GOSPODARKA SUROWCAMI MINERALNYMI

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# The possibilities of underground $CO_2$ storage in the Zaosie Anticline

## Introduction

The possibility of storing $CO_2$ in deep Mesozoic (saline) aquifers of the Polish Lowland have been described in many papers published by specialists of the MEERI PAS (e.g. Tarkowski (ed.) 2005, 2008; Tarkowski, Uliasz-Misiak 2005, 2006; Tarkowski et al . 2009). Some of the papers mention the Zaosie structure that is located in the Kujawy and Pomeranian Swell, along its SW edge. It is located near Łódź and Bełchatów and therefore is one of the most suitable geological structures for $CO_2$ storage in Poland.

During discussions held within the Consortium implementing the program entitled *Assessment of formations and structures for safe $CO_2$ storage, including their monitoring program* and coordinated by the PGI-NRI, the Zaosie structure, in addition to the Tuszyn and Wojszyce structures, was placed in the list of structures intended for underground $CO_2$ storage for the Bełchatów Power Station, for which detailed work was commissioned. The monographic study entitled: *Potential geological structures for $CO_2$ storage in Mesozoic deposits of the Polish Lowlands (their characteristics and ranking)* (Tarkowski (ed.) 2010) presented an initial geological characterisation of the Zaosie Anticline in terms of underground storage of carbon dioxide (Marek, Tarkowski, Dziewińska 2010). Three aquifers for $CO_2$ storage have been considered (Lower Jurassic: Borucice Formation and Komorowo Formation; Lower Triassic: Baltic Formation of the Lower Buntsandstein and basal part of the Middle Buntsandstein).

Specialists from the MEERI PAS undertook its more detailed study. The work has been done based on available, most up-to-date geological and geophysical data. The results of the

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work are presented in this article discussing the following issues: geological characteristics of the Zaosie Anticline on the background of regional geology of the area, characteristics of potential formations and their usefulness for underground storage of carbon dioxide.

## 1. Geological setting

A chain of the Rogoźno-Justynów-Zaosie salt-cored structures stretches along the south-western edge of the Kujawy Swell (Rawa Mazowiecka structural unit) between Zgierz in the north and Tomaszów Mazowiecki in the south (Dadlez ed. 1988; Marek ed. 1977; Marek, Znosko 1972a, b) (Figs. 1, 2). These geological structures are represented by the Rogoźno salt stock and the Zaosie and Justynów salt pillows, separated by the Tomaszów Mazowiecki-Buków faults. In the geological map without Cenozoic deposits (Fig. 1), the Rogoźno salt stock is manifested by Zechstein subcrops, the Justynów salt pillow – by Middle Jurassic subcrops, and the Zaosie salt pillow – by Oxfordian subcrops, which constitute the core of the Kujawy Swell.

The subsurface geological structure of the Zaosie region has been imaged by regional and semi-detailed seismic reflection surveys (Białek, Grzesik, Hałoń 1992; Łobaziewicz, Misiewicz, Majewska 1976) and several deep boreholes that penetrated the Zechstein-Mesozoic succession: Budziszewice IG-1; Buków 1; Buków 2; Zaosie 1 (Enclosure1); Zaosie 2 (Enclosure 2); Zaosie 3 (Enclosure 3) (Bloch 1979; Dadlez 2001; Deczkowski, Franczyk 1988; Dziewińska, Marek, Jóźwiak 2001; Leszczyński ed. 2008; Maliszewska ed. 1999, Marek 1959; Marek ed. 1971; Nocoń ed. 1990; Pieńkowski 2004; Wysocka-Kudla 1989).

Information on the subsurface geological structure of the study area also comes from both hydrogeological tests performed in the boreholes (Bojarski 1996) and geothermal studies (Majorowicz 1983).

## 2. The internal structure of the Zaosie Anticline

The Zaosie Anticline is located in the south-western end of the Rawa structural unit of the Kujawy Swell. The relief of the Lower/Middle Buntsandstein structural surface indicates that the Zaosie salt pillow is an oval-ellipsoidal structure, 15 km in length and 8 km in width. Its area is about 120 km$^2$ (Table 1). The height of the salt pillow in relation to the neighbouring synclines is approximately 300 m (from the northeast) and about 350–400 m (from the southwest) (Figs. 3–7). In the longitudinal axis (NW-SE), its amplitude (truncated to the northwest by the Tomaszów Mazowiecki-Buków faults) is much smaller and is about 200 m.

In the images of younger structural surfaces, the Zaosie Anticline is flattened in appearance. The anticline amplitude at the structural surface of the top of the Lower Jurassic, as measured in relation to the syncline extending to the northeast, is about 150 m, and in

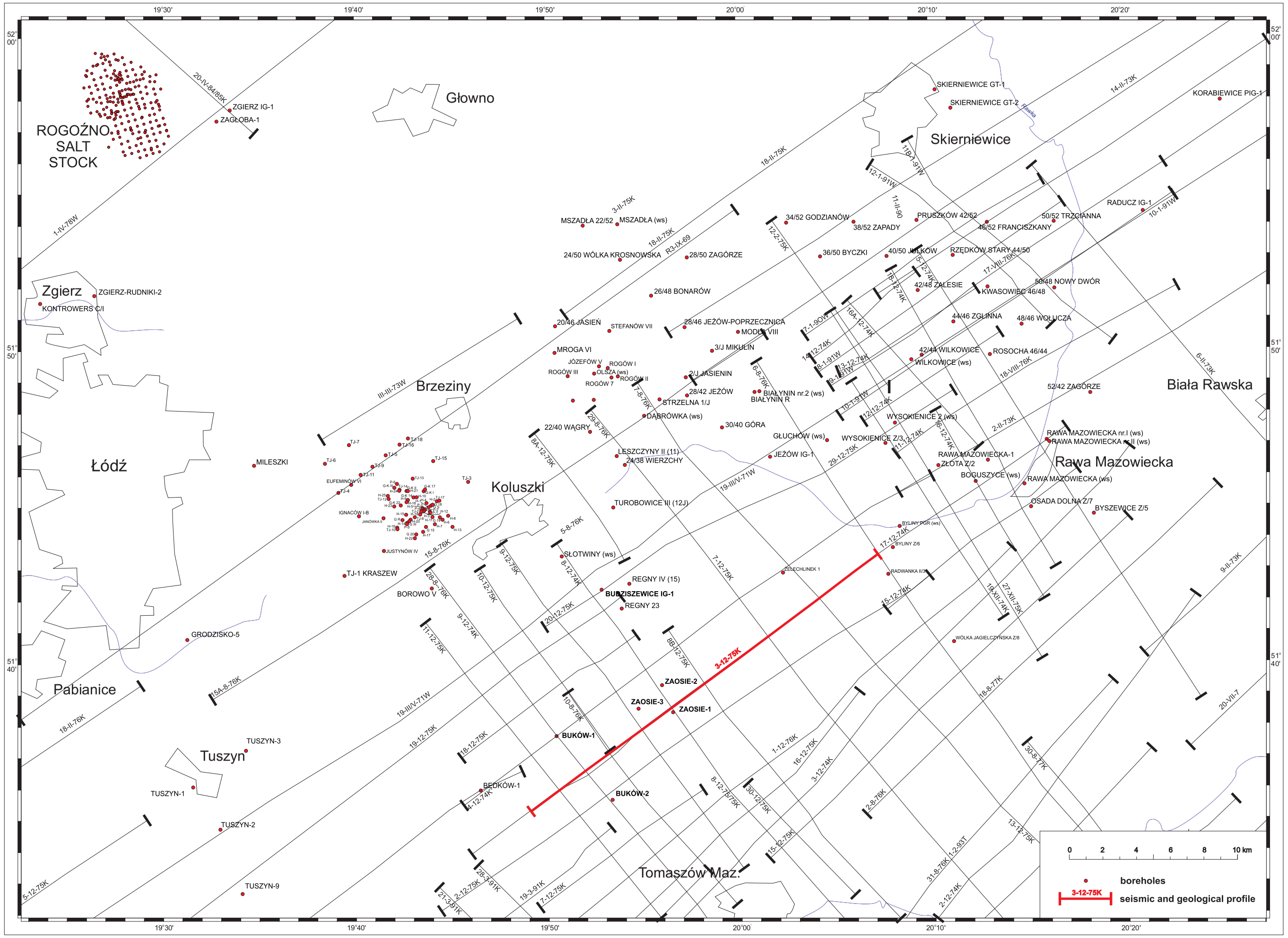
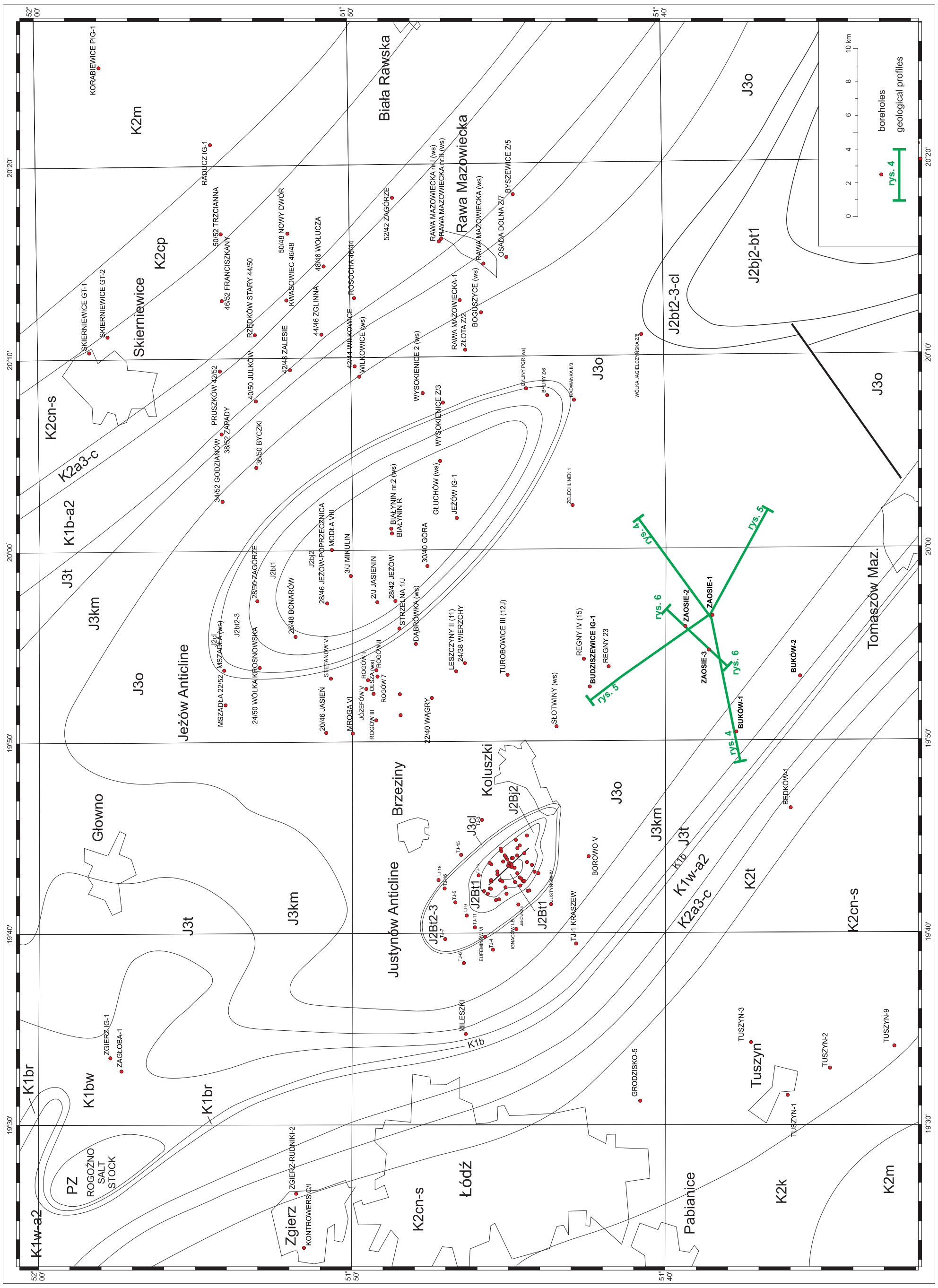



Fig. 1. Location of seismic profiles and boreholes in the Łódź-Justynów-Zaosie-Jeżów-Rawa Mazowiecka region

Fig. 1. Lokalizacja profili sejsmicznych i otworów wiertniczych w rejonie: Łódź-Justynów-Zaosie-Jeżów-Rawa Mazowiecka


Biała Rawska
Rawa Mazowiecka
Skierniewice
Tomaszów Maz.
Jeżów Anticline
Justynów Anticline
Brzeziny
Koluszki
Głowno
Łódź
Zgierz
Pabianice
Tuszyn
PZ
ROGOŹNO
SALT
STOCK
K2m
K2cp
K2cn-s
K2a3-c
K1b-a2
J3t
J3km
J3o
J2bj2-bt1
J2bt2-3-cl
K1bw
K1br
K1w-a2
K2t
K2k
rys. 4
rys. 5
rys. 6
boreholes
geological profiles
10 km

relation to the syncline extending to the southwest it is about 200 m. The anticline is not clearly marked in the intersection image of sub-Cenozoic subcrops of Mesozoic deposits because it lies in the field of Oxfordian deposits. Deep-rooted faults (of a small displacement amplitude of tens of metres), bounding the Zaosie salt pillow, cut part of the succession and die out mostly in the Upper Triassic and lowermost Jurassic (Figs. 3–7).

## 3. Aquifers

As a result of lithostratigraphic, physico-chemical and hydrogeological studies to assess the possibilities of $CO_2$ storage, the following aquifers have been selected in Mesozoic deposits of the Zaosie Anticline (Table 1):

— Baltic Formation (Scythian),
— Komorowo Formation (Upper Pliensbachian, Domerian),
— Borucice Formation (Upper Toarcian).

The primary aquifer is the Baltic Formation (sandstones) fully tested in the Zaosie 1 borehole at a depth of 2882.0–3391.0 (509.0 m) and in the Budziszewice IG-1 borehole at a depth of 3231.0–3605.5 (374.5 m). In the Zaosie 3, it was found at a depth of 3009.0–3255.0 (> 246.0 m). The Baltic Formation consists of fine- and medium-grained sandstones, in places cross bedded, locally slightly calcareous and containing lenses and infrequent clay-silt laminae (Szyperko-Teller, Moryc 1988; Szyperko-Teller 1997). An increase in clay content is observed in the lower part of the section. In the upper portion, referred to the Middle Buntsandstein, there is an increase in calcium carbonate content expressed in the form of limestone and dolomite intercalations. The proportion of sandstones

Fig. 2. Geological map of the Łódź-Justynów-Zaosie-Jeżów-Rawa Mazowiecka region (without Cenozoic deposits)
K2 – Upper Cretaceous, K2m – Maastrichtian, K2cp – Campanian, K2cn-s – Coniacian-Santonian, K2t – Turonian, K2a3-c – Upper Albian-Cenomanian, K1 – Lower Cretaceous, K1b-a2 – Berriasian-Middle Albian, K1w-a2 – Valanginian-Middle Albian, K1b – Berriasian, K1br – “upper” Berriasian (Ryazanian), K1bw – “lower” Berriasian (Upper Volgian = Purbeck), J3 – Upper Jurassic, J3t – Tithonian (Lower and Middle Volgian), J3km – Kimmeridgian, J3o – Oxfordian, J2 – Middle Jurassic, J2cl – Callovian, J2bt2-3-cl – Upper and Middle Bathonian, J2bt1 – Lower Bathonian, J2bj2-bt1 – Upper Bajocian and Middle Bathonian, J2aa-bj1 – Aalenian and Lower Bajocian, PZ – Zechstein

Fig. 2. Mapa geologiczna obszaru Łódź-Justynów-Zaosie-Jeżów-Rawa Mazowiecka (bez utworów kenozoiku)
K2 – kreda górna, K2m – mastrycht, K2cp – kampan, K2cn-s – koniak – santon, K2t – turon, K2a3-c – alb górny – cenoman, K1 – kreda dolna, K1b-a2 – berias – alb środkowy, K1w-a2 – walanżyn – alb środkowy, K1b – berias, K1br – berias „górny” (riazań), K1bw – berias „dolny” (wołg górny = purbek), J3 – jura górna, J3t – tyton (wołg dolny i środkowy), J3km – kimeryd, J3o – oksford, J2 – jura środkowa, J2cl – kelowej, J2bt2-3-cl – baton górny i środkowy, J2bt1 – baton dolny, J2bj2-bt1 – bajos górny i baton dolny, J2aa-bj1 – aalen i bajos dolny, PZ – cechsztyn

TABLE 1

Data on the Zaosie Anticline
Aquifers: 1. Borucice Formation (Upper Toarcian);
2. Komorowo Formation, Upper Sławęcin Beds (Pliensbachian, Domerian);
3. Baltic Formation (Scythian, Induan); Lower Buntsandstein and lowermost Middle Buntsandstein

TABELA 1

Dane dotyczące antykliny Zaosia
Poziom zbiornikowy: 1. Formacja borucicka (toars górny);
2. Formacja komorowska, warstwy sławęcińskie górne (pliensbach, domer);
3. Formacja bałtycka (scytyk, ind); pstry piaskowiec dolny i spągowa część pstrego piaskowca środkowego

| Name | Zaosie Anticline |
|---|---|
| Area (of anticline) | 15 km × 8 km = 120 km$^2$ |
| Thickness (aquifer) | 1. 145.0–201.0 m; average 160 m<br>2. 85.0–95.0 m; average 85 m<br>3. 374.5–509.0 m; average 450 m |
| $CO_2$ storage (volumetric) capacity of the aquifer | 1. 222 million tons<br>2. 115 million tons<br>3. 340 million tons |
| Depth to the aquifers | 1. Zaosie 1: 500.0 (–303.0)–665.0 (–468.0 m)<br>Zaosie 2: 518.0 (–313.0)–686.0 (–481.0 m)<br>Zaosie 3: 537.0 (–352.0)–680.0 (–495.0 m)<br>Budziszewice IG-1: 649.0 (–449.0)–850.0 (–650.0 m)<br>2. Zaosie 1: 755.0 (–558.0)–850.0 (–653.0 m)<br>Zaosie 2: 775.0 (–570.0)–860.0 (–655.0 m)<br>Zaosie 3: 770.0 (–585.0)–855.0 (–670.0 m)<br>Budziszewice IG-1: 902.0 (–702.0)–1000.0 (–800.0 m)<br>3. Zaosie 1: 2882.0 (–2685.0)–3391.0 (–3194.0 m)<br>Zaosie 3: 3009.0 (–2824.0)–>3255.0<br>Budziszewice IG-1: 3231.0 (–3031.0)–3605.5 (–3205.5 m) |
| Permeability (aquifer rocks) | 1–2. <1000 mD<br>3. 10–100 mD |
| Porosity (aquifer rocks) | 1–2. 15%<br>3. <10% |
| Formation pressure | Pressure gradient Gc = 0.93–1.0 × 10$^3$ hPa/10 m |
| Maximum pressure | Gcmax = 1.0 × 10$^3$ hPa/10 m |
| Formation temperature in the aquifer | Geothermal gradient Gt = 2.2°C/100 m |
| Percentage of sandstones in the aquifer | 1. 80%<br>2. 60–80%<br>3. 60% |

TABLE 1. cont.

TABELA 1. cd.

| Name | Zaosie Anticline |
|---|---|
| Pore water (in the aquifer) | 1–2. Cl-Ca-type brines of Class I<br>$Na^+ : Cl^- = 0.95–0.96$<br>3. Cl-Ca-type brines of Class IV–V<br>$Na^+ : Cl^- = 0.50–0.52$ |
| Total Dissolved Solids | 1–2. 7–9 g/dcm$^3$<br>3. 250 g/dcm$^3$ |
| Stratigraphy<br>(of the aquifer) | 1. Upper Toarcian: Borucice Formation<br>2. Upper Pliensbachian. Domerian: Komorowo Formation<br>3. Scythian – Lower Buntsandstein and lowermost Middle Buntsandstein (Baltic Formation. sandstones) |
| Lithology (of the aquifer) | 1–2. Sandstones (80%) with claystone and siltstone interbeds<br>3. Sandstones (60%) with claystone and siltstone interbeds |
| Lithological investigations | Microscopic and physico-chemical studies |
| Geographical coordinates: X, Y | Zaosie 1: 5723919.7 4426733.9<br>Zaosie 3: 5724135.6 4424659.9<br>Budziszewice IG-1: 5731276.3 4422615.2 |
| Geographic coordinate system | Cartesian coordinate system 1942 |
| Overburden stratigraphy | 1. Middle Jurassic (Aalenian-Bajocian)<br>2. Ciechocinek Formation, Lower Toarcian<br>3. Scythian – Middle Buntsandstein (Claystone Formation) + + Upper Buntsandstein (Röt) |
| Overburden lithology | 1. Middle Jurassic: alterbating sandstones, siltstones and claystones, total thickness about 400 m<br>2. Ciechocinek Formation: claystones and siltstones with ferruginous sandstone interbeds, about 80 m thick<br>3. Claystones and siltstones with sandstone, limestone and evaporite interbeds |
| Faults | Faults in the Triassic and Lower Jurassic |
| Number of boreholes | 4 boreholes |
| Total depth | Zaosie 1: 3500.0 m (Zechstein)<br>Zaosie 2: 2071.0 m (Middle Triassic, Muschelkalk)<br>Zaosie 3: 3250.0 m (Lower Buntsandstein)<br>Budziszewice IG-1: 5601.0 m (Carboniferous) |
| Boreholes located near the anticlinal crest | Zaosie 1 |

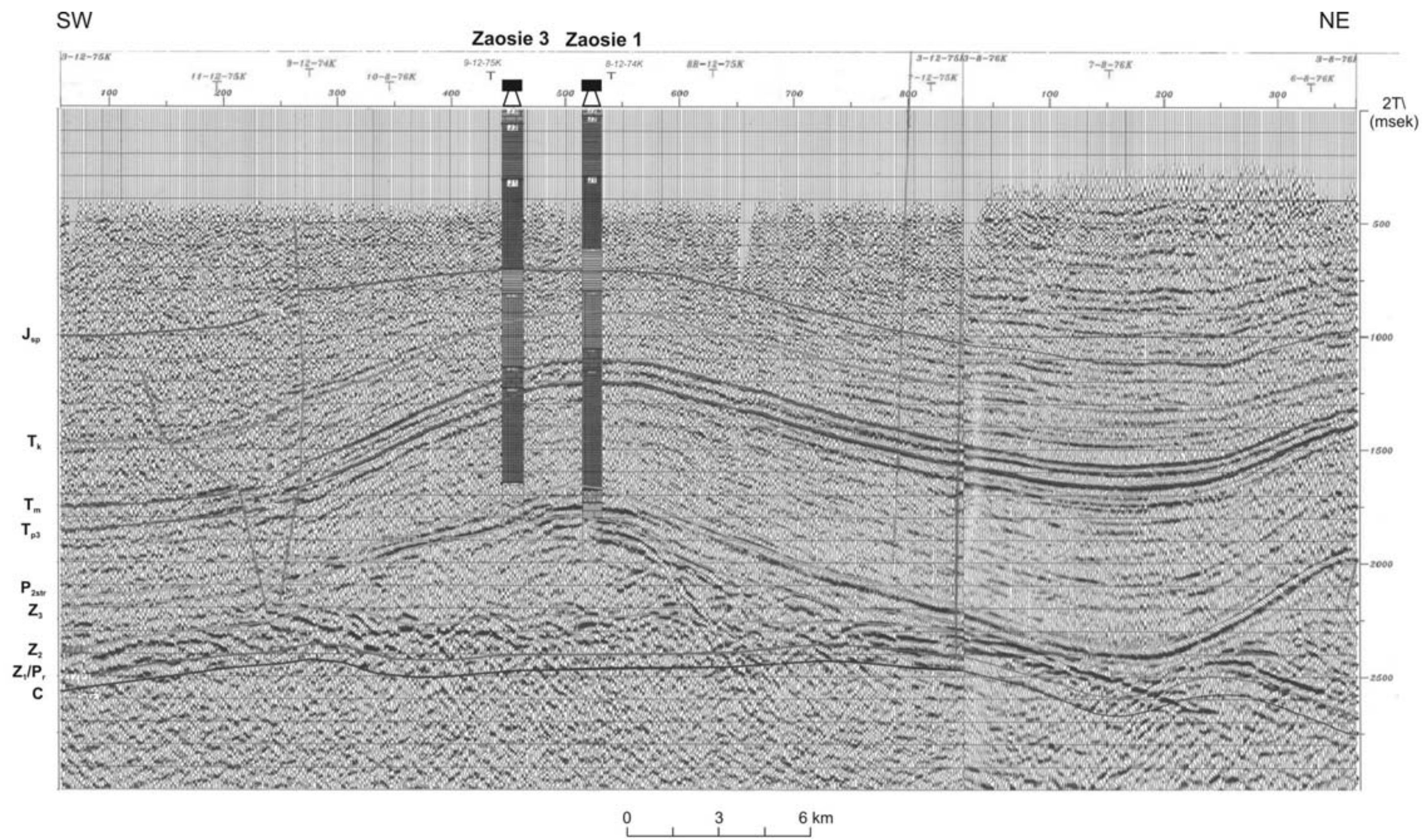



Fig. 3. Time seismic-geological section along the line 3-12-75K/3-8-76K (Buków-Zaosie-Budziszewice); symbols of seismic boundaries: Jsp – base of Jurassic; Tk – Keuper; Tm – Triassic, Muschelkalk; Tp3 – Upper Triassic, Buntsandstein; P2str – top of Zechstein; Z3 – Leine cyclothem; Z2 – Stassfurt cyclothem; Z1/P1 – Lower Zechstein/Upper Retligend boundary; C – Carboniferous

Fig. 3. Czasowy przekrój sejsmiczno-geologiczny wzdłuż linii 3-12-75K/3-8-76K (Buków-Zaosie-Budziszewice); symbole granic sejsmicznych: Jsp – spąg jury; Tk – kajper; Tm – trias, wapień muszlowy; Tp3 – trias górny, pstry piaskowiec; P2str – strop cechsztynu; Z3 – cyklotem Leine; Z2 – cyklotem Stassfurt; Z1/P1 – spąg cechsztynu/strop czerwonego spągowca; C – karbon

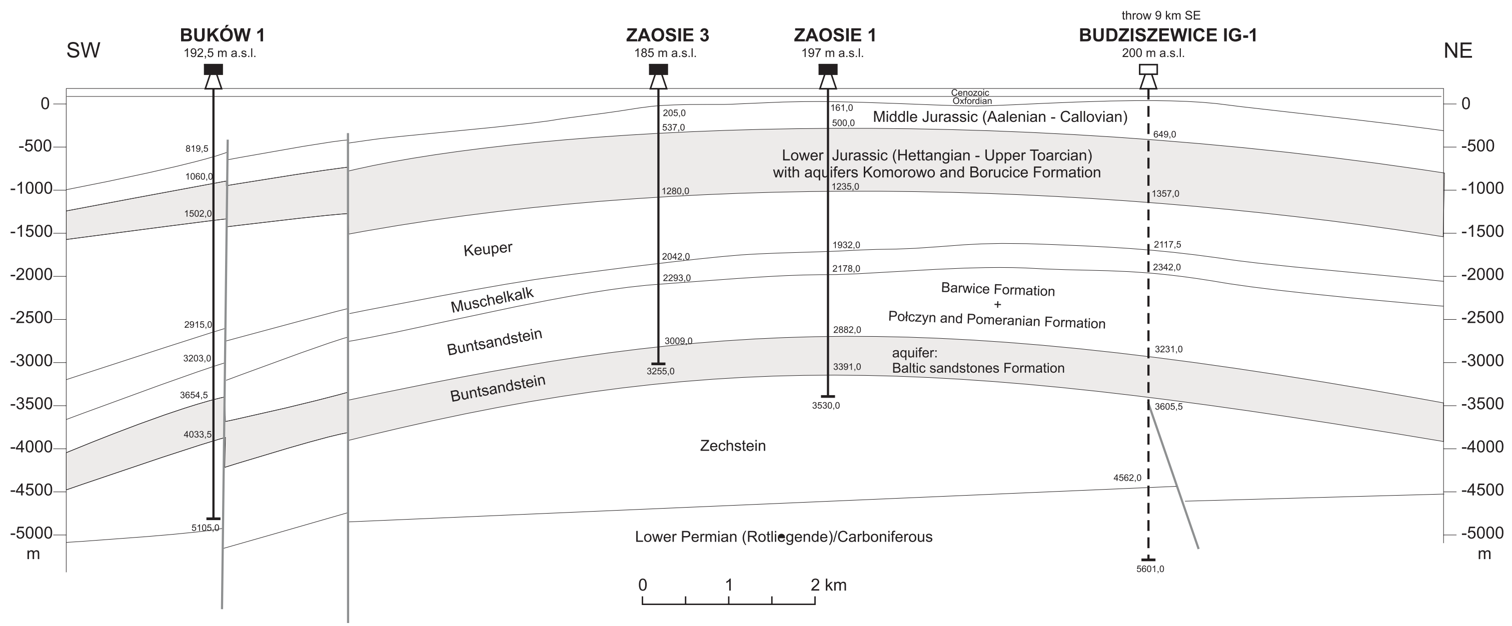



Fig. 4. Geological cross-section through the Zaosie Anticline (Buków 1-Budziszewice IG-1)

Fig. 4. Przekrój geologiczny poprzeczny przez antyklinę Zaosie (Buków 1-Budziszewice IG-1)

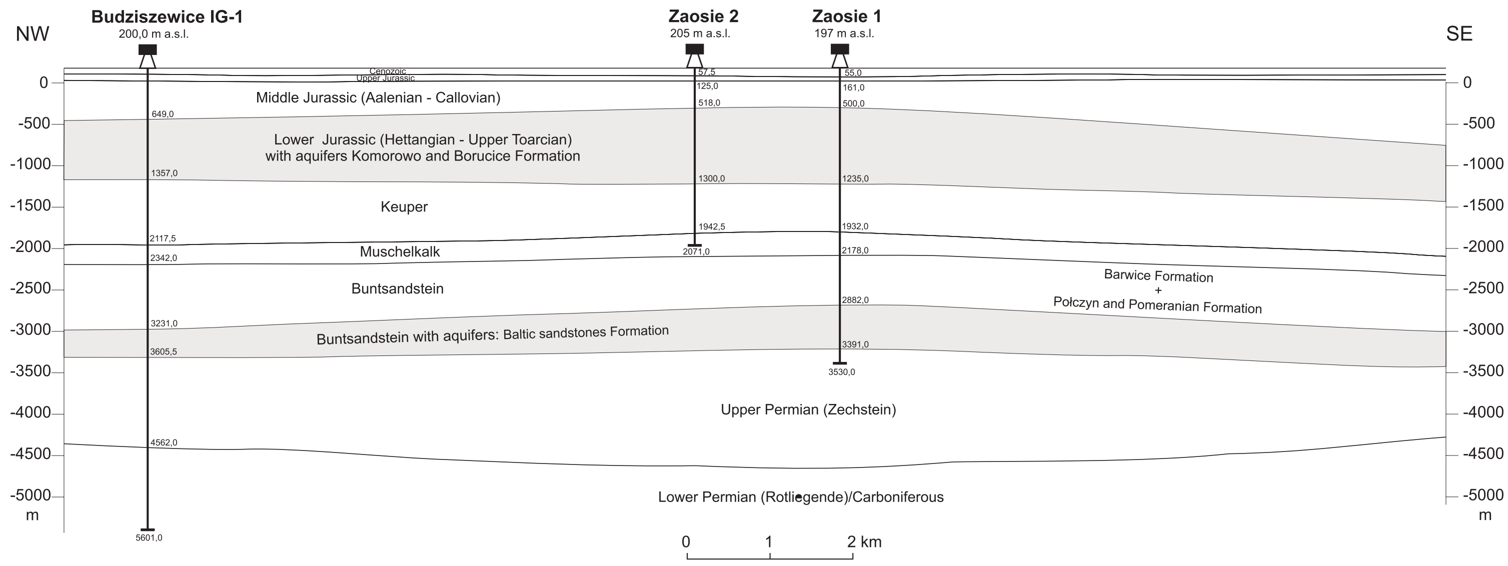



Fig. 5. Longitudinal geological cross-section through the Zaosie Anticline (Budziszewice IG-1, Zaosie 2, Zaosie 1)

Fig. 5. Przekrój geologiczny podłużny przez antyklinę Zaosia (Budziszewice IG-1, Zaosie 2, Zaosie 1)

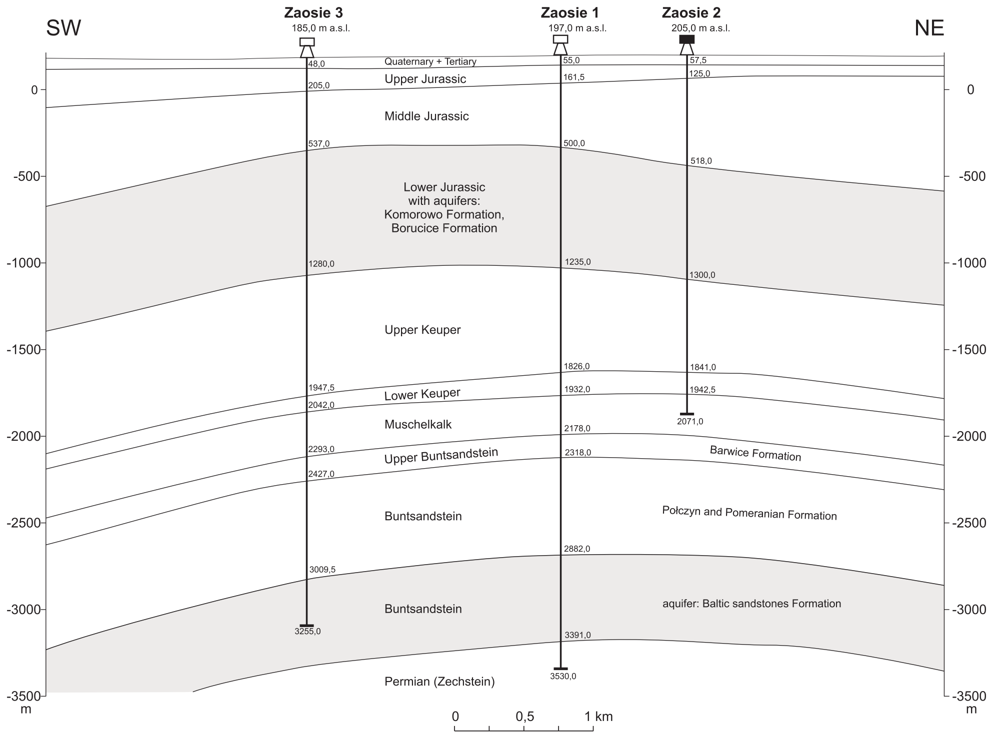



Fig. 6. Geological cross-section through the Zaosie Anticline (Zaosie 3, Zaosie 1, Zaosie 2) (after Wysocka-Kudła 1989, modified by the authors)

Fig. 6. Przekrój geologiczny poprzeczny przez antyklinę Zaosie (Zaosie 3, Zaosie 1, Zaosie 2) (na podstawie Wysocka-Kudła 1989 ze zmianami autorów)

in the Baltic Formation exceeds 60%. The porosity of the sandstones is up to 10%, and the permeability is 10–100 mD. Volumetric $CO_2$ storage capacity (at the $CO_2$ storage efficiency coefficient of 0.1) is approximately 340 million tons. The amount of Total Dissolved Solids in the formation water is high – 250g/dcm$^3$. This is a Cl-Ca-type brine of Class IV–V, and the degree of metamorphism $Na^+ : Cl^-$ is 0.50–0.52. Formation pressure Gc = 0.93–1.0 · · 103 hPa/dcm$^3$. The Baltic Formation is sealed by a complex of rocks representing the Pomeranian and Połczyn formations of the Middle Buntsandstein, and the Barwice Formations (Röt) of the Upper Buntsandstein. These are mainly clay-silt and clay-carbonate--evaporite sediments, respectively. The total thickness of the overburden ranges from approximately 704.0 (Zaosie 1) to 889.0 m (Budziszewice IG1), and the average thickness is about 770 m.

Another promising level in terms of underground $CO_2$ storage is the Upper Pliensbachian (Domerian) Komorowo Formation. This aquifer was investigated with the boreholes of Zaosie 1, depth 755.0–850.0 m (95.0 m), Zaosie 2, depth 775.0–860.0 m (85.0 m), Zaosie 3, depth 770.0–855.0 m (85.0 m) and Budziszewice IG-1, depth 902.0–1000.0 m (98.0 m). It is represented by fine- and medium-grained sandstones interbedded with sandy mudstones and

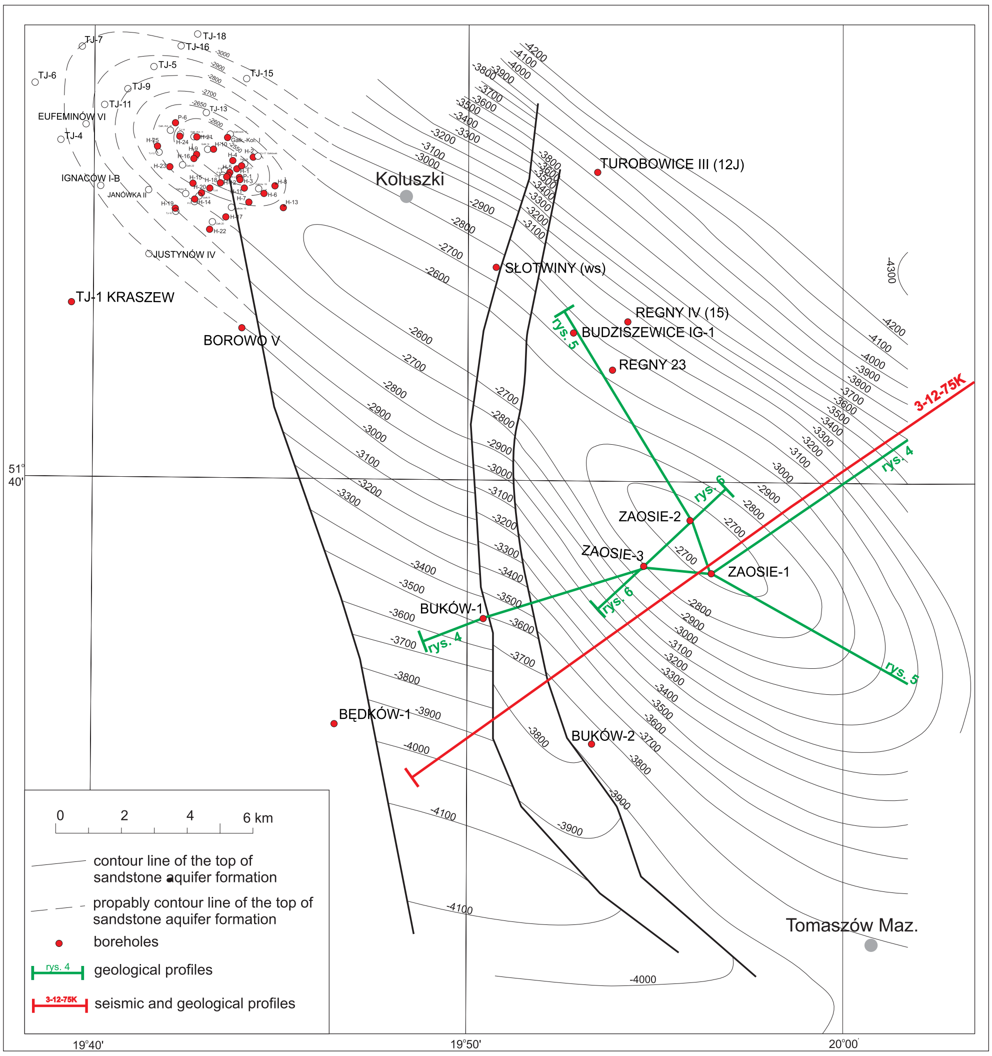


Fig. 7. Structural map of the top of the Baltic Formation sandstone aquifer
(Lower Buntsandstein and lowermost Middle Buntsandstein)
(after Wysocka-Kudła 1989, modified by the authors)

Fig. 7. Mapa strukturalna stropu poziomu zbiornikowego formacji bałtyckiej piaskowcowej pstrego piaskowca dolnego i spągowej części pstrego piaskowca środkowego
(na podstawie Wysocka-Kudła 1989 ze zmianami autorów)

claystones. The proportion of sandstone ranges from 60 to 80%, the porosity is about 15% and the permeability is up to 1000 mD. Volumetric $CO_2$ storage capacity (with the $CO_2$ storage efficiency coefficient of 0.1) is approximately 115 million tons. This formation contains weakly mineralized chloride-calcium brines of class I, containing flammable gas. The brine contains up to 9 g/dcm$^3$ of TDS and the hydrochemical index $Na^+ : Cl^- =$ = 0.95–0.96. This ratio indicates a possible contact of the water with meteoric waters. The Upper Pliensbachian aquifer of the Komorowo Formation is directly sealed by clay-silt rocks of the Lower Toarcian Ciechocinek Formation, about 52–90 m thick. The quality of sealing is insufficiently determined.

The uppermost potential aquifer of the Upper Toarcian Borucice Formation was tested in the boreholes of Zaosie 1, depth 500.0–665.0 m (165.0 m), Zaosie 2, depth 518.0–686.0 m (168.0 m), Zaosie 3, depth 537.0–680.0 m (143.0 m) and Budziszewice IG-1, depth 649.0–850.0 m (201.0 m). This aquifer shows good reservoir properties (in terms of geological structure, thickness, lithology and physico-chemical characteristics) (Table 1) and is probably infiltrated by surface waters. Volumetric $CO_2$ storage capacity (at the $CO_2$ storage efficiency coefficient of 0.1) is approximately 222 million tons. Due to the small depth to the aquifer, the Borucice Formation does not fully meet the requirements for $CO_2$ storage in the Zaosie Anticline.

## Discussion

The Zaosie Anticline is one of the structures selected for $CO_2$ storage in the Kujawy Swell. It was examined by seismic profiles and four deep boreholes. The present paper provides an analysis of the following aquifers suitable for underground $CO_2$ storage: Lower Jurassic (Borucice and Komorowo formations) and Lower Triassic (Baltic Formation). The following parameters have been considered: capacity of the structure, properties of the aquifer (depth to the top, effective thickness, porosity, permeability, total dissolved solids) and properties of the overburden (presence of faults and their extent, thickness) (see Best pratice… 2006; Tarkowski, Marek, Uliasz-Misiak 2009).

The *sine qua non* of suitability for $CO_2$ storage is adequate storage capacity (assumed to be at the level of 60 Mt, that corresponds to 30-year emission from an electric generator emitting annually 2 Mt of $CO_2$). All the three aquifers meet the criterion; the Baltic Formation shows the greatest volumetric capacity (340 Mt). The depths to the top of the aquifers are variable: more than 800 m for the Borucice Formation, and below 800 m for the two remaining aquifers. In the former case, the depth is considered a negative factor, limiting the possibility of $CO_2$ storage in the Borucice Formation. It should be stressed that the formation lies at considerably large depths (2800 m and more), which significantly affects the $CO_2$ storage costs. The thickness of the formation is the greatest (about 450 m), but the Lower Jurassic formations show better values of porosity and permeability of rocks. It should also be noted that the Lower Jurassic groundwater has unfavourably low values of total dissolved solids (< 10 g/dcm$^3$), indicating the possibility of contact with meteoric waters, while the TDS values of the Lower Triassic groundwater is high. The Borucice Formation is well sealed by the rocks of the Pomeranian, Połczyn and Barwice formations of the upper Lower Triassic and by a thick complex of Triassic and Jurassic deposits. The degree of sealing of the Lower Jurassic aquifers is determined insufficiently, and the faults in the eastern part of the structure extend up to the lowermost Upper Jurassic.

The primary aquifer, suggested for $CO_2$ storage in the Zaosie Anticline, is the Baltic Formation of Scythian age. The secondary aquifer is the Upper Pliensbachian (Domerian) Komorowo Formation. The Borucice Formation aquifer is not recommended for $CO_2$ storage because it occurs at a small depth. The Lower Triassic aquifer is conspicuous by its large storage capacity, a thick package of overburden seal (Middle – Upper Triassic and Jurassic rocks) and high mineralisation of formation waters. However, its disadvantage is the large depth to its top, which also negatively affects its petrophysical properties of reservoir rocks.

The analysis of aquifers suitable for underground $CO_2$ storage in the Zaosie Anticline confirms the previous suggestions (Uliasz-Misiak, Tarkowski 2010) about its poor conditions for $CO_2$ storage. Therefore, if the structure is of interest for such operations, further work should be focused mainly on the study of integrity of the overburden rocks, reservoir properties of the selected aquifers and mineralisation of formation waters.

The Zaosie structure is of interest to the Bełchatów Power Station. Relatively near the structure (up to 50 km) are also the Dalkia Łódź ZEC SA plants. The following plants are located a little further (up to 100 km): KCW Warta SA, Kozienice Power Plant SA, ZE PAK SA (Power Plant Group Company, Adamów), Vettenfall Heat Poland SA – (Siekierki and Żeran in Warsaw) and LaFarge Cement Poland SA (Małogoszcz).

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## MOŻLIWOŚCI WYKORZYSTANIA ANTYKLINY ZAOSIA DO PODZIEMNEGO SKŁADOWANIA $CO_2$

### Słowa kluczowe

Składowanie $CO_2$, struktury geologiczne, poziomy wodonośne, Polska

### Streszczenie

Antyklina Zaosia znajduje się w bliskiej odległości od Łodzi i Bełchatowa i jest jedną z bardziej interesujących struktur geologicznych do składowania $CO_2$ w Polsce, dlatego też dokonano szczegółowego jej opracowania. Przedstawiono charakterystykę geologiczną antykliny Zaosia na tle budowy geologicznej regionu, szczegółową budowę geologiczną, charakterystykę potencjalnych poziomów do składowania $CO_2$ oraz przydatność rozważanych poziomów zbiornikowych do podziemnego składowania dwutlenku węgla.

Antyklina Zaosia została rozpoznana profilami sejsmicznymi i czterema głębokimi otworami wiertniczymi. Do składowania $CO_2$ przeanalizowano poziomy zbiornikowe: dolnojurajskie (formacja borucicka i formacja komorowska) oraz dolnotriasowy (formacja bałtycka). Pierwszoplanowym poziomem zbiornikowym dla składowania $CO_2$ w antyklinie Zaosia jest poziom formacji bałtyckiej scytyku, natomiast drugoplanowym poziomem zbiornikowym jest poziom formacji komorowskiej górnego pliensbachu.

Pierwszoplanowy dolnotriasowy poziom zbiornikowy został rozpoznany trzema głębokimi otworami, jego wolumetryczna pojemność składowania wynosi około 340 mln ton, a mineralizacja wód złożowych osiąga 250 $g/dcm^3$. Jest on uszczelniony bezpośrednio grubym kompleksem skał ilasto-wapnisto-ewaporytowych oraz miąższym pakietem skał triasu środkowego i górnego oraz jury. Jego mankamentem jest znaczna głębokość, co wpływa ujemnie na cechy petrofizyczne skał zbiornikowych. Drugoplanowy poziom zbiornikowy formacji komorowskiej posiada lepsze parametry petrofizyczne skał pod kątem składowania $CO_2$, ma odpowiednią głębokość zalegania, a jego mankamentem jest mała mineralizacja wód złożowych i prawdopodobieństwo kontaktu z wodami powierzchniowymi. Poziom zbiornikowy formacji borucickiej nie jest rekomendowany do składowania $CO_2$ z uwagi na jego małą głębokość i możliwy kontakt z wodami infiltracyjnymi.

Struktura Zaosia stanowi przedmiot zainteresowania Elektrowni w Bełchatowie. W bliskiej odległości (do 50 km) od niej znajdują się zakłady Dalkia Łódź ZEC SA, a w nieco dalszej (do 100 km): KCW Warta SA, Elektrownia Kozienice SA, Zespół Elektrowni PAK SA (Adamów), Vattenfall Heat Poland SA – (Siekierki i Żerań w Warszawie), LaFarge Cement Poland SA (Małogoszcz).

## THE POSSIBILITIES OF UNDERGROUND $CO_2$ STORAGE IN THE ZAOSIE ANTICLINE

### Key words

$CO_2$ storage, geological structure, aquifer, Poland

### Abstract

The Zaosie Anticline is located not far from Łódź and Bełchatów. It is one of the most interesting geological structures for underground $CO_2$ storage in Poland and thus it requires a detailed study. The paper presents the geological characteristics of the Zaosie Anticline against the background of the geological structure of the region as well as the potential aquifers for $CO_2$ storage, including their suitability for $CO_2$ storage.

The Zaosie Anticline was examined by seismic profiles and four deep boreholes. The following formations suitable for underground $CO_2$ storage were analysed: Lower Jurassic Borucice and Komorowo formations and Lower Triassic Baltic Formation. The primary aquifer for $CO_2$ storage in the Zaosie Anticline is the Baltic Formation of Scythian age. The secondary aquifer is the Upper Pliensbachian Komorowo Formation.

The primary Lower Triassic aquifer was surveyed by three deep boreholes. Its volumetric storage capacity is approximately 340 million tons, and the TDS content in the formation water reaches 250g/dcm$^3$. The aquifer is sealed directly by a thick series of clay-carbonate evaporite rocks and a thick packet of Middle and Upper Triassic and Jurassic deposits. Its disadvantage is a considerable depth to this level, which affects the petrophysical characteristics of reservoir rocks. The secondary aquifer, the Komorowo Formation, shows better petrophysical parameters of rocks in terms of $CO_2$ storage, the depth to the aquifer is adequate, but its disadvantage is a low content of TDS in the formation water and the likelihood of contact with surface waters. The Borucice Formation aquifer is not recommended for $CO_2$ storage because it occurs at a small depth and possibly contacts with meteoric waters.

The Zaosie structure is of interest to the Bełchatów Power Station. Relatively near the structure (up to 50 km) are also the Dalkia Łódź ZEC SA plants, and the following plants are located a little further (up to 100 km): KCW Warta SA, Kozienice Power Plant SA, ZE PAK SA (Power Plant Group Company, Adamów), Vattenfall Heat Poland SA – (Siekierki and Żeran in Warsaw) and LaFarge Cement Poland SA (Małogoszcz).

ENCLOSURE 1

Stratigraphy and lithology of the Zaosie 1 borehole (197.0 m a.s.l.)

ZAŁĄCZNIK 1

Profil geologiczny otworu wiertniczego Zaosie 1 (197,0 m n.p.m.)

Drilled in 1978; Geological documentation by: Bloch 1979.

0.0–55.0 (55.0 m) Quaternary

55.0–161.5 (106.5 m) Upper Jurassic; Oxfordian; Spongy Limestone Formation

161.5–500.0 (338.5 m) Middle Jurassic; **overburden**: alternating sandstones, siltstones and claystones: Callovian. Bathonian. Bajocian. Aalenian

500.0–1235.0 (735.0 m) Lower Jurassic

500.0–665.0 (165.0 m) Upper Toarcian; Borucice Formation; **aquifer 1**: sandstones (80%) with mudstone and claystone interbeds

665.0–755.0 (90.0 m) Lower Toarcian; Ciechocinek Formation; **overburden:** claystones and mudstones, subordinate sandy-ferruginous intercalations

755.0–850.0 (95.0 m) Upper Pliensbachian. Domerian; Komorowo Formation (= Upper Sławęcin Beds); **aquifer 2:** sandstones (80%) interbedded by claystones and mudstones

850.0–1235.0 (385.0 m) Lower Pliensbachian. Carixian-Upper Sinemurian; Łobez Formation + Ostrowiec Formation pars (=Main Sławęcin Beds); sandstones, siltstones and claystones and Lower Sinemurian-Hettangian; Ostrowiec Formation pars + Skłoby Formation (=Ksawerów Beds+Upper Kłodawa Beds)

1235.0–1826.0 (591.0 m) Upper Triassic; Rhaetian-Norian-Carnian; Upper Keuper

1826.0–2318.0 (492.0 m) Middle Triassic; Ladinian-Anisian-Olenekian pars)

1826.0–1932.0 (106.0 m) Lower Keuper (Sulechów Beds)

1932.0–2178.0 (246.0 m) Muschelkalk

2178.0–2318.0 (140.0 m) Upper Buntsandstein; Röt; Barwice Formation; **overburden:** claystones and siltstones interbedded by sandstones, limestones and evaporites

2318.0–3391.0 (1073.0 m) Lower Triassic; Scythian: Olenekian + Induan

2318.0–2882.0 (564.0 m) Middle Buntsandstein; Połczyn Formation (mudstones) and Pomeranian Formation (=claystones); **overburden:** claystones and siltstones

2882.0–3391.0 (509.0 m) Lower Buntsandstein and lowermost Middle Buntsandstein; Baltic Formation (=sandstones); **aquifer 3:** sandstones (60%) with claystone and siltstone interbeds

3391.0–3530.0 (>139.0 m) Zechstein

ENCLOSURE 2

Stratigraphy and lithology of the Zaosie 2 borehole (205.0 m a.s.l.)

ZAŁĄCZNIK 2

Profil geologiczny otworu wiertniczego Zaosie 2 (205,0 m n.p.m.)

Drilled in 1989; Geological documentation by: Nocoń 1989;

0.0–57.5 (57.5 m) Quaternary

57.5–125.0 (67.5 m) Upper Jurassic; Oxfordian; Spongy Limestone Formation

125.0–518.0 (393.0 m) Middle Jurassic; **overburden:** alternating claystones and mudstones (60% ) and sandstones (40%): Callovian. Bathonian. Bajocian. Aalenian

518.0–1300.0 (782.0 m) Lower Jurassic

518.0–686.0 (168.0 m) Upper Toarcian; Borucice Formation; **aquifer 1:** sandstones (80%) with claystone and mudstone intercalations

686.0–775.0 (89.0 m) Lower Toarcian; Ciechocinek Formation; **overburden:** claystones and siltstones

775.0–860.0 (85.0 m) Upper Pliensbachian. Domerian; Komorowo Formation; **aquifer 2:** sandstones (80%) with claystone and mudstone intercalations

860.0–960.0 (100.0 m) Lower Pliensbachian. Carixian-Upper Sinemurian (Upper Sławęcin Beds). Łobez Formation+Ostrowiec Formation pars

960.0–1120.0 (160.0 m) Lower Sinemurian-Upper Hettangian; Ostrowiec Formation pars (= Ksawerów Beds); sandstones (80%), claystone and mudstone interbeds

1120.0–1300.0 (180.0 m) Lower Hettangian; Skłoby Formation (= Upper Kłodawa Beds); claystones and siltstones

1300.0–1841.0 (541.0 m) Upper Triassic; Rhaetian-Norian-Carnian; Upper Keuper

1841.0–2071.0 (>230.0 m) Middle Triassic; Ladinian-Anisian; Lower Keuper + Muschelkalk

1841.0–1942.5 (101.5 m) Lower Keuper

1942.5–>2071.0 (>128.5 m) Muschelkalk

ENCLOSURE 3

Stratigraphy and lithology of the Zaosie 3 borehole (185.0 m a.s.l.)

ZAŁĄCZNIK 3

Profil geologiczny otworu wiertniczego Zaosie 3 (185,0 m n.p.m.)

Drilled in 1990; Geological documentation by: Wysocka-Kudła 1989;

0.0–48.0 (48.0 m) Quaternary

48.0–205.0 (157.0 m) Upper Jurassic; Oxfordian; Spongy Limestone Formation

205.0–537.0 (332.0 m) Middle Jurassic; **overburden:** alternating claystones, siltstones and sandstones: Callovian. Bathonian. Bajocian. Aalenian.

537.0–1280.0 (743.0 m) Lower Jurassic

537.0–680.0 (143.0 m) Upper Toarcian; Borucice Formation; **aquifer 1:** sandstones (80%) with claystone and mudstone interbeds

680.0–770.0 (90.0 m) Lower Toarcian; Ciechocinek Formation; **overburden:** claystones and siltstones

770.0–855.0 (85.0 m) Upper Pliensbachian. Domerian; Komorowo Formation (Upper Sławęcin Beds); **aquifer 2:** sandstones (80% with claystone and mudstone intercalations)

855.0–920.0 (65.0 m) Lower Pliensbachian-Upper Sinemurian; Łobez Formation + Ostrowiec Formation pars (=Main Sławęcin Beds); claystones, siltstones and sandstones

920.0–1280.0 (360.0 m) Lower Sinemurian-Hettangian; Ostrowiec Formation pars + Skłoby Formation (Ksawerów Beds+Upper Kłodawa Beds)

1280.0–1947.5 (667.5 m) Upper Triassic; Rhaetian-Norian-Carnian; Upper Keuper

1947.5–2427.0 (479.5 m) Middle Triassic

1947.5–2042.0 (94.5 m) Ladinian; Lower Keuper (Sulechów Beds)

2042.0–2293.0 (251.0m) Muschelkalk; Ladinian-Anisian

2293.0–2427.0 (134.0 m) Upper Buntsandstein; Röt; Olenekian; Barwice Formation; **overburden**: claystones and siltstones with sandstone, limestone and evaporite interbeds

2427.0–3255.0 (828.0 m) Lower Triassic; Scythian: Olenekian-Induan

2427.0–3009.0 (582.0 m) Middle Buntsandstein; Olenekian; Połczyn Formation (mudstones) and Pomeranian Formation (=claystones); **overburden:** claystones and siltstones

3009.0–3255.0 (>246.0 m) Lower Buntsandstein+lowermost Middle Buntsandstein; Induan (Baltic Formation; sandstones); **aquifer 3:** sandstones (60%) with claystone and siltstone interbeds