

Seismic and geochemical anomalies related to vertical migration of gas in the Radlin gas field

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In the Radlin Rotliegend gas field (southwestern Polish Lowlands, Fore-Sudetic Region, Poznań Depression), modelling and reinterpretation of seismic data combined with surface gas surveys (free gas method) help identify “gas chimneys” and locate pathways of vertical migration. An almost impermeable Zechstein evaporite cover reduces the stream of vertical gas migration so that a dry surface geochemical zone occurs at the surface and no seismic disturbances are observed directly above the pay zone of the gas field. The surface gas anomalies form a halo-type pattern surrounding the gas field. The majority of surface hydrocarbon microseepages from the subsurface agrees with the seismically visualised geological structure. The belts of surface gas anomalies and the dry zones separating them run along the strike of Permian structures and faults. Vertical pathways of gas migration are recognisable as zones of seismic discontinuity and chaotic distribution of distinct reflections and diffracted waves. Seismic “gas chimney” effects coincide with surface hydrocarbon gas anomalies. Particularly, they appear above the upper terminations of faults disturbing the Zechstein deposits. The faults create the main avenues for secondary vertical migration of gas from the reservoir to the surface. “Gas chimneys” are observable in a shallow zone above the Muschelkalk (Tm) where higher gas saturation of more porous rocks produces a seismically traceable velocity effect.

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Key words: vertical gas migration, seismic anomalies, surface hydrocarbon gas anomalies (geochemical anomalies), “gas chimneys”, Radlin gas field.

INTRODUCTION

This paper demonstrates an unconventional use of seismic methods combined with surface geochemical surveys in petroleum prospecting. These could be particularly useful in the areas of low quality seismic data, where direct seismic hydrocarbon indications cannot be used in interpretation. In the study area (Radlin gas field, Fore-Sudetic Region, SW Polish Lowlands — Fig. 1) the aim was to define the relationship between the distribution of hydrocarbon gas microseepages and the deep geologic structure as reflected in seismic sections. Also, an attempt was made to identify zones of anomalous seismic record produced by vertical migration of gas from reservoir to the surface. The example of the Radlin gas field area shows that the sites of anomalous seismic record and the surface hydrocarbon gas anomalies distribution are related to the pathways of gas migrating vertically up from the Early Permian

Rotliegend reservoir sandstone through the Late Permian Zechstein evaporites and Mesozoic cover.

GEOLOGY OF RADLIN GAS FIELD AREA ON PALAEOZOIC PLATFORM OF POLISH LOWLANDS

The major part of western Polish Lowlands, i.e. west from the Teisseyre-Tornquist (T-T) Fault Zone (Znosko, 1979), represents an epi-Variscan platform covered with Early Permian continental Rotliegend sandstones (P. H. Karnkowski, 1999), cyclic Late Permian (Zechstein) Z₁–Z₄ carbonates and evaporites (Wagner, 1994) and Mesozoic strata (Dadlez, 1997).

A number of gas deposits sourced from Carboniferous coals and coaly shales, sealed with Zechstein evaporites, were discovered in Rotliegend sandstone and/or Zechstein limestone reservoirs in the Fore-Sudetic Region (Fore-Sudetic Monocline), SW Poland (P. H. Karnkowski, 1995).

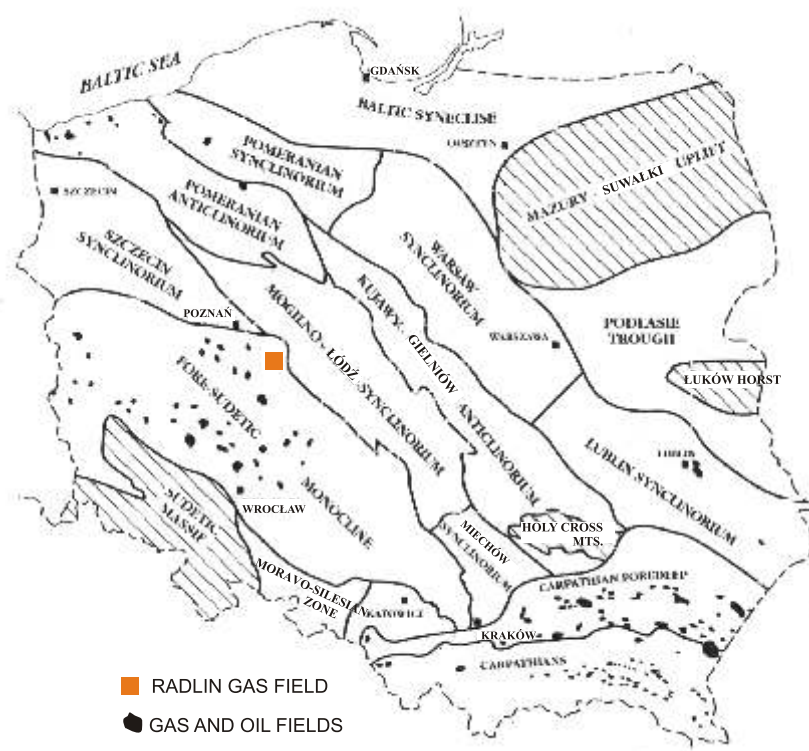


Fig. 1. Location of the Radlin gas field zone on the map of the geological provinces of Poland

Also, numerous oil and gas fields were discovered in the Main Dolomite Formation (Zechstein, Stassfurt cyclothem Z_2) both in the Fore-Sudetic Monocline and in Western Pomerania (Baltic coast) — Fig. 1 (P. Karnkowski, 1999).

According to Dadlez (1994) during the Variscan orogeny a system of conjugate strike-slip faults following the T-T Zone (Pomeranian Synclinorium–Warsaw Synclinorium–Lublin Synclinorium; Fig. 1) originated between the rectilinear edge of the East European Craton (Baltic Syneclise–Mazury-Suwalki Uplift–Podlasie Trough; Fig. 1) and the arcuate front of the Variscan fold belt in the SW (Szczecin–Kujawy-Gielniów Anticlinorium; Fig. 1) (Po aryski, 1986). In post-Variscan times, starting from the Early Permian (Rotliegend) the Mid-Polish(-Danish) Trough oriented NW–SE (along with T-T Zone) developed as an abandoned rift arm of the North Sea triple junction, subsequently being transformed into an aulacogen (Dadlez, 1980; Ziegler, 1990; Dadlez *et al.*, 1995).

Evolution of narrow synsedimentary grabens in Late Triassic, Jurassic and Early Cretaceous times was accompanied by salt movements. Zechstein salts mobilised during Triassic formed pillows and diapirs, thus controlling the thickness-facies distribution of overlying strata (Dadlez, 1994).

In latest Cretaceous-earliest Tertiary times the Mid-Polish Trough was converted into the Mid-Polish Swell (Pomeranian Anticlinorium–Kujawy-Gielniów Anticlinorium + Holy Cross Mts. massif in SE — Fig. 1). This resulted from Laramide tectonic inversion caused by Carpathian folding and thrusting from the south.

The development of the T-T Zone and the Mid-Polish Trough until its inversion into the Mid-Polish Swell was closely related to strike-slip fault tectonics (Brochwicz-Lewiński *et al.*, 1981; Po aryski, 1986; Ziegler, 1990; Dadlez, 1994).

This was also the case for the Radlin area under study, where the curvilinear course, variable throw amount and throw denomination of faults, as well as their *en echelon* arrangement and alternate location of fault-related synclines and anticlines, indicate wrench tectonics (Fig. 2).

The Radlin gas field situated about 80 km SE of Poznań in the seismically located sub-Zechstein elevation trapped in Rotliegend sandstone was discovered in 1982 (Wolnowski, 1995; Malaga and Wolnowski, 1999) (Fig. 2). The gas field accumulated within an elongated anticline, striking NW–SE and covering an area of 11.5 x 1.5–2.2 km, is enclosed by the gas/water contour at –3131 m depth. It is sealed by the main longitudinal fault affecting the structure in the SW. The Radlin elevation is reflected in the structure of Triassic strata. Farther to the SW the Triassic trough separates the Radlin field from the next gas-producing Kl ka structure (Wolnowski, 1995). The main Radlin fault, of strike-slip character dipping NE, throws the top of Lower Permian to the SW by 60–70 m. In such a way it seals the Rotliegend reservoir sandstone by juxtaposing it with the Lower Anhydrite and the Werra (Z1) Salt across the fault plane. The Radlin gas field is sealed at the top by a Zechstein evaporite cover (Wolnowski, 1995; Górski, 1995; Malaga and Wolnowski, 1999).

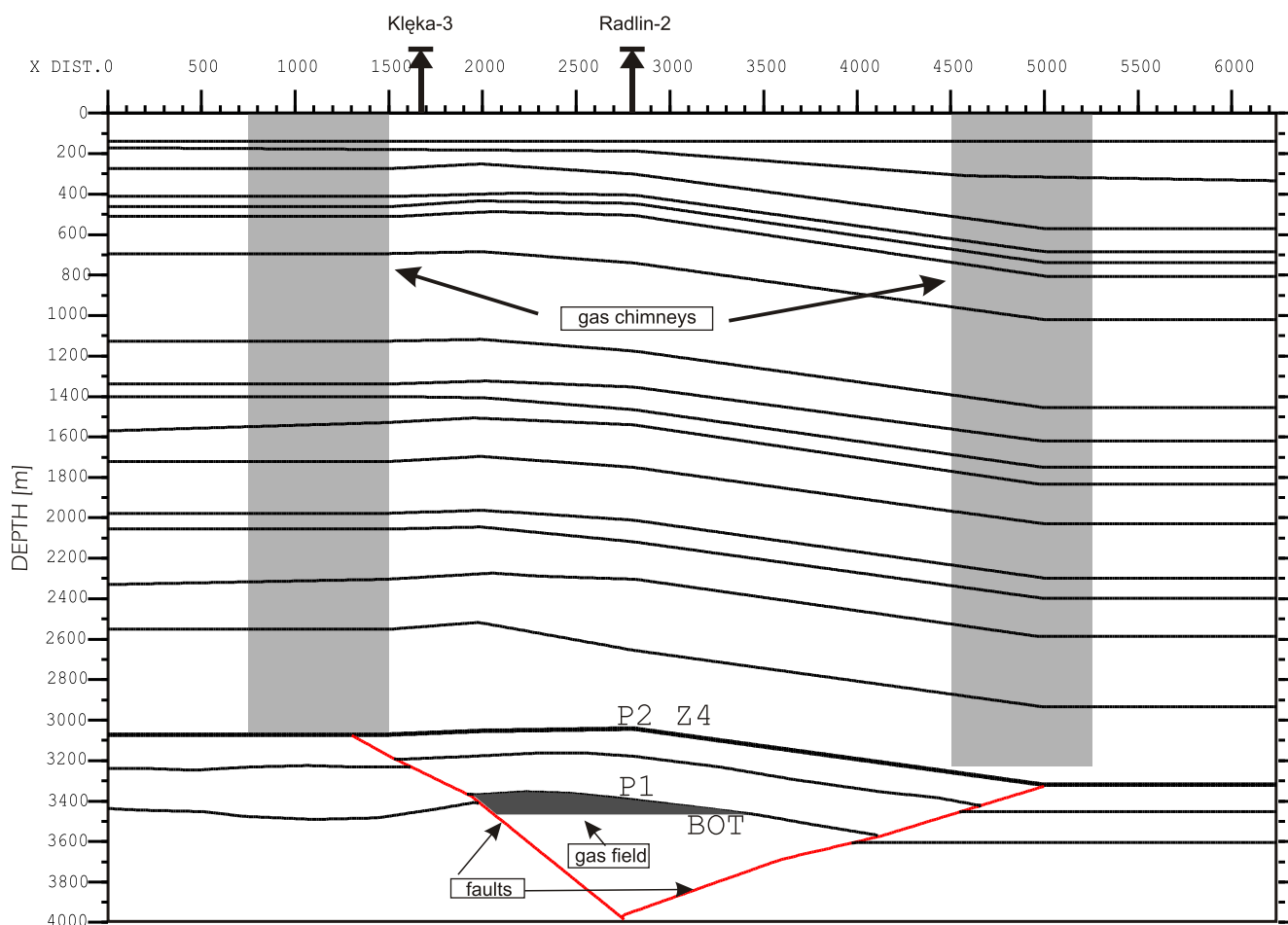


Fig. 3. Seismogeological model of the Radlin structure

(sampling density 200 m) beneath the active exchange level (usually from a depth of 1.0–1.5 m) along geochemical profiles that followed the seismic lines (Figs. 2, 9, 10).

Gas chromatography and FID laboratory analysis allowed determination of the concentrations of methane, the sum of higher alkanes (C_2 – C_5) and the sum of alkanes (C_2 – C_4). From statistical processing of laboratory data the threshold level was established and the relative variations in concentration of hydrocarbon gases were displayed along the surface geochemical profiles. The latter were correlated with appropriate seismic cross-sections.

Also, the surface geochemical maps showing the hydrocarbon gas distribution pattern as related to the Permian structure were contoured.

Figure 2 shows a summary of the surface hydrocarbon gas microseepage distribution over the Radlin structure and the neighbouring area.

It has been proved that the surface hydrocarbon gas anomalies are of deep subsurface origin. These form belts trending along the prevailing tectonic structures. Specifically, the surface hydrocarbon gas anomalies and “silent” (dry) zones separating them are closely related to the strike of Lower Permian structures and faults oriented NW–SE (Fig. 2). The most distinct anomalies (such as no. 3 and 4) are associated with the

strike of the main longitudinal faults that disturb Early Permian strata and range up to the Zechstein as well as with the faults disturbing Zechstein evaporites and reaching up into Triassic strata (Figs. 2, 9, 10).

The fault-related surface gas microseepages prove the importance of the fault planes and near-fault fracture zones in providing avenues for the vertical migration of hydrocarbons. Most likely, the buoyancy-related movement of colloidal-sized hydrocarbon gas microbubbles through water-filled pores, micro-fractures and fissures was the dominant mechanism for this migration (Price, 1986; Saunders *et al.*, 1999).

The faults dipping at high angles may act both as an efficient seal for lateral migration and as a venue favourable for vertical leakage of hydrocarbons from the petroleum deposit (Logan and Decker, 1995). In the latter case the fault-confined fracture zone is usually more permeable than the fault plane itself. The latter is often clogged with fault gouge material.

Considering the faults at Radlin and others disturbing Rotliegend gas-productive structures, the decrease in fault-zone fracture permeability most probably results from secondary sulphate and chloride mineralisation (Jaroski, 1999). However, such diagenetic cementation of fissures may have been hindered by hydrocarbon gas leaking from the petroleum deposit (Evans *et al.*, 1995).

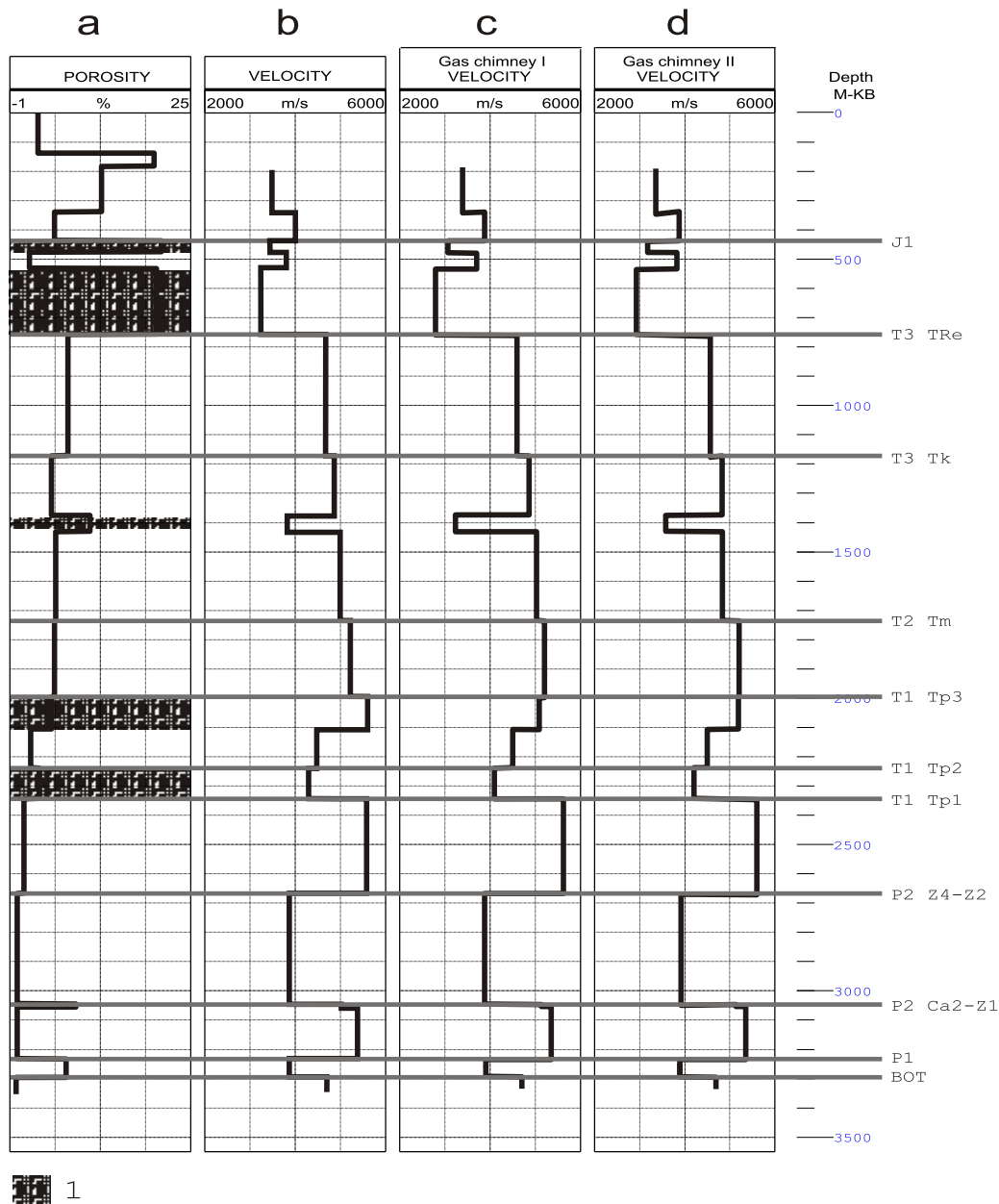


Fig. 4. Results of well-logging in Radlin-2 well

A palaeostructural evolution study (Strzetelski, 1999) suggests that the Radlin structure elevation developed due to Early Kimmerian movements reaching its maximum height by the end of Jurassic (Late Kimmerian). The accumulation of gas is also dated at Late Jurassic, when the trap was definitely closed by the sealing fault.

The later the formation of the fault the higher the frequency of non-cemented fractures (Harper and , 1997). Particularly important is the fault valve mechanism of repeated reactivation of the fault fractures which turns the subsequent segments of the fault from temporarily impermeable to permeable ones (Sibson, 1995).

Commonly, diffusion has been taken as the dominant mechanism of vertical migration of hydrocarbon gases from the petroleum deposit to the surface (Klusman and Saeed, 1996).

However, it has been shown that diffusion of low-molecular hydrocarbons through water-filled pore-space is extremely slow and may become significant only over a longer periods of time i.e. more than 10–100 Ma (Kroos and Leythausser, 1996). The coefficient and rate of diffusion are so low that in a period of 30 Ma the front of diffusion may move only a distance of 300 m in sandstones or 20–30 m in shales (Matthews, 1996). The diffusion of higher hydrocarbons (C^{2+}) is negligible (Zarella *et al.*, 1967).

The most reasonable hypothesis involves vertical ascent of ultrasmall gas bubbles of light hydrocarbons through a network of interconnected water-filled microfractures (Mac Elvain, 1969; Price, 1986; Saunders *et al.*, 1999). The basement-related pattern of fractures and joints is often activated in overlying rock formations and retains its character throughout

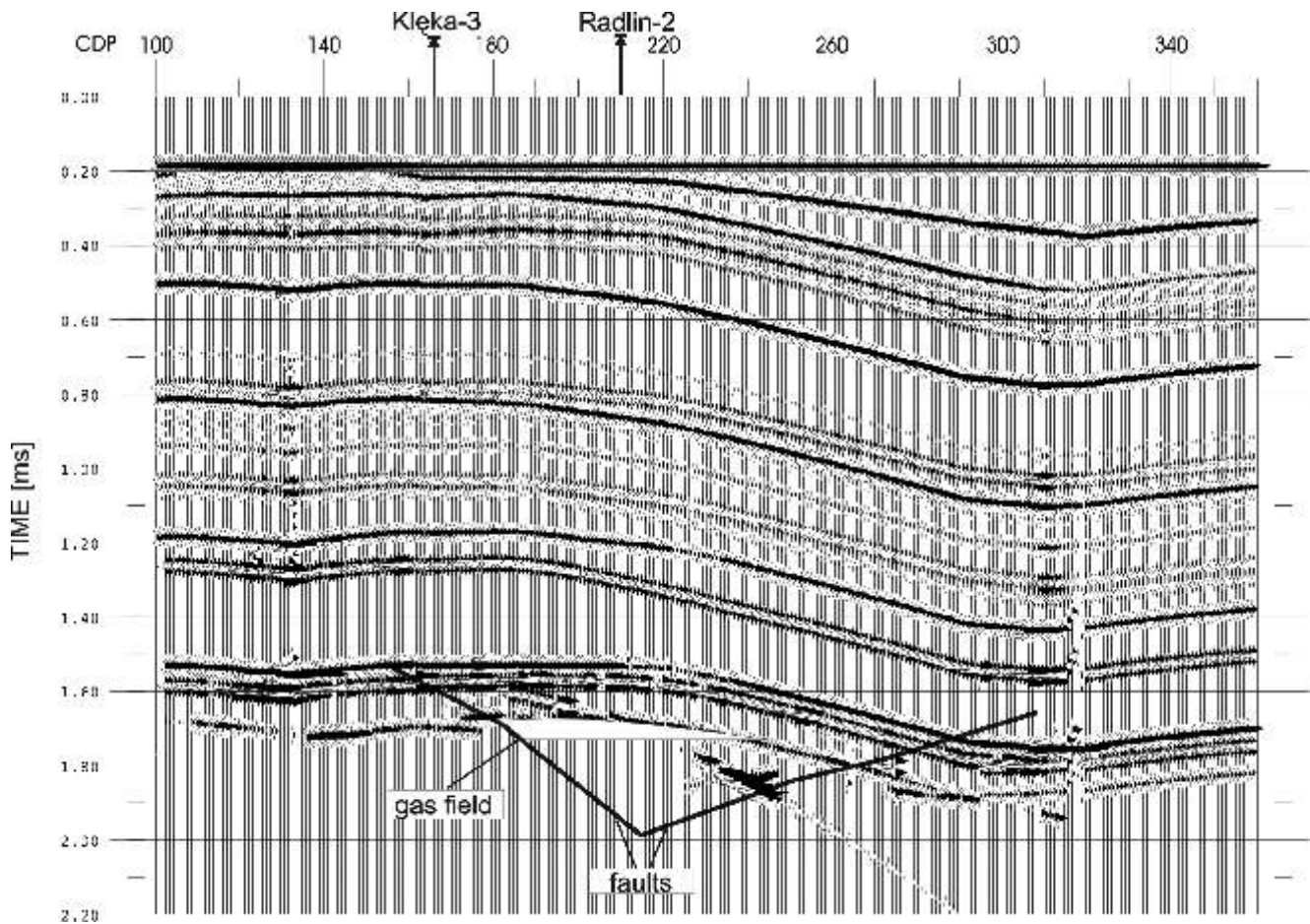


Fig. 5. Theoretical seismic section assuming the absence of gas migration

the sedimentary column, thus extending from the petroleum-bearing reservoir to the surface (Komar *et al.*, 1971; Alpay, 1973). This is also the case for Zechstein evaporites in Polish Lowlands where the densest network of microfractures and joints may extend across mostly curved and deformed structure surfaces. Apparently, this appears also in fault-related fracture zones, thus creating vertical venues permeable to hydrocarbon gas microbubbles.

It has been noted that in the Polish Lowlands area overlain by Zechstein evaporites and Mesozoic strata the surface hydrocarbon gas anomalies related to deposits in the Rotliegend form halo-type patterns surrounding the Lower Permian gas productive structures (Górecki *et al.*, 1995a, b, 1998; Strzetelski *et al.*, 1996). The latter are manifested as surface geochemically “silent” (hydrocarbon dry) zones. A dry zone is also observable over the Radlin gas field where the surface hydrocarbon gas concentration decreases to the threshold level or below (Figs. 2, 9, 10).

It has been shown from numerous petroleum-bearing structures in the world that many surface gas anomalies form halos with hydrocarbon gas concentration lows above the pay zone and highs at the edges of the petroleum deposit (Horvitz, 1981; Duchscherer, 1984; Salisbury, 1990).

The origin of halo-type anomalies is still not clear. Tedesco (1995) suggested that the pressure depletion resulted from long term production of petroleum field decreases the surface microseepage of hydrocarbon gases over the productive zone. Halo-type anomalies may also result from intense growth of hydrocarbon-consuming bacteria and bacterial oxidation of hydrocarbons that migrate vertically up from the petroleum deposit (Price, 1986). In that case a primarily high apical surface anomaly over the petroleum productive zone is “bacterially consumed” and changed into a geochemically “silent” (dry) zone where relatively low gas concentrations are observed (Saunders *et al.*, 1999). Beyond the contour of the petroleum deposit the flow of hydrocarbon gases is too low to maintain the abundant development of bacteria, making the surface gas concentrations higher there (Soli, 1957). As a consequence the surface hydrocarbon gas anomaly becomes reversed into a halo-type one with the low over the productive zone encircled by the ring of relatively high surface gas concentrations that roughly follow the water contour of the petroleum field.

Intense activity of hydrocarbon-consuming bacteria, and diagenetic near-surface alteration (mineralisation and cementation) that resulted from hydrocarbon-rock chemical reactions, form specific “hard cover” zone over the petroleum deposit. The “hard cover” may be manifested as a seismic velocity in-

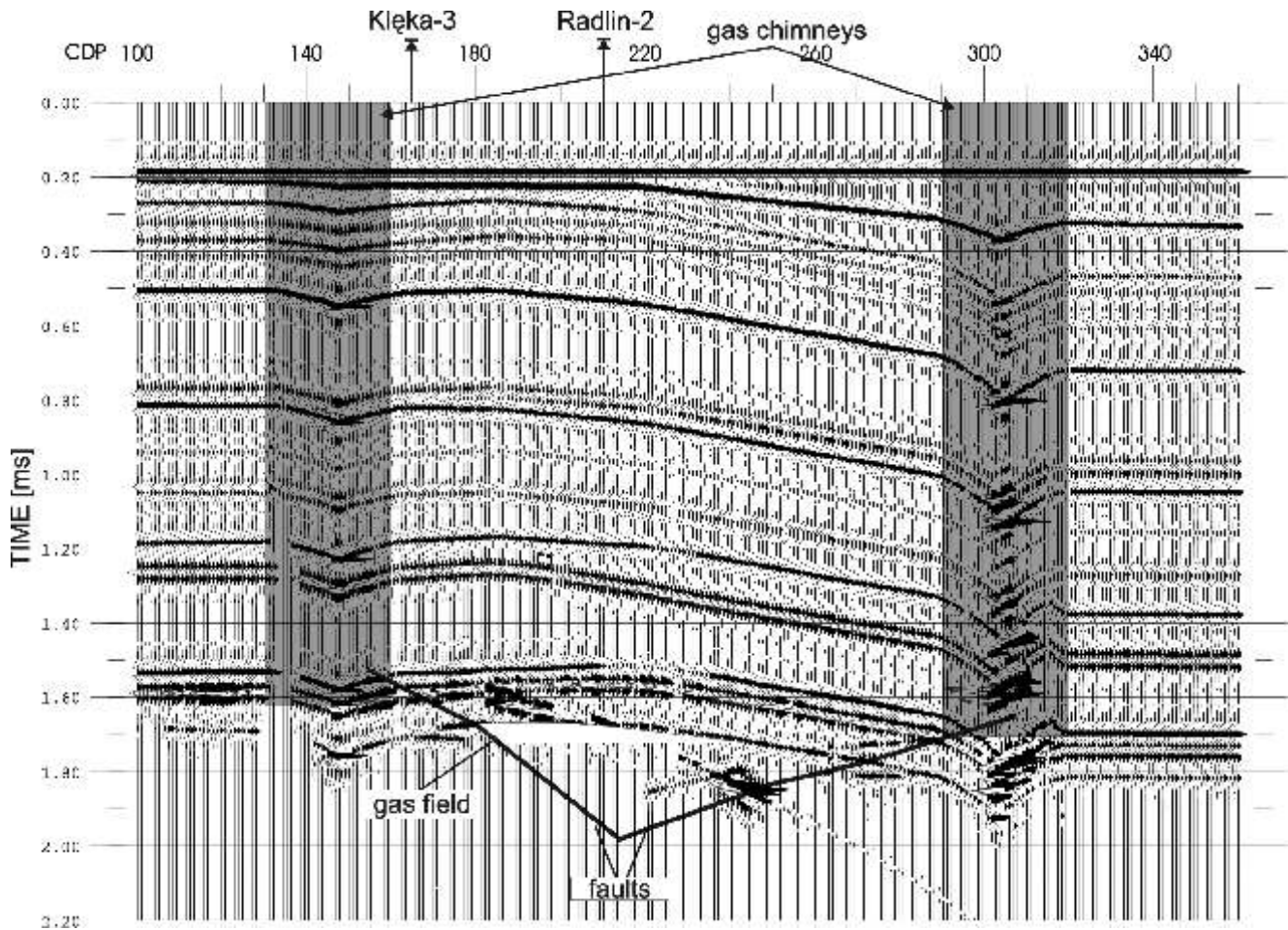


Fig. 6. Theoretical seismic section assuming vertical gas migration (gas saturation 5%)

crease (Davidson, 1984; Duchscherer, 1984), soil alteration (Segal *et al.*, 1986), radioactivity anomalies (Saunders *et al.*, 1994), or magnetic susceptibility and airborne magnetic anomalies (Donovan *et al.*, 1986; Foote, 1992). The “hard cover” zone of secondary cementation clogs the escape routes over the petroleum field so that migrating gases would be deflected to the edges of alteration zone, thus producing the relatively high “contouring” anomalies which appear above the edges of hydrocarbon accumulations (Saunders *et al.*, 1999).

In the Polish Lowlands where the Zechstein evaporites form an almost perfect sealing cover for the gas-productive Rotliegend sand reservoir the halo-type surface gas anomalies result most likely from the densest fracture network development being on the deformed limbs and axial plunge segments of Permian anticlines. In platform-type structures the successive sets of fissures, fractures and faults appear along mostly curved and deformed parts of the structure, thus leaving its relatively flat crest more impermeable.

SEISMIC IDENTIFICATION OF VERTICAL GAS MIGRATION PATHWAYS

The anomalous seismic record associated with the “gas chimney” effect comes from variations in the velocity of elastic waves. This is mainly related to the type, phase composition and ratios between reservoir fluids (gas, oil and water) that fill the pore-space of the rock. Equally important is the geometry and distribution of gaseous and liquid fluids in pores and rock openings (Kuster and Töksoz, 1974; Domenico, 1976; Bourbie *et al.*, 1987; Bała, 1994). In such a way the seismic disturbances of “gas chimney” type are also related to petrophysical and matrix structure properties of the rock. However, there are no clear criteria available for seismic identification of gas migration zones (van den Bark and Thomas, 1980; Eliason *et al.*, 1983; Andrew *et al.*, 1991). For this reason, seismic modelling was applied to recognise “gas chimneys” in seismic profiles and to locate the pathways of vertical gas migration.

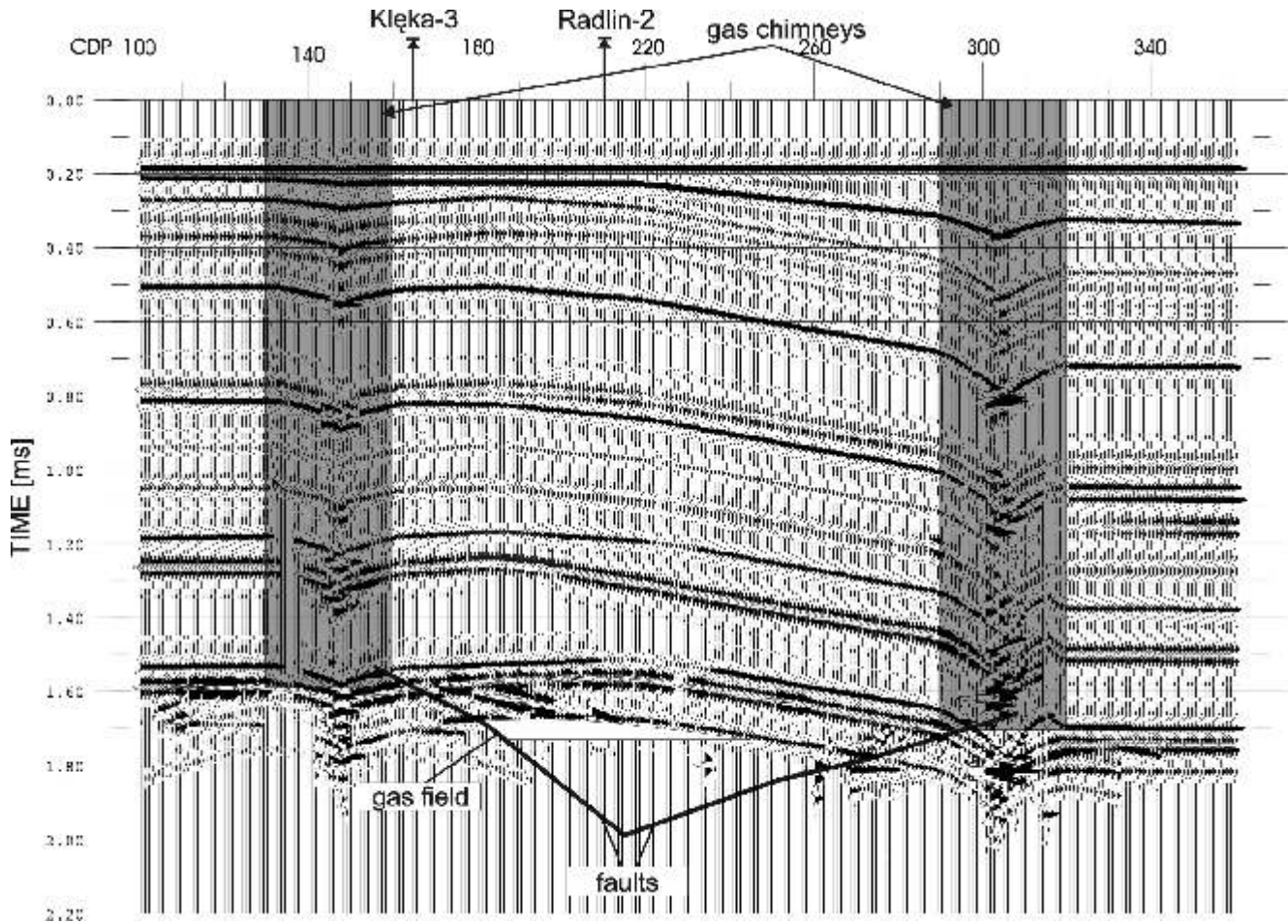


Fig. 7. Theoretical seismic section assuming vertical gas migration (gas saturation 2%)

THEORETICAL SEISMIC WAVE FIELD

The criteria for “gas chimney” identification were drawn from theoretical seismic sections produced for the modelling as based upon the following assumptions:

- the absence of gas migration,
- the presence of vertical gas migration.

The calculations were made using GMA plus STRUCT programs, version NORMAL INCIDENCE (Geophysical Micro Computer Application International Ltd. — licence of 1999). The GrITS GMA program was applied for estimation of signal from the seismic trace.

Petrophysical and subsurface structure data necessary to produce seismogeological models of the Radlin gas field zone were derived from well logs of the Radlin-1, -2, -3, -7, -8, -9, -27, -28, Kl ka-3, and Witowo-3 wells (Geofizyka Toru Ltd. POGC Co.) and the seismic data for Radlin-Kl ka-Witowo area (32-09-82K, 5-09-83K, 9-09-83K, 10-09-83K, 22-09-89K, 23-09-83K, 22-09-93K) acquired by Geofizyka-Kraków Ltd. POGC Co. and Geofizyka-Toru Ltd. POGC Co. (Górski, 1995).

The geometry of the geologic structure for seismogeological modelling was taken from the reinterpreted

9-09-83K seismic profile (Fig. 9). As based upon surface geochemical data (Fig. 9) the zones above the main elongate faults framing the Radlin structure from SW and NE were assumed to be the principal pathways of vertical gas migration.

The petrophysical data from an average velocity-porosity profile for the Radlin structure were taken for modelling of a “no gas migration” version (Fig. 4a, b). For “gas chimney” zones, when modelling a “gas migration” version, the decrease in velocity was estimated with assumptions of 5 and 2% gas saturation of reservoir pore space (Fig. 4c — “gas chimney I” and 4d — “gas chimney II”) considering the microbubble buoyancy mechanism for vertical gas migration. The calculations of increase in velocity coming from the presence of gas were made with the use of a computer program by Bała (1994, 1999).

Analysis and comparison of calculated sections “without gas” (Fig. 5) and “with gas chimneys” (Figs. 6, 7) showed that all the seismic boundaries considered in the model were identifiable and their amplitudes were controlled by the acoustic impedance contrast and lithologic boundaries of the rock layers.

It has been shown that assumed vertical gas migration pathways appear as zones of breaks in continuity of seismic boundaries, associated with chaotic distribution of distinct reflections and diffracted waves (Figs. 6, 7).

SEISMICALLY TRACEABLE “GAS CHIMNEYS” AND THEIR CORRELATION WITH SURFACE HYDROCARBON GAS ANOMALIES

Surface geochemical profiles, correlated with geologically interpreted seismic cross-sections, shown a close relationship between the distribution of surface hydrocarbon gas anomalies and the subsurface structure, especially along the main fault zones.

Geological interpretation of seismic profiles from the study area was carried on using the CHARISMA System (Schlumberger). As a result, the following marker seismic boundaries were recognised and correlated: the bottom contour of the Radlin gas field (BOT), the top of the Early Permian Rotliegend (P1), the Main Dolomite Formation P2 Ca2, the top of the Zechstein P2 Z4, the Middle Buntsandstein (Tp2), the Muschelkalk (Tm), the top of the Keuper (Tk) — Fig. 8.

Figure 9 shows a segment of the seismic profile 9-09-83K correlated with the D–D’ surface geochemical profile (prepared by Dzieniewicz and Sechman (in: Górecki *et al.*, 1993).

A segment of the seismic profile 22-09-93K, correlated with the surface geochemical profile G–G’ (prepared by Dzieniewicz and Sechman (in: Górecki *et al.*, 1993, 1995a, b, compiled by Strzetelski, 1999) is shown in Figure 10.

Surface hydrocarbon gas anomalies from the D–D’ profile (Fig. 9) — gas measurement stations (sta.) 402–396 are related of the main elongate fault sealing the Radlin gas field from the SW. At the maximum of that anomaly directly above the upper termination of the fault (in Zechstein evaporites) there occurs a distinct seismic anomaly. This is expressed as a discontinuity of seismic boundaries above the Muschelkalk Tm horizon (CDP 145–210) which is assumed to be the manifestation of the “gas chimney” originating from gas leakage from the reservoir in the subsurface. This shows the main Radlin fault to be the migration a venue for gas escaping from this structural trap. The two-humped shape of the surface hydrocarbon gas anomaly suggests various effusion permeabilities due to different near-fault fracture network densities on opposite walls of the fault. The northeastern hanging-wall of the fault that shows a higher surface gas anomaly seems to be more permeable to the vertical ascent of gas microbubbles. The productive zone of the Radlin gas field itself is marked with a dry (“silent”) zone where relative hydrocarbon gas concentrations are mostly below the threshold level. Consequently, directly above the gas field, no seismic anomalies that could have originated from direct vertical migration of gas from the Radlin deposit were observed. This also shows the high sealing efficiency of the Zechstein-Mesozoic cover over the gas field. The “over-field” dry zones are contoured by halo-type hydrocarbon gas anomalies that form a ring surrounding the gas productive zone (Fig. 2).

The seismic cross-section 22-09-93K, correlated with the surface geochemical profile G–G’ (Fig. 10), confirms this relationship of surface hydrocarbon gas anomalies (sta. 39–59) and geochemically dry zones distribution with the seismic image of Permian structure and the location of a “gas chimney” effect on the seismic profile (CDP 680–740).

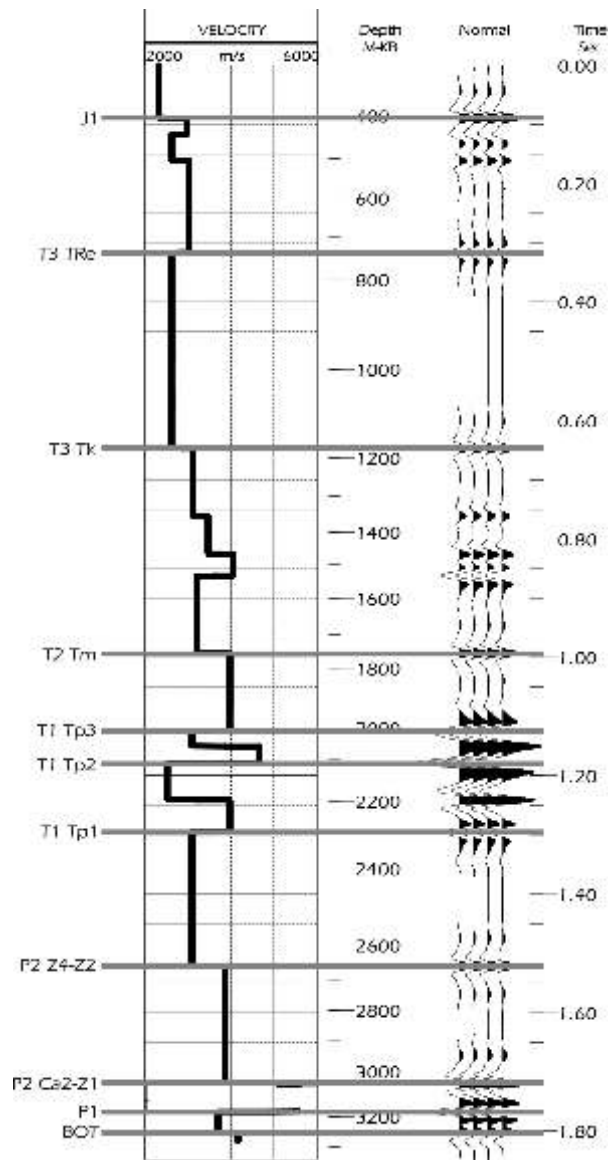


Fig. 8. Seismogeological model Radlin-2 well

The stream of gases migrating vertically up across the almost impermeable Zechstein evaporites then across Lower-Middle Triassic strata is probably too narrow to affect the seismic record distinctively enough. Over the fault and surrounding fracture zones it grows wider up the profile, where above the Muschelkalk (Tm) boundary the Keuper-Rhaetian, Liassic and Dogger sandstones increase in porosity by over 10% (Fig. 4a). Assuming a stationary vertical gas flow, a considerable amount of gas held in larger pore-spaces in shallow rock layers may be sufficient to produce a seismically traceable effect of velocity decrease (Pietsch and Bała, 1996). In that case the anomalous seismic record is observed above the Tm boundary, which agrees with the position of surface hydrocarbon gas anomaly and may represent a “gas chimney” effect.

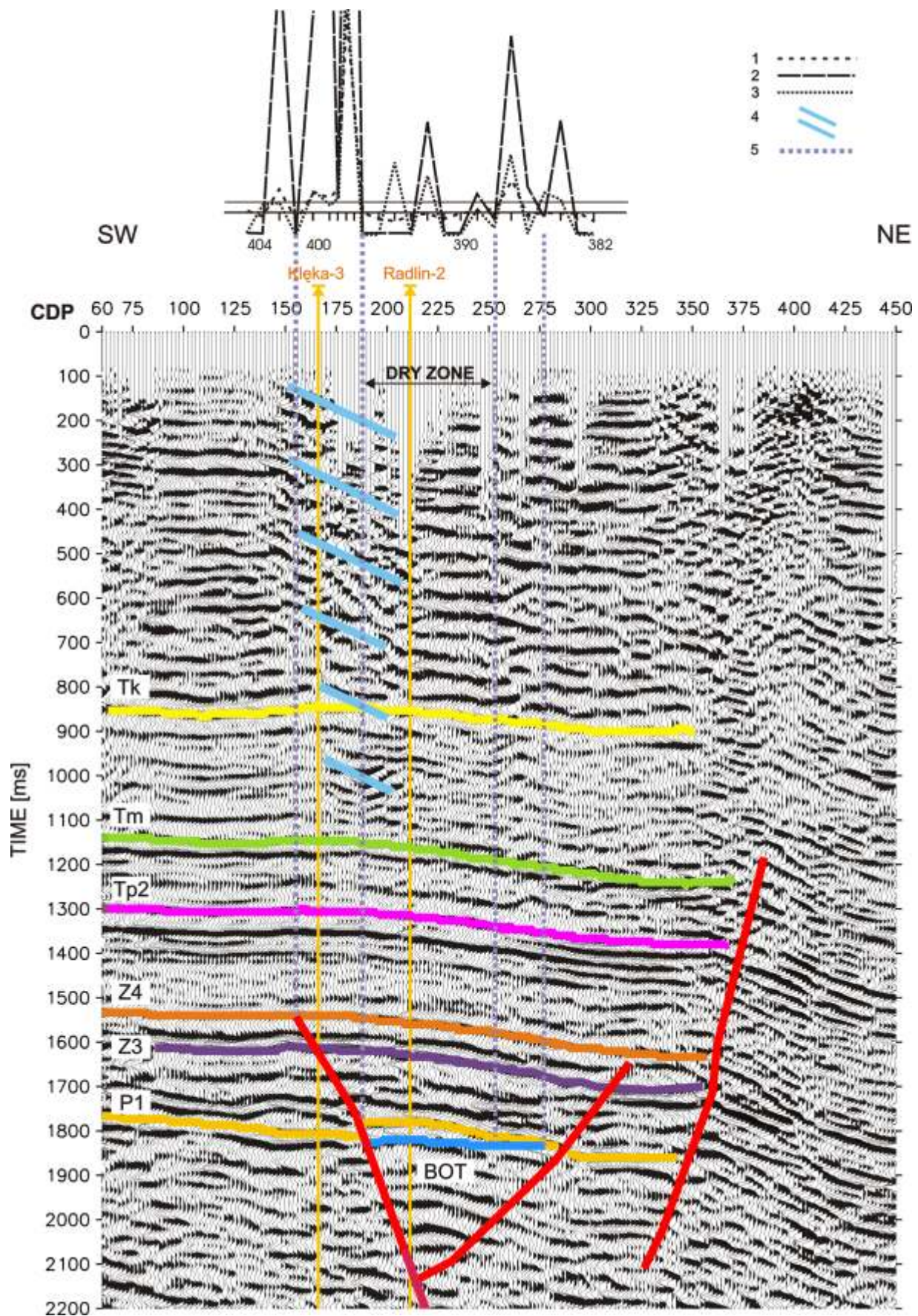


Fig. 9. Seismic cross-section 9-09-83K correlated with surface geochemical profile D-D'

1 — methane, 2 — sum of higher alkanes (C_2-C_5), 3 — sum of alkanes (C_2-C_4), 4 — location of “gas chimney”, 5 — correlation between subsurface structure and surface gas anomalies; surface geochemical profile by Dzieniewicz and Sechman (in: Górecki *et al.*, 1993)

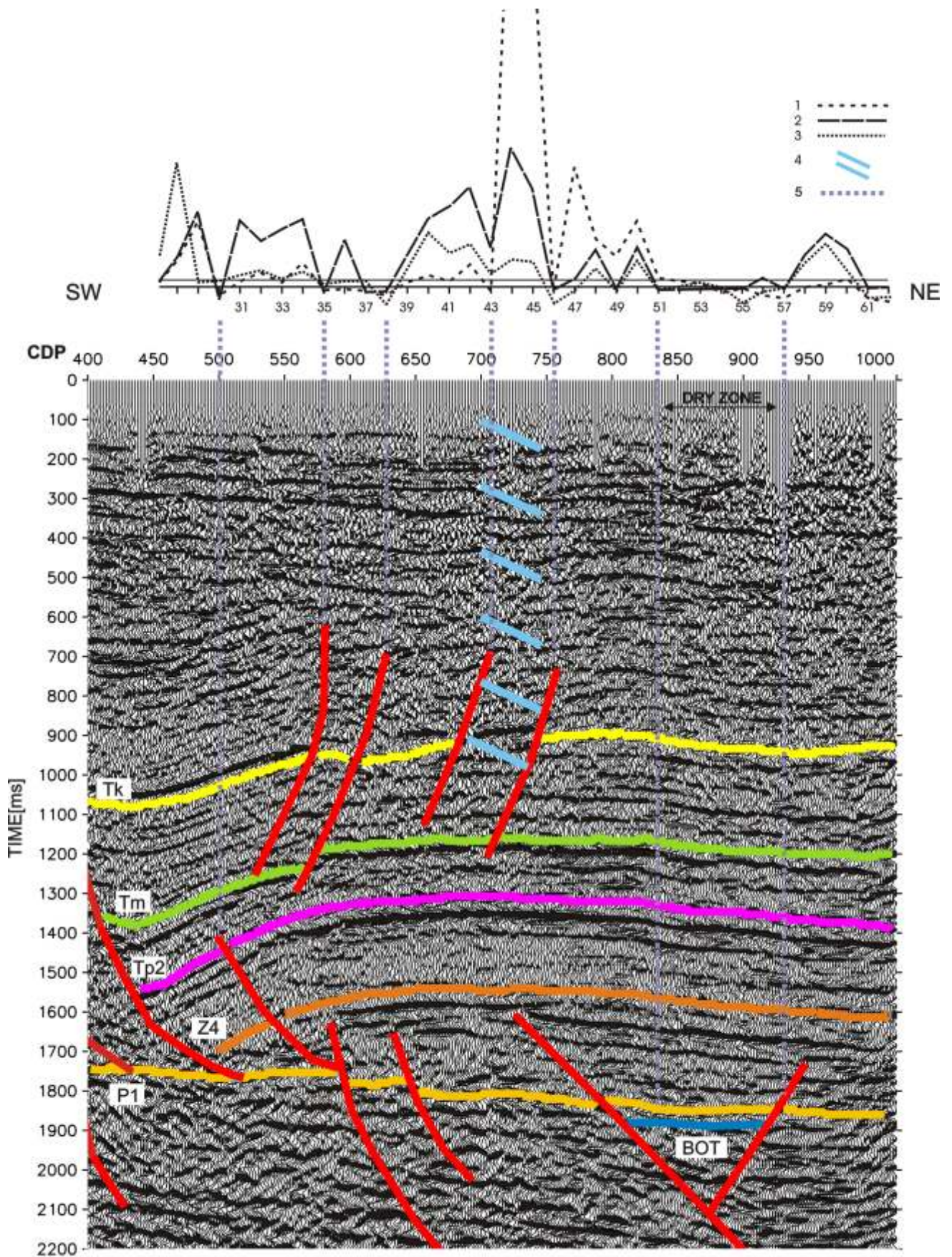


Fig. 10. Seismic cross-section 22-09-93K correlated with surface geochemical profile G-G'

For explanations see Fig. 9; surface geochemical profile by Dzieniewicz and Sechman (in: Górecki *et al.*, 1993, 1995a, b and Strzetelski, 1999)

CONCLUSIONS

1. The method of modelling and interpretation of seismic data, combined with a surface gas survey, is proposed here to identify pathways of vertical hydrocarbon migration and to locate petroleum fields in the subsurface.

2. In the Polish Lowlands the majority of traceable surface hydrocarbon gas microseepages detected using the free gas method come from subsurface reservoir sources (gas-bearing Rotliegend and Carboniferous as well as oil and gas-bearing Main Dolomite Formation).

3. The presence of a thick Zechstein evaporite cover and highly variable Upper Jurassic carbonates decreases the quality of seismic record and limits its range to the top of the Early Permian Rotliegend. An almost impermeable cover of Zechstein evaporites narrows the vertical gas migration pathways, thus making surface gas anomalies more distinct.

4. The seismic sections as correlated with surface geochemical profiles show that the surface hydrocarbon microseepages form belts trending along the strike of Permian structures.

5. Anomalous seismic records typical of "gas chimney" effects are observable from shallow reflection patterns, which come from more porous, and gas saturated Mid-Triassic-Jurassic strata. These agree with the location of surface hydrocarbon gas anomalies, thus reflecting the vertical gas migration pathways.

6. Specifically, a close relationship is noted between hydrocarbon gas anomalies at the surface, "gas chimney" effects in

seismic cross-sections and the trend and character of major faults.

7. Halo-type surface gas hydrocarbon anomalies surround Lower Permian (Rotliegend sandstone) gas fields (e.g. Radlin). Consequently, over the gas-productive pay zones the seismic gas-derived anomalies are low or absent and the location of gas fields can be correlated with relative "geochemically silent" — dry surface hydrocarbon gas zones.

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