIAL GAS CONCENTRATION ZONES AT THE ZECHSTEIN LIMESTONE LEVEL IN THE "RUDNA" MINING AREA, SW POLAND

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Abstract: A block development operation at the "Rudna" copper mine (KGHM Polska Miedź S.A.) encountered a "compressed gas trap" that caused the ejection of fragmented rock material into a drift. Faced with a new threat of gas ejection the mine needed to find methods to identify potential gas concentration zones prior to any further exploration work. Surface seismic surveying was chosen as a widely-accepted standard method of investigating rockmass structure and tectonics and pinpointing natural gas deposits. An area of one square kilometre was selected directly above the ejection site, a 3D seismic survey, known as Duża Wólka 3D, was performed and a survey well S-421A was drilled. The objective was to investigate the overall rock structure, especially the structure of Zechstein and top Rotliegendes formations, as well as to attempt identifying anomalous zones, which could be linked with the gas saturation of Ca1 dolomites, on the 3D seismic image at the P1 level (Zechstein/Rotliegendes boundary).

An interpretation of multi-scenario seismic modelling of the recorded data helped to:

– recognize the structure and tectonics of the area, including minor faults cutting through the top-level Rotliegendes formations and floor-level Zechstein formations. Such faults could constitute migration channels for Carboniferous-period gases,

– locate zones with nearly zero-reflection amplitude at the surface of the top-level Rotliegendes (P1 seismic boundary), which would suggest a reduction of elastic parameters of the Ca1 dolomite. This reduction could be linked to an increased porosity and fracturing of the dolomite and its saturation with gas (a reduction of the seismic wavelet propagation velocity).

Credibility of this interpretation is already partly corroborated by data from wells drilled in the Zechstein limestone by the mine.

The paper presents the first in the world attempt to use the surface seismic survey for location of zones with small gas concentration in porous rocks at the Zechstein/Rotliegendes boundary. Such zones should not be identified with gas pools that occur in the Zechstein Limestone (Ca1) in the area of the Fore-Sudetic Monocline.

Key words: 3D seismics, seismic modelling, gas accumulation zones, Zechstein limestone, "Rudna" copper mine, SW Poland

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INTRODUCTION

The deposits of copper ore with silver that occur in the Fore-Sudetic Monocline are exploited by KGHM Polska Miedź S.A. in the mines ZG Lubin, ZG Sieroszowice – Polkowice and ZG Rudna. The mine workings are cut mostly in the bottom part of the Zechstein strata and in sandstones of the Weissliegendes.

The "Rudna" copper mine (part of KGHM Polska Miedź S.A.) is engaged in preparatory work of developing a new section of a copper deposit in the Głogów Głęboki–Przemysłowy Mining Area. The block development operation is heading in the northwestern direction.

In September 2009, while extending the No. 169 set of drifts, the miners encountered a "gas trap" with small volume, but high pressure in drift T169a. As a result of rock cracking caused by blasting operation, the compressed gas caused an ejection of fragmented rock material (small dolomite fragments) into drift W-169a. In face of the threat of new gas ejections in this part of mine, the mining work was

Fig. 1. "Rudna" mine – map of drifts and location of seismic 3D surveys

suspended until causes of the event are explained. At the same time attempts were started to find methods which would enable determination of possible places with potential gas concentration.

Gas samples taken from the encountered "gas cavern" and from mining well Jm20H5 drilled from drifts 169 were geochemically tested in order to identify their molecular and isotopic composition. The tests showed that, in terms of its origin, the gas resembled natural gas accumulated in reservoir rocks of the Zechstein limestone and Rotliegendes formations in the Polish Lowlands. Such gas accumulations are, among others, also known from the Fore-Sudetic Monocline, some of them located 30–40 kilometres from the "Rudna" mining area. They were sourced by Carboniferous and Devonian source rocks (Dąbrowska *et al.*, 1993; Kotarba, 2010). Faults found in the mine that cut the Rotliegendes and the bottom layers of the Zechstein can be paths for gas migrating to porous parts of Ca1.

Apart from the research conducted within the deposit itself, surface seismic survey was employed as it represents a basic method used for location of hydrocarbon deposits. A 3D seismic survey was proposed to help understand the structure of the Zechstein and top Rotliegendes formations and to attempt identifying anomalous zones in the seismic image at the Zechstein/Rotliegendes boundary (P1). It was assumed that the zones could be linked with areas of increased porosity and/or fracturing of the Zechstein dolomite rocks and could serve as potential gas concentration zones. Similarly, it was assumed that the tectonic faults could be used as channels for gas migration into the loosened zones in the Ca1 dolomites.

Plausible interpretation of seismic data is only possible when linked with geological and geophysical data obtained from deep wells. A need for detailed understanding of petrophysical properties of the Zechstein and Rotliegendes formations called for such an interpretation. The cross-method requirement was satisfied by drilling the well S-421A at a horizontal distance of 250 metres from the "gas cavern" and by performing a 1 km^2 sized 3D seismic survey "Duża Wólka 3D" around the well (Fig.1).

GEOLOGICAL STRUCTURE OF THE DEPOSIT IN THE STUDY AREA

The "Głogów Głęboki–Przemysłowy" Mining Area is located in the southern-central part of the Fore-Sudetic Monocline (Fig. 2)

Formations older than Carboniferous are known from a few well sections only. They are represented by phyllites and quartz schists of the Precambrian age (Oberc, 1978). Sub-Permian Carboniferous strata are composed principally of argillaceous rocks with interbeds of greywackic sandstones that pass into younger sediments of typical molasse nature (Wierzchowska-Kicułowa, 1996). On the basement, Permian and Mesozoic strata rest. They dip gently (4–5°) and honoclinally to NE (Fig. 3).

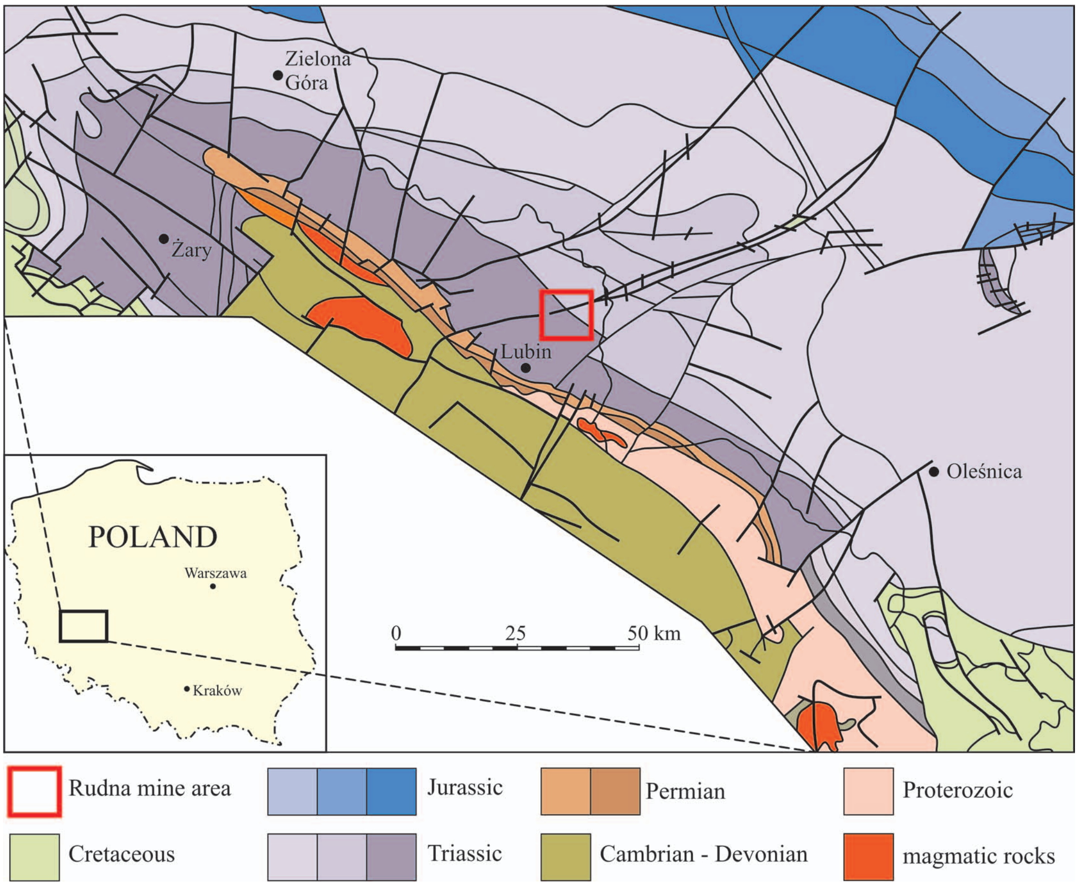

Fig. 2. Geological map of Fore-Sudetic Monocline without Cainozoic strata (by Pożaryski, 1979)

The Permian succession is represented by the Rotliegendes and Zechstein formations (Kłapciński & Peryt, 1996, 2007). The Lower Rotliegendes (Autunian) is developed as basal conglomerates, brown-red sandstones and shales, quartz conglomerates, rhyolites and rhyolitic tuffs. The Upper Rotliegendes (Saxonian) is developed as brown-red fine- and medium-grained sandstones with glauconite (Kłapciński & Peryt, 1996, 2007). The Rotliegendes sediments occur in the whole analysed area and range from 200 m to ca 400 m in thickness. At the uppermost part of the Rotliegendes, sandstones (2–6 m thick) of the Weissliegendes occur. They represent transgressive deposits of the Zechstein sea (Błaszczyk, 1981; Jerzykiewicz *et al.*, 1976; Krasoń & Grodzicki, 1964; Zaczek, 1972).

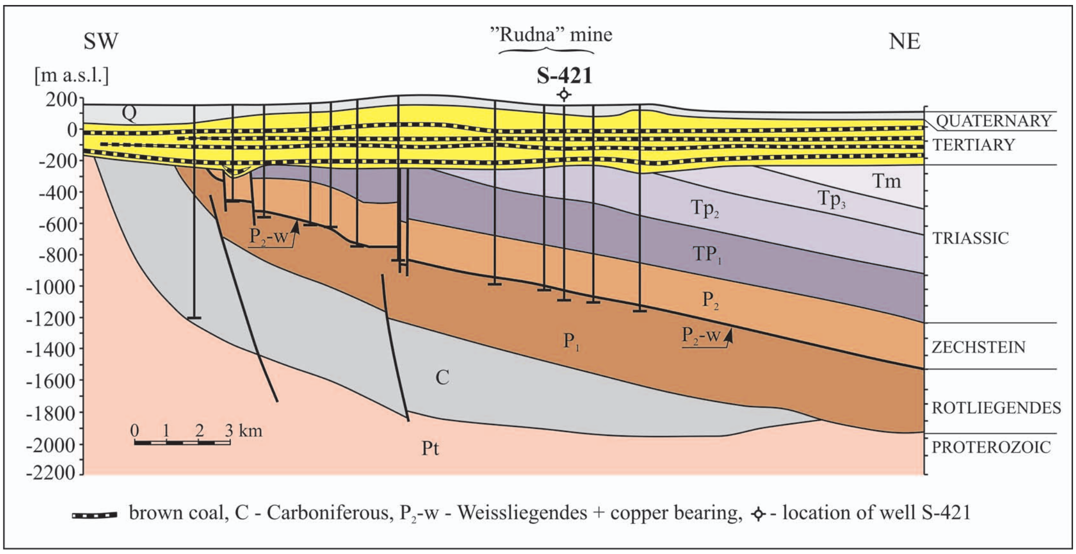

Fig. 3. Fore-Sudetic Monocline. Geological cross-sections through the Lubin–Głogów copper deposit (Kłapciński *et al.*, 1984 – modified)

The Zechstein succession is composed of four cyclothems (Kłapciński & Peryt, 1996, 2007; Pajchlowa & Wagner, 2001):

The PZ1 cyclothem (Z1, Werra) is developed as the Border Dolomite, the Kupferschiefer (ŁM), limestones and dolomites of the Zechstein Limestone (Ca1), the Lower Werra Anhydrite (A1D), the Oldest Halite (Na1), and the Upper Werra Anhydrite (A1G);

The PZ2 cyclothem (Z2, Stassfurt) is composed of the Main Dolomite (Ca2), the Basal Anhydrite (A2), the Older Halite (Na2), the Older Potash Salt, breccias, and cavernous anhydrites;

The PZ3 cyclothem (Z3, Leine) is composed of the Platy Dolomite (Ca3) with interbeds of the anhydrite (A3), dark- grey laminated shales of the Grey Salt Clay (I3), and the Younger Halite interbedded locally with the Younger Potash Salt (Na4).

The PZ4 cyclothem (Z4, Aller) is developed as brown-red shales with interbeds of gypsum or anhydrite (I4), the porous Pegmatite Anhydrite (A4), the Youngest Halite, and brown-red shales.

In the "Głogów Głęboki–Przemysłowy" Mining Area, the PZ2, PZ3 and PZ4 cyclothems have small thicknesses (*ca.* 100 m in total).

In the study area, Mesozoic sediments are represented only by sandstones of the Buntsandstein.

The Zechstein formations of the Fore-Sudetic Monocline are overlain by the Triassic, Jurassic and Cretaceous successions (Kłapciński & Peryt, 1996, 2007) which gently dip to NE. They are overlain by Cainozoic sediments. During the Tertiary, limy, quartzose and glauconitic sandstones were deposited, as well as gravels, clays and brown coals. They are overlain by the Poznań Clay (Kłapciński & Peryt, 1996, 2007). Quaternary sediments are represented mainly by sands, gravels, tills and clays (Kłapciński & Peryt, 1996, 2007).

The study area was surveyed using a grid of surface-drilled wells at 1.5 × 1.5 km intervals (S-421, S-420, S-441, S-640, S-422, S-379, S-369, S-368), an additional well S-421A with a full range of drilling geophysical measurements, mining drifts T and W-169 and with additional wells drilled from the drifts. Unfortunately, no one well reached formations older than the Rotliegendes.

In the mining area, three principal fault systems are dominant: NW–SE, W–E and N–S. The northwest-southeast-trending faults, which are part of the Middle Odra dislocation zone, play a major role with regard to extent and amplitude (Markiewicz, 2007).

The most detailed information about the lithology of the deposit and surrounding rocks was provided by well S-421A where cores were analysed for lithology, facies, and sedimentary conditions at the boundary between the Rotliegendes and Zechstein formations (KGHM POLSKA MIEDŹ S.A. OZG "Rudna", 2010).

The Zechstein formations rest on a very thick (400–500 m) series of brown-red sandstones of aeolian origin. Well S-421A penetrated 42.5 metres into the Rotliegendes sediment. The sediment was formed in aeolian conditions and featured clearly visible, slanted large-scale layering typical of desert/dune conditions of terrestrial sedimentation.

Atop the Rotliegendes formation lies a *ca.* 10 metre-thick layer of sandstone with nearly flat-parallel layering of the sandy material that is typical of Weissliegendes fluvial sedimentation. The sedimentation series of clastic formation ends with a series of white-grey sandstones, 8.5 m thick. These are typical light-grey Weissliegendes sandstones with numerous sedimentary structures characteristic of marine environments.

The entire sandy series (including both the Rotliegendes and Weissliegendes) is built of quartzite sandstones with clay and clay/carbonate cement. Only at the very top of the formation there is a considerably harder, 10 centimetre thick layer with carbonate cement.

The sandy residue of the Weissliegendes is covered by a thin series of non-ferrous, ore-bearing clay shales of highly varied thickness and with strong local distortions caused by secondary sedimentation, diagenetic and tectonic processes. Shale formations were found in drifts T, W-169 and in a small number of adjacent wells drilled from the surface.

Carbonaceous formations of the Werra Cyclothem (Ca1) range from 9 to 15 metres in thickness and are shaped as cryptocrystalline and fine-crystalline grey-beige dolomite and limestone. These formations are predominantly very hard and highly compacted. The dark-grey cryptocrystalic dolomite with clay laminae constitutes the floor-level link of the carbonaceous series. The middle link consists of cryptocrystalline grey-beige or beige dolomite with few laminations. The section that contains the "gas traps" is dark-beige with cryptocrystalline or fine-crystalline structure. It is also either porous or densely cracked, the latter visible under a microscope. The rocks are relatively loose and susceptible to mechanical damage. The top-level section of the carbonaceous series is occupied by dark-grey dolomites with a degree of fine lamination and streaks of clay substance, often anhydrite or is mixed with fine-grained or fine-crystalline, dark-grey anhydrite.

Above the carbonaceous series, a 20–80-m-thick continuous and rigid Zechstein anhydrite layer was found. The anhydrite (A1D) is ash-grey in colour, fine-crystalline, hard and compacted. Most of the anhydrite series is overlain by a thick deposit of the oldest halite (Na1).

The geology of the area is strictly related to the palaeomorphology of the top of the Weissliegendes and subsequent deformation related to the development of the Fore-Sudetic monocline (Jerzykiewicz *et al.* 1976; Jarosz & Zalewska, 1977; Błaszczyk, 1981; Kaczmarek *et al.* 2005).

OUTLINE OF MINING PROBLEMS

As it was mentioned above, the "Rudna" copper mine carries on the mining work in new part of the copper deposit in the Głogów Głęboki–Przemysłowy Mining Area and the block development operation is heading in the northwestern direction.

The mining work, involving the digging of a set of drifts cutting through the deposit, was carried out at a depth of *ca.* 1190 m. Because of the thin (0.3–0.6 m) copper-bearing shale formations, the drifts cut into both the Rotliegendes formations (Weissliegendes sandstones) and the dolomite formations of the Zechstein limestone (Ca1). In the working area, the dolomite formation layer is approximately 11 m thick while the drift height is 4 metres, of which 3.2 metres cuts into the dolomite.

While extending the No. 169 set of drifts, the miners encountered a "gas trap" with small volume, but high pressure in drift T169a. As a result of rock cracking caused by a blasting operation, the compressed gas caused an ejection of fragmented rock material (small dolomite fragments) into drift W-169a. According to a geomechanical analysis of the event, the ejection was caused by top dolomite slab snapping-off from the anhydrite formation, which opened the trap filled with debris and gas (Zorychta, 2010). In face of the threat of new gas ejections, the mining work was suspended until causes of the event are explained and potential gas concentration spots are identified.

The geological services of the mine started drilling their own survey wells to determine possible gas concentration spots in the rockmass surrounding the "gas cavern" (Fig. 4). Altogether, 11 horizontal and sloping wells were drilled at various azimuths in the Ca1 Zechstein limestone (dolomite).

Evidence of gas was found in three wells. 2.6% of methane was found in an outflow in well Jm20H5, (containing primarily nitrogen) at a pressure of 27 at and the combined volume of 6,956 m^3. In well Jm20H8, an outflow had a pressure of 60 at and a combined volume of 28,634 m^3, of which 5.1% was methane. Finally, 2,088 m^3 gas leaked from well Jm20H10 at pressure 38 at and included 5.25% of methane (KGHM POLSKA MIEDŹ S.A. OZG "Rudna", 2010).

The results of these drillings suggest an irregular occurrence of gas concentration zones around the original "gas cavern" in drift T-169a. It suggests new gas ejections risk during mining work in this part of the deposit.

In the light of these results, a need for 3D seismic data became even more apparent in order to assess rocks properties at the Zechstein/Rotliegendes boundary (P1) and to locate areas of increased total porosity as potential gas concentration areas.

METHODOLOGY OF SEISMIC DATA ACQUISITION AND PROCESSING

To investigate geological structure of the study area (1 km^2 target area), a 3D seismic survey was made by the Geofizyka Kraków Ltd., POGC Group. The 1 km^2 area surface must be regarded as the area where the seismic image will achieve its nominal parameters.

The horizontal resolution of seismic investigation was set at 10 m (bin 10×10 m), which implied the interval between receivers at 20 m and the same for shot points.

The fold number, the main parameter in 3D surveying, was set at 64. The other main parameter, offset, ought to correspond at its maximum to the target depth, which in this case was the P1 boundary (top of the Rotliegendes at *ca.* 1,200 m). It was set at 1,236 m and the minimum offset was at 156 m. To achieve these nominal parameters the central setup must have the following split-spread parameters:

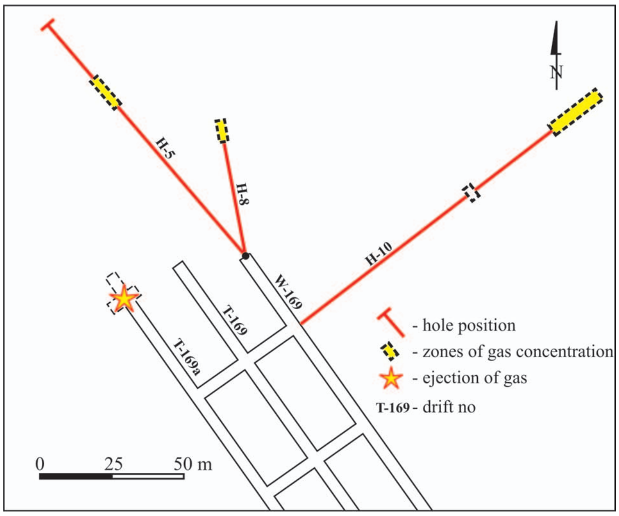

Fig. 4. "Rudna" mine – site of gas eruption and location of investigation boreholes and gas concentration zones

– 16 receiver lines at 100 metres apart to ensure the cross line fold of 8,

– 96 receiver points ensuring in-line fold of 8 at 120 metres between shot lines (clusters every 6 receiver points),

– 18 shot point lines at 120 metres apart (in line shot interval 6),

– 95 shot points per line (Fig. 5).

For the Duża Wółka 3D survey, the methodology was simplified, but recording was carried out along 20 lines, which ensured that a nominal fold of 64 was achieved along the target area (Fig. 5). This methodology required a limiting of the offset range during data processing.

A Sercel 408 UL device was used for field measurement. Recording time was three seconds each, with sampling interval of 2 milliseconds. SM-24 geophones, with the resonance sensitivity of 10 Hz, were used as vibration sensors and were grouped in three lines of 12 geophones each in parallel to the profile, at a 5 metre grouping base and one metre between the geophones. Two Vibroseis Failing Y-2400 Mark IV devices were used per shot point. At every shot point eight sweeps were generated without moving of the vibroseis. Each sweep lasted 16 seconds at a frequency range of 8–110 Hz (Geofizyka Kraków Ltd. POGC Group, 2010c).

Data processing involved standard and some advanced procedures, the latter including automatic correction of static adjustments, velocity analysis, spectral whitening and DMO procedure along passes designated for velocity analysis. The final processing involved post-DMO velocity analysis, DMO stack for all the data (maximum fold in middle of area equal to 300), spectrum whitening of the amplitude seismic record, signal to noise improvement, frequency filtering, final amplitude scaling and wavelet phase adjustment to obtain a zero-phase record (Geofizyka Kraków Ltd. POGC Group, 2010d). As a result, the wave field obtained had an improved resolution but less than good horizontal resolution. To improve this parameter an attempt was made to apply migration, but 3D migration procedure tests

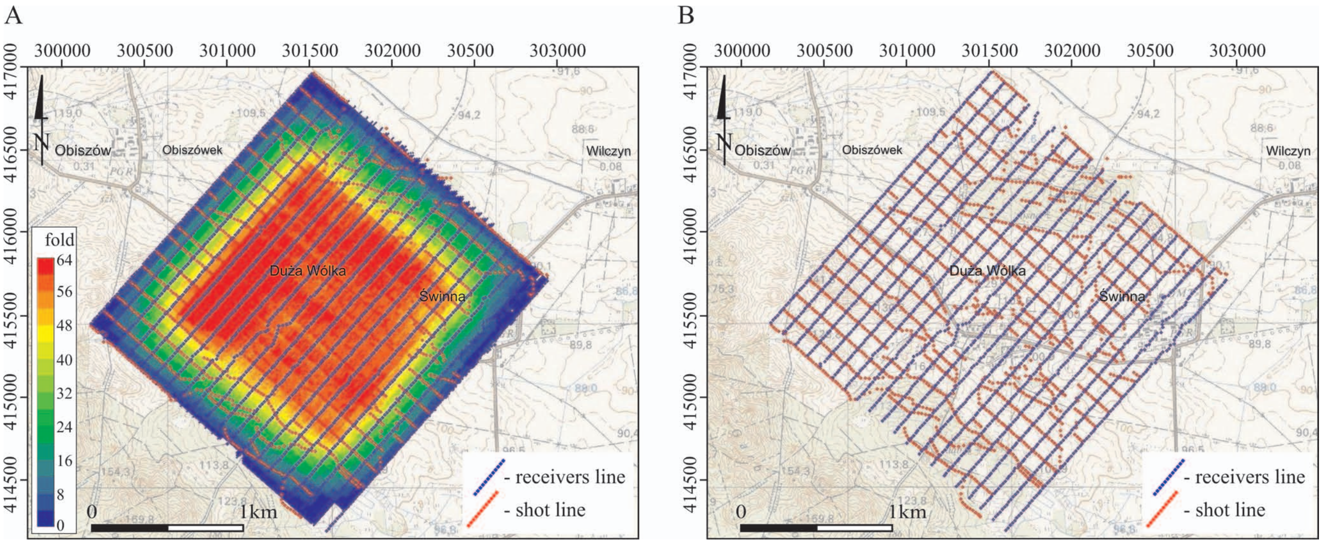

Fig. 5. "Rudna" mine area – place of seismic investigation in Duża Wólka village region. **A** – shots and receivers location, **B** – effective fold after offset range reduction (Geofizyka Kraków Ltd. POGC Group, 2010c)

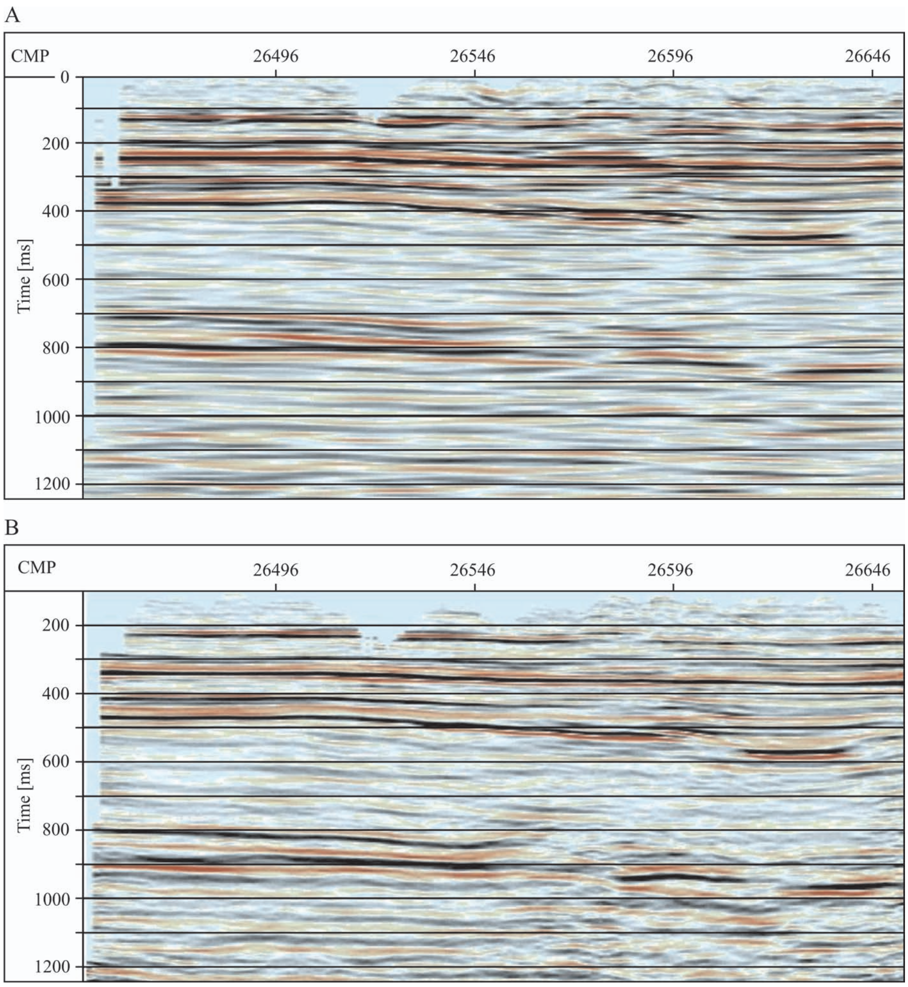

Fig. 6. Time seismic profile (in line 113). **A** – after advanced processing and migration, **B** – after offset range reduction, DMO stack and 180 degrees phase rotation

showed, after stacking, that the migration side effects (smiles) were still visible (Fig. 6A).

In a further effort to improve horizontal resolution, the reflections registered at high incident angles were eliminated by limiting offsets to 1,200 metres (fold reduction to 64) and a set of data thus prepared went through a final processing pattern involving:

– velocity analysis (4 times), residual statics (3 times),

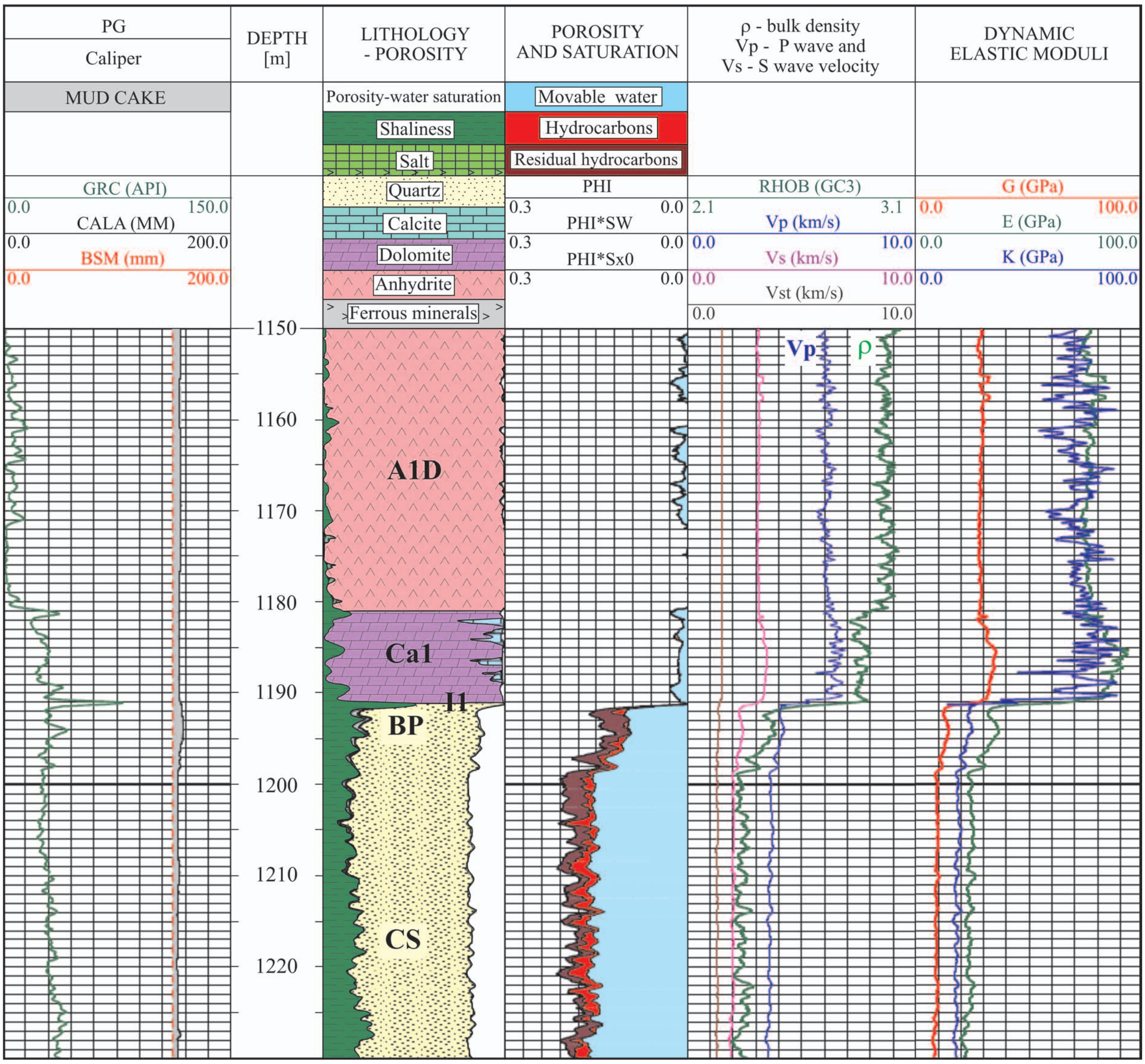

Fig. 7. Well logging results from well S-421A. Elastic parameters of deposit zone. A1D – Lower anhydrite; Ca1 – Zechstein limestone; I1 – Copper bearing; BP – Weissliegendes sandstone; CS – Rotliegendes sandstone (Geofizyka Kraków Ltd. POGC Group, 2010b)

– DMO stack, RNA3D (random noise attenuation), spectral whitening,

– FK 3D filter, TV filter, instant gain, zero phase conversion, harmonizer deconvolution,

– 180 degrees phase rotation.

Migration was not applied in this instance. High resolution seismic 3D volume was obtained (Fig. 6B) and used for geological interpretation.

SEISMIC INTERPRETATION

Geological calibration of seismic boundaries

In accordance with requirements of geological documentation of the deposit, there are a dozen deep wells that reached through the deposit zone and into the Rotliegendes formations underneath. Geophysical measurements were, however, performed in only one well, S-421A, located at the centre of the seismic survey (Fig.1).

Well logs obtained for the deposit zone (Geofizyka Kraków Ltd. POGC Group, 2010b.), which are most important to seismic interpretation (velocity logs and density logs) as well as information on lithology and porosity and saturation and elastic parameters are shown in Fig. 7. The logs showed a change of these parameters at the boundary between the Zechstein and Rotliegendes formations. This is where a fundamental change occurred in the V velocity, the ρ volume density and the dynamic elasticity parameters, such as the modulus of rigidity (G), Young's modulus (E) and the bulk modulus (K). A change of these parameters is strictly linked with a transition from sulphate-carbonate sediments (A1D-Ca1), with their trace porosity levels, to clastic sediments of the Rotliegendes, with its porosity up to more than ten percent and hydrocarbon saturation levels in the order of single-percentage points (see Fig. 7). In the re-

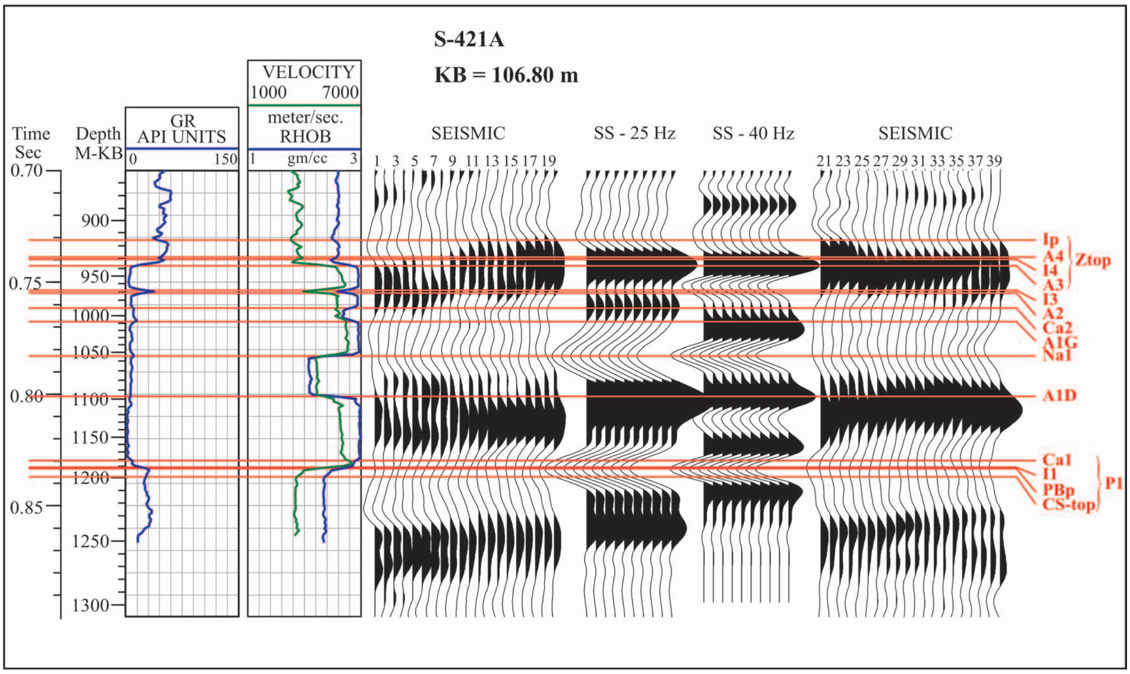

Fig. 8. Part of synthetic seismogram for Zechstein interval. GR – Gamma ray profiling; VELOCITY – P wave velocity; RHOB – bulk density, SEISMIC – part of seismic profile, SS – synthetic seismogram

cord of petrophysical parameters, a boundary between the bottom anhydrite A1D and dolomites of the Zechstein limestone Ca1 also comes out. A pronounced drop in density and a minor increase in velocity are linked to this boundary.

Well-logging data are necessary to geological linking of seismic horizons. The well-to-seismic tie was performed using synthetic seismograms (GeoGraphix program Log M *Landmark Graphics Corp*.). Data necessary to construct synthetic seismograms include velocity curve and density curve (RHOB) obtained from acoustic and density profiling performed at well S-421a (Geofizyka Kraków Ltd. POGC Group, 2010b.), as well as a 20–40 Hz seismic wavelet that was extracted from traces recorded near the well for Permian formations (Pietsch *et al.*, 2010).

Such low frequencies mean that it was possible to unequivocally identify seismic reflections from Miocene coal deposits and the top of Triassic formations, which have greater velocities and densities as compared to the overlying Tertiary strata (Pietsch *et al.*, 2010). The seismic imaging of the Zechstein formations is, however, less clear. This can be seen in a part of synthetic seismogram for the Zechstein strata (Fig. 8).

From the seismic perspective the Zechstein is a thin-layer medium. To obtain separate reflections from the bottom and the top of a layer, the thickness of the layer should be about 60–70 metres at velocity of *ca.* 6,000 m/s (in anhydrite and dolomite) and *ca.* 40–50 metres at a velocity of ca. 4,000 m/s (salt) for frequencies of the order of 25 Hz. With the actual layer thicknesses in the mine, the unequivocal correlation can be obtained only for the reflections from the top of the oldest halite Na1 (strong negative reflection) and the top of anhydrite A1D (strong positive reflection). However, seismic events related to the top (Ztop) and floor (P1) of Zech- stein are interfered signals.

The P1 reflection (Fig. 8) that is related to dolomite layer (Ca1), copper-bearing layer (I1) and white sandstone layer (BP), is particularly important to mining works. A slight velocity increase and accompanying drop of density results in the reflection coefficient close to zero at the top of the dolomite (Ca1). Therefore, the anhydrite/dolomite boundary has no effect on the reflection and the seismic boundary P1 is clearly linked with the strong reflecting boundary between the Ca1 dolomite and the BP white sandstone (top of the Rotliegendes) (see Fig. 8). The amplitude of the reflection depends not just on petrophy- sical parameters of the layers mentioned above, but also on parameters of the top of the lower anhydrite (A1D) and of the bottom Rotliegendes (CS). Looking at the calculated synthetic seismogram and at velocity and density summaries in Figures 7 and 8, the reflection linked with the Zechstein/Rotliegendes boundary has a negative amplitude. Its scale depends on the petrophysical parameters of all the layers that form the above mentioned deposit zone, and also on their thickness.

Summing up the linking of well-logging data with seismic records, it may be concluded that the current capabilities of seismic method offer no realistic prospect of achieving higher frequencies that are required to obtain a separate reflection from the top of Ca1 and the floor of P1 Zechstein. Additionally, it is worth noting that in the study area the Ca1 top boundary is not a seismic boundary, because of the similarities between petrophysical parameters of A1D and Ca1.

Structural map of the Zechstein bottom (P1)

The recorded seismic profiles have shown the structural setting of the study area. The northern part is cut by a series of faults orientedd NW–SE. The faults (see: seismic profile

IL 140 – Fig. 9) cut through the Triassic and Zechstein strata and within the latter the fault displacement is much smaller. The A fault running S–N (see: seismic arbitrary profile along well correlation line – Fig.10), as well as faults B and C running NEE–SWW, are limited to the Rotliegendes formations and disappear either in the A1D anhydrite or in the Na1 halite.

To construct the structural map at the top of the Rotliegendes, the time-to-depth conversion method, based on the formula $V_{avg} = V_0 + kZ$, was used. The k coefficient was calculated from linear approximation of the vertical hodograph. Average velocities V_{avg} were calculated on the basis of the depth to the Rotliegend rocks in the wells and mine drifts and corresponding time values t_0 in the seismic sections. Considering the small number of depth measurements within the 3D survey and their irregular distribution (concentrated in the centre of the mapped area), the method of the velocity V_0 interpolation and extrapolation gives smaller errors of the time-to-depth conversion in comparison with the method based upon a map of average velocities V_{avg}. Moreover, it is not necessary to include, in the V_0 velocity wave field, faults that are characterized by small throws.

A structural depth map of the P1 level in Fig. 11 is only calibrated by wells S-421 and S-421A and by depth of the gas eruption level (mine proprietary data). It shows honoclinal dip of the basement of the Zechstein towards NE (1,000–1,200 m). In the mining area, three principal fault systems are dominant: NW–SE, NWW–SEE and N–S. The NW–SE system is superior. It occurs in the northern part of the survey area, and major dislocations 2, 3 and 4 bound a regional trough. Their throws reach 100 m. Systems of subordinate faults (transverse and longitudinal ones), oriented N–S and NEE– SWW, have throws of up to a few metres (Nieć, 1997).

Seismic modelling as a basis for developing identification criteria for anomalous zones linked with gas saturation

The thin-layered structure of the deposit zone and the lack of detailed information on the petrophysical parameters, V and ρ, leads to a conclusion about that obtaining information about an effect of increased porosity and possible gas saturation of Zechstein floor formations on the wave field is possible through seismic modelling. The theoretical wave fields calculated for assumed seismogeological models can give an answer to the question whether the seismic method is able to record anomalous wave field that would develop in such a case. Seismic modelling helps link individual components of a seismic model with their rendering in the seismic wave field, which can also offer a basis for developing interpretation criteria for the wave field (Neidell & Poggiagliolmi, 1977; May & Hron, 1978; Hardage, 1987; Fagin, 1991; Pietsch & Strzetelski, 2001; Pietsch & Jarzyna, 2002; Kobylarski *et al.*, 2007; Pietsch *et al.*, 2007; Pietsch *et al.*, 2008; Golonka *et al.*, 2009).

The theoretical wave field was computed with the Geo Graphix system (*Landmark Graphics Corp.*) and the LogM Model Builder and LogM Struct packages using zero-phase Ricker wavelet at 20 Hz and 40 Hz (frequency of seismic reflections).

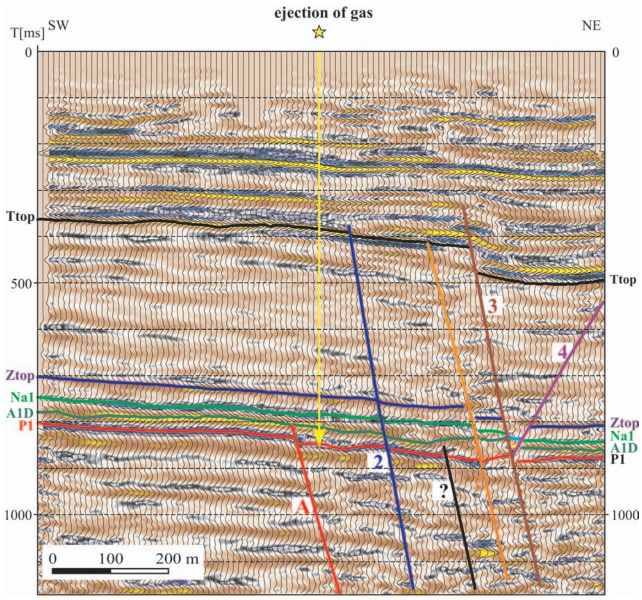

Fig. 9. Seismic time profile – IL 140 (location see Fig. 11)

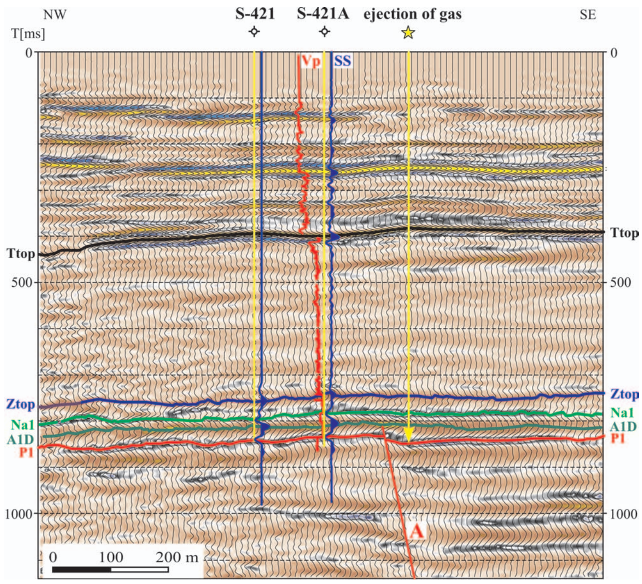

Fig. 10. Seismic time profile along well correlation profile (for location see Fig. 11)

The first modelling step involved construction of seismic models using as input data a correlated geological profile of the Zechstein formations (Pietsch *et al.*, 2010) developed based on borehole data from wells (W to E): S-420, S-421, S-421A and S-422. This geological cross-section is shown in the map of the P1 boundary depth (Fig. 11). Thicknesses of subsequent Zechstein layers were used to construct the models. Due to lack of well-logging data, velocities and densities were adopted from only one well in the area, *i.e.* the S-421A, where well logs were available. For this reason, there is no lateral variability of layer velocities in the initial model.

In the initial model, the presence of faults was assumed in accordance with the recorded seismic profile (Fig. 10). It

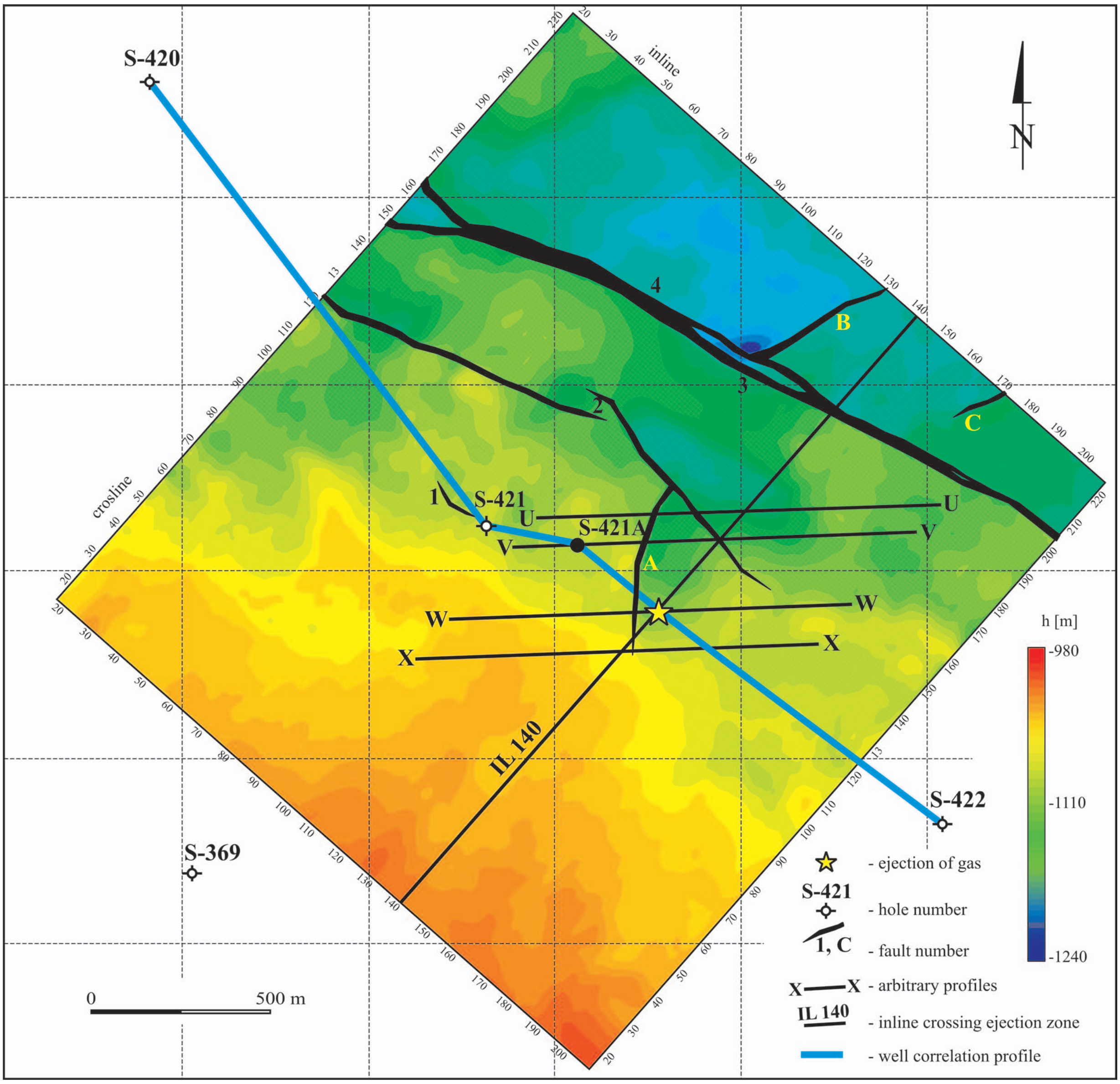

Fig. 11. Structural map of the seismic horizon Zechstein/Rotliegendes (P1)

was specifically assumed that fault A, located between the site of ejection and well S-421A, could have acted as a migration channel for Carboniferous gases (Kotarba, 2010). In this situation, saturation zones could have been located both in the Rotliegendes and Ca1 dolomite formations. The assumption of an increased porosity and gas saturation necessarily required that values of seismic velocity and bulk density had to be reduced. At high porosity values and low gas saturation level, the velocity can decrease by up to 30% (Kuster & Toksöz, 1974 a, b; Bała, 1994; Bała & Cichy, 2007).

The impact of gas saturation on the wave field in the fault zone was analysed with two saturation scenarios. In the first scenario (model I), it was assumed that the gas saturation zone was located in the Rotliegendes formation and the unsaturated dolomites Ca1 (non porosity) provided an impermeable barrier. In this case the saturation zone was located in the upthrown block of the fault. The model is shown in Figure 12A, rendered in the version of acoustic impedance (AI=Vρ), which equals approximately 6,500 in the assumed saturation zone. The reduction in velocity and density results in an increase in the difference of impedance values between the complex containing the A1D anhydrite and the Ca1 dolomite, on the one hand, and the complex with the white sandstone BP and the Rotliegendes on the other. This should lead to higher amplitude of the negative reflection on P1. In this particular example, taking into account the fact that it was a fault zone, the decreased velocity value for the white sandstone (BP – Weissliegendes) was adopted at *ca.* 3,000 m/s and density at *ca.* 2.2 g/cm^3. Wave fields calculated for this model, for 20 and 40 Hz frequency, are shown in Figures12B and 12C. In the wave field calculated for both frequency (Fig. 12B and 12C), there is no visible impact on the seismic record of the impedance reduction in the white sandstone. However, the model fails to match the actual situation in the mine, as the ejected rock material contained dolomite, but no Weissliegendes rock.

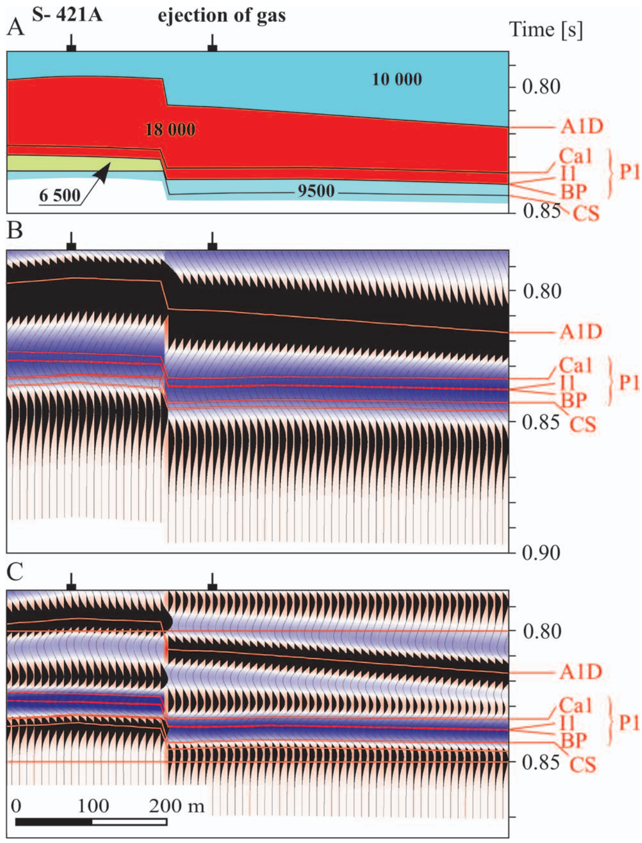

Fig. 12. Seismic modelling – Model I – anomaly zone: near fault part of Weissliegendes sandstone (upthrown wall), V = 3,000 m/s, ρ = 2.2 g/cm^3, AI~6500. **A** – seismogeological model, **B** – theoretical wave field – Ricker wavelet 20 Hz, C – 40 Hz

The second modelling scenario (models II to IV) assumed that the saturation zone was located in the Ca1 formations in the downthrown wall. This assumption was based on an analysis of seismic profile located close to gas ejection zone (Fig. 10). It was specifically assumed that the affected zone was a porous pocket within compacted dolomite. Gas migrating through the fault might have saturated the pocket in the dolomite and small gas quantities might have reached the Rotliegendes level. This is shown by well logging measurements from well S-421A (Figs 7, 8).

A number of models were constructed of seismically modified zones in Ca1 saturated with gas to provide a plausible answer to the question whether such zones could be detected using seismic data, especially in spite of lack of any information about their structure, volume, saturation, and about petrophysical parameters within these zones.

Model II (Fig. 13A) assumed that close to the fault the affected zone occupied the entire Ca1 and that velocity and density are slightly higher than in the white sandstone BP. The specific values assumed for the block dolomite include: V = 6,300 m/s, ρ = 2.85 g/cm^3, while for the pocket: V = 4,500 m/s and ρ = 2.5 g/cm^3 (AI~12000). The seismic wave field calculated for this model (40 Hz) has shown a slight decrease of the negative amplitude of P1 reflection around the zone containing the gas-saturated pocket (Fig. 13B).

Model III (Fig. 14A) included the same gas-saturated pocket size, but different petrophysical parameters of the

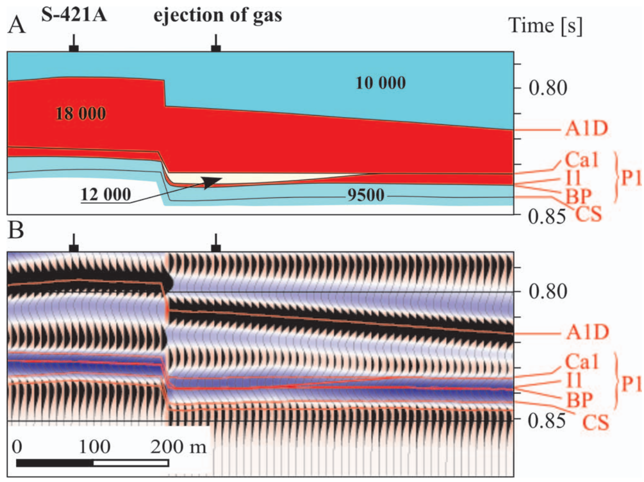

Fig. 13. Seismic modelling – Model II – anomaly zone: near-fault part of Ca2 (downthrown wall), V = 4,500 m/s, ρ = 2.5 g/cm^3, AI~12000. **A** – seismogeological model, **B** – theoretical wave field – Ricker wavelet 40 Hz

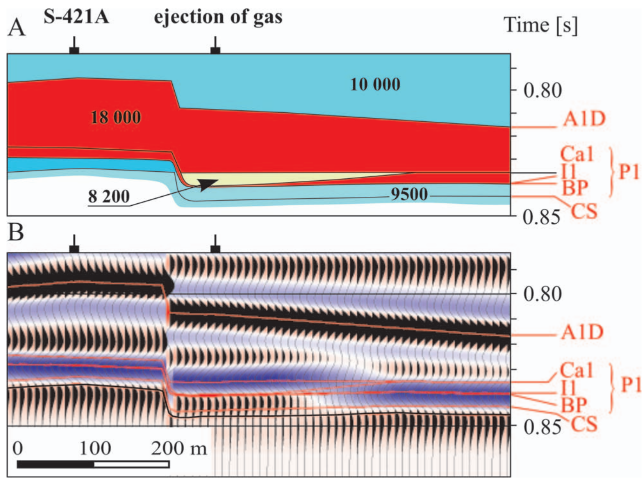

Fig. 14. Seismic modelling – Model III – anomaly zone: near-fault part of Ca2 (downthrown wall), V = 3,500 m/s, ρ = 2.34 g/cm^3, AI~8200. **A** – seismogeological model, **B** – theoretical wave field – Ricker wavelet 40 Hz

deformed dolomite at V = 3,500 m/s and ρ = 2.34 g/cm^3. These values are similar to parameters typical of the Rotliegendes rocks (AI~8200). The theoretical wave field calculated for the 40Hz Ricker wavelet is shown in Figure 14B. With this level of reduced parameters within Ca1 it can be clearly seen how the amplitude of the P1 reflection drops to around zero. The interfered reflection P1 is a composite reflection related to boundaries with opposite reflection coefficient. This type of distortion in the registered wave field may be interpreted as a mark of a fault.

A significant reduction of petrophysical parameters assumed in model IV (Fig. 15A) to V = 3000 m/s, ρ = 2.0 g/cm^3 and AI = 6000 means that the theoretical wave field calculated for a wavelet of 40 Hz (Fig. 15B) in the affected zone differs clearly from all records used previously. Here, the high negative amplitude generated by the P1 boundary in the compact Ca1 dolomite shifts to high positive amplitude. This means that the P1 reflection changes its polarity

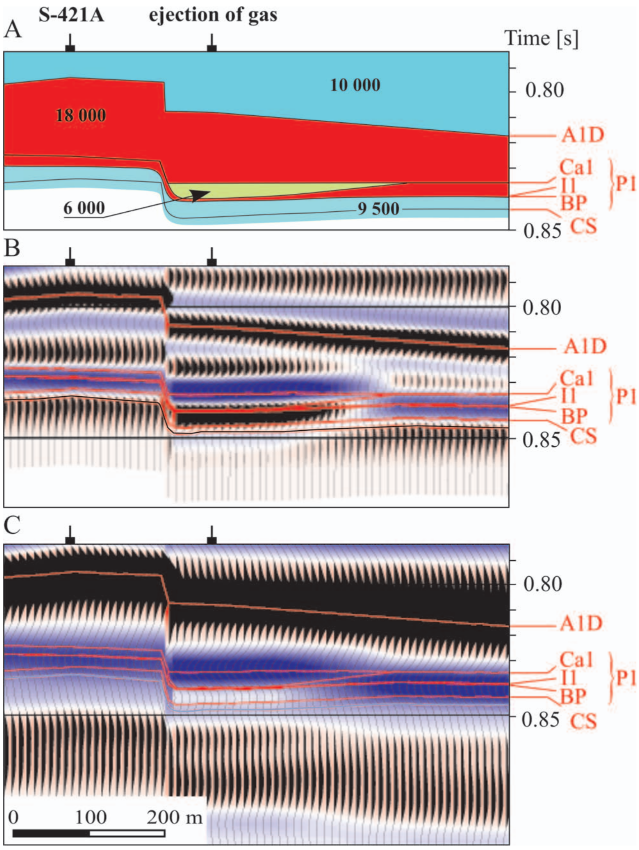

Fig. 15. Seismic modelling – Model IV – anomaly zone: near-fault part of Ca2 (downthrown wall), V = 3,000 m/s, ρ = 2.0 g/cm^3, AI~6000. **A** – seismogeological model, **B** – theoretical wave field – Ricker wavelet 40 Hz, **C** – 20 Hz

on the top of the Rotliegendes. In the compact dolomite, the P1 reflection is created at the boundary of formations with high impedance values (A1D and Ca1 formations) and Rotliegendes formations with low impedance. In this case the reflection coefficient is negative and the P1 reflection has high negative amplitude. The picture is reverse in the zone with the porous dolomite saturated with gas. Here the anhydrite, with its high impedance, borders with a porous and saturated Ca1 layer with the lowest impedance and which sits on top of a layer with a higher impedance again. Because the dolomite Ca1 and white sandstone (BP) layers are thin from the seismic perspective, reflections from subsequent thin layers interfere producing as a result the high positive amplitude of the P1 reflection. An analyst attempting to interpret these data would probably always mark the P1 boundary along the negative phase as it shows two minor faults along its course. A distortion along the P1 horizon is also visible on the record obtained with a signal extracted from seismic traces at 20Hz (Fig. 15C). Also in this case it seems that the P1 boundary would be marked by an analyst along the strong negative reflection and a weak positive reflection visible beneath would have not been taken into account at all. The petrophysical values in this model, reduced to a level considerably below the values characteristic of gas deposits discovered in Ca1 reef formations, would have only be realistic if the pocket had been filled with nearly-loose debris, which is not confirmed by mine data.

The modelling provided criteria to identify fractured and gas-saturated Ca1 dolomite zones in seismic records and showed that only a significant change in the parameters in this zone causes visible changes in a theoretical seismic record.

Modelling results can be used to interpretation of the seismic data recorded in the direct vicinity of well S-241A. It must be borne in mind that the seismic models were based on petrophysical data from one well, that there was no information about the structure and petrophysical parameters of the zone where the gas ejection occurred, nor was there any information on the structure, velocity and density of the Rotliegendes layers, whose data may vary highly and their impact on the P1 reflection could be significant. The lack of information about the facies and petrophysical parameters of the Rotliegendes rocks was the reason why the variability of assumptions in the modelling was restricted to just the dolomites of the Ca1 Zechstein lime- stone.

Identification of anomaly zones in seismic data

The gas ejection site is located near fault A, as shown in the structural map of the P1 seismic boundary (Fig. 11). The fault is connected with the main fault 2, which constitutes the southern boundary of a trench running along the NW–SE axis. Fault A runs between well S-421A and the ejection site. The models discussed above assumed that this fault provided a migration path for Carboniferous gas upwards to the pocket built of porous and fractured Ca1 formations. Arbitrary seismic profiles perpendicular to the fault line represent the seismic wave field recorded in this zone. These profiles are shown in Figures: Fig. 16A – profile U-U, Fig. 16B – profile V-V, Fig. 16C – profile W-W and Fig. 16D – profile X-X. The fault interpretation focused on seismic profiles before migration and that is why there are visible in the fault zone also diffraction waves that are generated at discontinuities of seismic boundaries. These waves can be helpful in identifying faults, especially if the fault displacements are small.

In the first two profiles, starting from the NW, *i.e.* U-U (Fig. 16A) and V-V (Fig. 16B), a possible presence of a fault is suggested by clearly marked discontinuities of the P1 horizon and by the dislocation of the downthrown wall by *ca.* 20 ms (*ca.* 30 m), disruption of the continuity of horizon A1D (top of the bottom anhydrite), presence of diffraction waves and reduction of the P1 amplitude in the downthrown wall. On the W-W profile (Fig. 16C), which cuts through the ejection site, there is a clear reduction in the fault displacement and its extent. In this case, the only two pieces of evidence indicating the presence of a fault include the P1 horizon discontinuity and the minor displacement. The diminishing of the fault displacement is also accompanied by its reduced vertical extent and the A1D boundary is not ruptured. In the last of the profile X-X (Fig. 16D), the fault is virtually invisible. This is where the fault extincts.

The reflection amplitude related to the dolomite/white sandstone boundary (Ca1/BP) reaches its maximum negative value, as shown by modelling, when the dolomite has good elastic properties. Any weakening of the dolomite, such as by an increased porosity and fracturing, leads to an

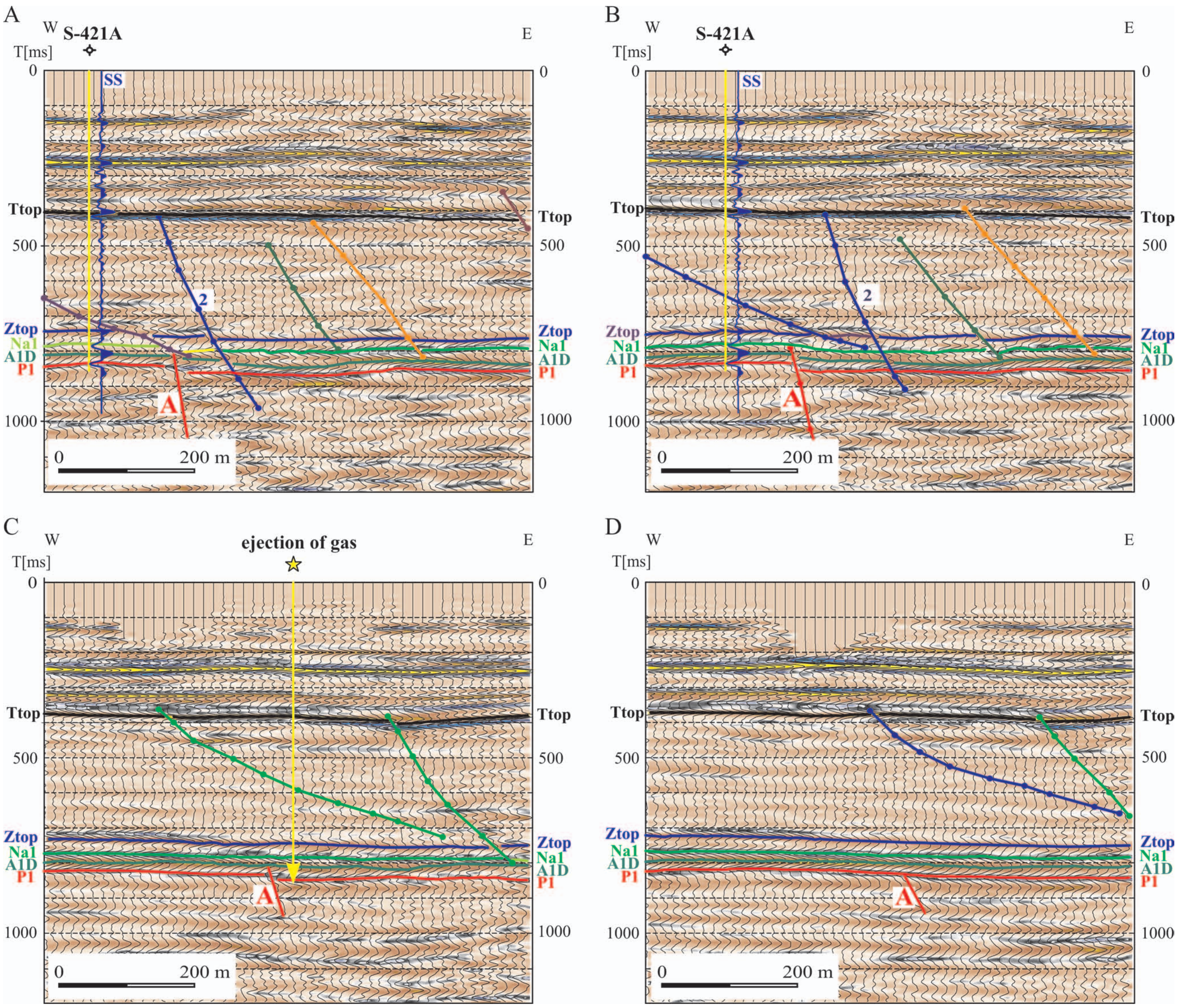

Fig. 16. Arbitrary time seismic profiles (location see Fig. 1). **A** – profile U-U, **B** – profile V-V, **C** – profile W-W, **D** – profile X-X

increase of the value of Ca1 petrophysical parameters bringing them closer to the values characteristic of BP and causing as a result a reduction of the negative amplitude. The amplitude can also be reduced by gas saturation (a decrease of seismic wave velocity value).

The documented (on the basis of theoretical wave fields) relationship between the amplitude of the signal reflected at the Zechstein/Rotliegendes boundary (P1) and reciprocal relations of acoustic impedance of contacting strata can be used to identify the Ca1 dolomite zones with lowered elastic parameters. The surface distribution amplitude of P1 reflection related to the Zechstein/Rotliegendes boundary is shown in Figure 17.

A 150-metre well (Jm20-H-5) drilled from drift W169 to investigate causes of the ejection failed to reveal any fault. The well is shown in a map of P1 reflection amplitude in Figure 17. The figure shows that the well stopped short of the fault and data were not obtained of the fault located using seismic data. An analysis of the map reveals that drilling of the well ended in a zone where the values of the P1 reflection amplitude are nearly to zero. Between metres 92 and 98, the well produced an inflow of gas at 27 at and the overall volume was *ca.* 7,000 m^3. This suggests reduced elastic properties related to an increase of the porosity and fracturing, as well as to gas saturation. The location of the zone on the map of P1 reflecion amplitudes (Fig. 18) coincides with a zone of small negative amplitudes.

Figure 19 presents a seismic image of an arbitrary profile G-G’, which overlaps with the drilling line (see location in Figures 17 and 18). An analysis of the P1 reflection along a segment that overlaps with the drilling line shows decreasing amplitude, a trend that continues to fault A concerned and includes both the upthrown and the downthrown wall. The zone could have contained concentrated gas that migrated from the Rotliegendes formations via fault A.

The quality of the seismic data, the lack of information about the nature of the ejection zone and its petrophysical parameters and of detailed information about the parameters

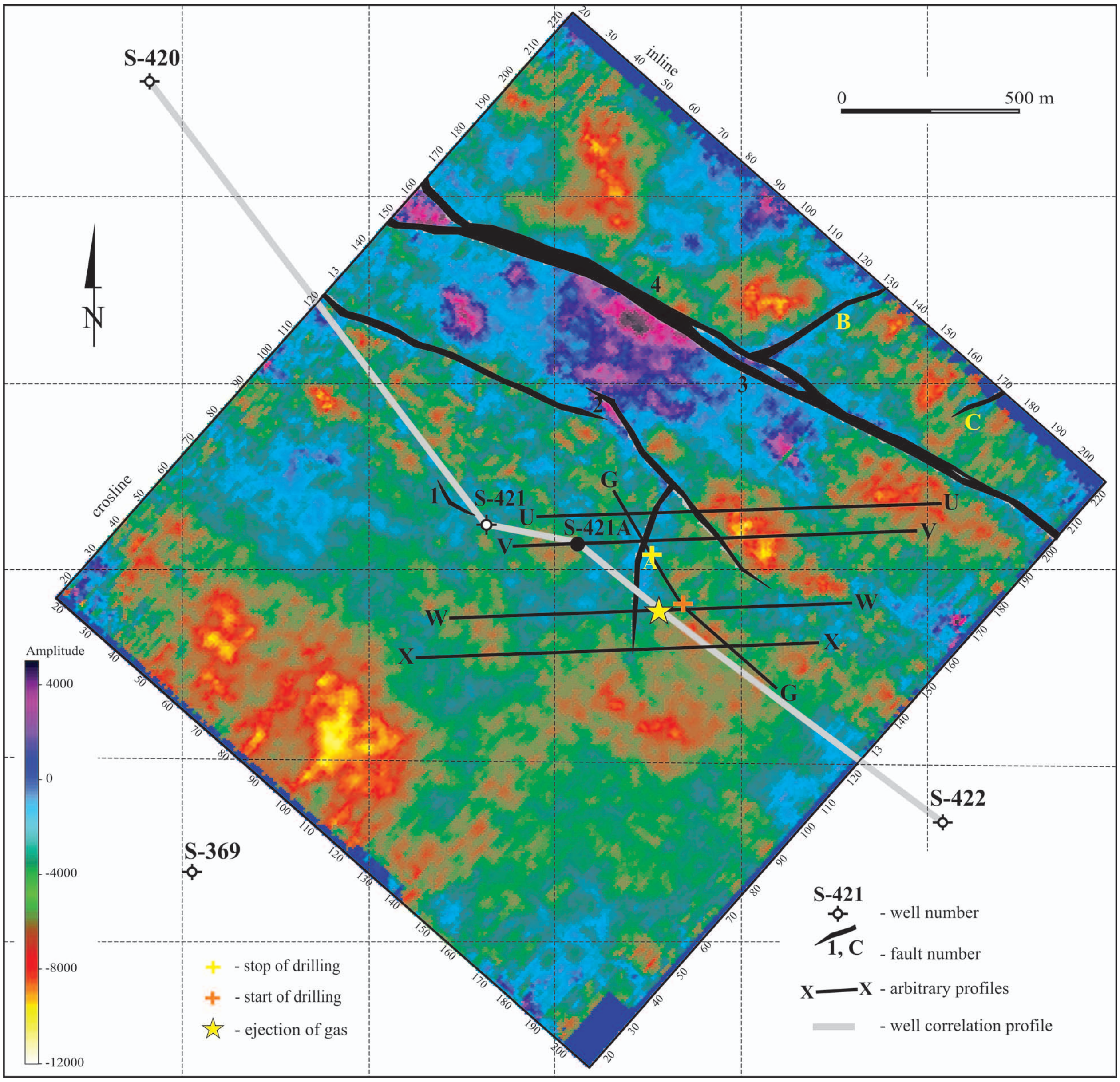

Fig. 17. Map of P1 reflection amplitude (seismic horizon Zechstein/Rotliegendes)

of the entire rockmass combined prevent a clear interpretation of the anomalous seismic record observed in this zone. This problem could be addressed to some degree by extending the mine's well Jm20-H-5, as suggested in map of P1 reflection amplitudes (Fig. 18).

Reliability of the above proposed interpretation and answer to the question about the role of 3D seismic survey in detecting small faults and ejection risk zones requires further confirmation. On the one hand, this confirmation should come from mine's own underground operations, and on the other hand additional research is needed to ensure a better insight in to the rocks parameters, especially the highly affected Rotliegendes formations. This enables clearer interpretation criteria for subtle changes of the recorded seismic wave field to be developed.

CONCLUSIONS

The seismic survey "Duża Wólka 3D", acquired in the Głogów Głęboki–Przemysłowy Mining Area at the "Rudna" copper mine, was performed to investigate the structure of the Zechstein and Rotliegendes, and on the other hand to attempt to develop a methodology of locating potential gas saturation zones in formations at the boundary of Zechstein/Rotliegendes. They may indeed constitute sites of gas and rock ejection risk during developing and exploiting the deposits.

The key role in the study was played by well S-421A drilled in the "gas cavern" zone. The geological and well-logging data obtained from the well allowed a detailed lithological description of the Zechstein formations, determination of their physico-mechanical properties and investigating petrophysical parameters that are important to seismics, including seismic wavelet propagation velocities and volume densities. Such data are essential for seismic modelling and interpretation of the seismic 3D survey.

The modelling results suggest that:

– The seismic event related to horizon P1 (boundary between the Zechstein and Rotliegendes formations) is an interfered reflection whose amplitude is influenced by the thickness and petrophysical parameters of the A1D anhydrite, Ca1 dolomite, Weissliegendes (BP) and Rotliegendes (CS) sandstones,

– The seismic P1 boundary is clearly linked to a strong reflecting boundary located between the Ca1 dolomite and the Weissliegendes BP sandstones (top section of the Rotliegendes),

– The amplitude of the reflection related to the dolomite/white sandstone (P1) boundary reaches its maximum negative value when the dolomite is characterised by good elastic properties,

– The decrease of elastic properties (elastic modulus) of dolomite caused by such factors as an increased porosity and fracturing, leads to a modification of Ca1 parameters at levels closer to those of BP, which causes the amplitude to decrease. Gas saturation could be an additional factor further reducing the amplitude (by reducing the seismic velocity),

– Diminishing of P1 reflection amplitude to values approaching zero may indicate potential gas traps.

Based on the last conclusion the seismic record was interpreted to determine an anomalous zone that could cause ejection threats. The location of the ejection site and the gas leaking zone found in well Jm20-H-5 overlaps with a zone where the negative reflection amplitude of the P1 boundary is found to diminish. The zone was located in direct vicinity of the small fault A visible on seismic cross-sections. The fault may be responsible for an increased fracturing of the Ca1 dolomite and in itself could constitute a channel providing a way for gases to migrate from Carboniferous formations through aeolian sedimentary Rotliegendes rocks to the loosened dolomite where a small gas trap could have developed as the dolomites were overlain by an impermeable A1D anhydrite complex.

Reliable interpretation proposed above and answer to the question about the potential of 3D seismic survey in locating small faults and ejection risk zones is, however, not entirely assured. It requires further confirmation, on the one hand by mine's own underground operations and on the other hand by additional studies to ensure a better geophysical insight (the seismic modelling was based on data from a single research well), especially in the highly varied Rotliegendes formations, the parameters of which significantly influence the formation of the P1 reflection. This would facilitate a development of clearer interpretation criteria for subtle changes of the recorded wave field.

The already obtained results indicate a possibility of new uses of high-resolution 3D seismic; in this particular case – to identify zones endangered by gas ejection in mines of KGHM Polska Miedź S.A.

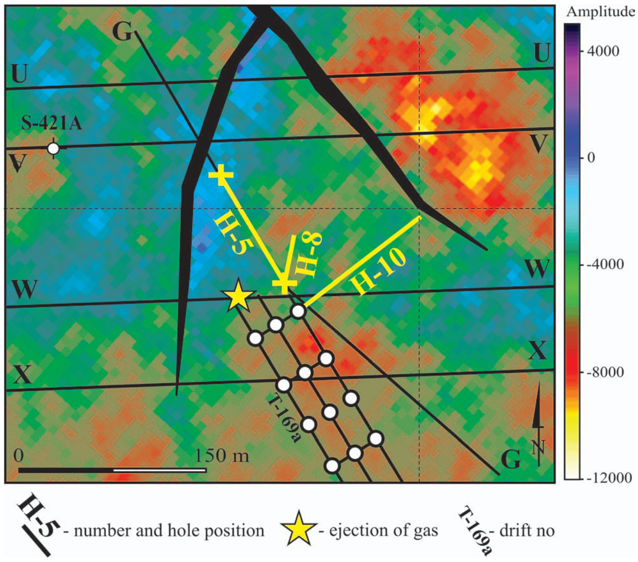

Fig. 18. Part of P1 reflection amplitude map with location of mine boreholes: Jm20-H-5, Jm20-H-8 and Jm20-H-10

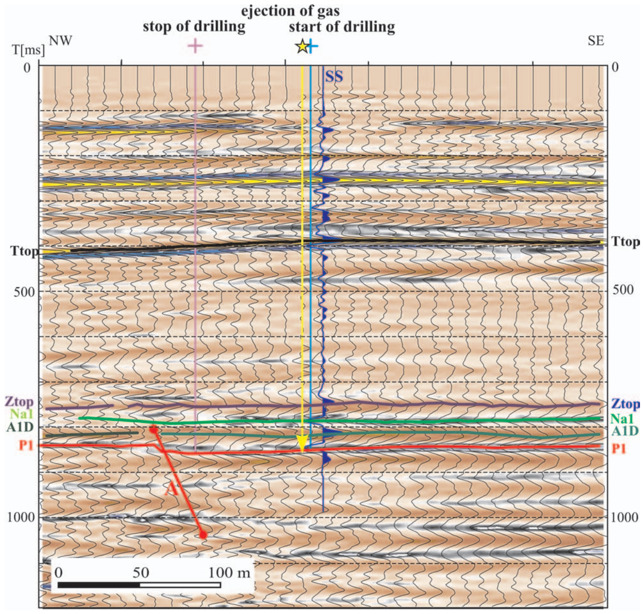

Fig. 19. Arbitrary time seismic profile G-G, along drilling line of borehole Jm20-H-5

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