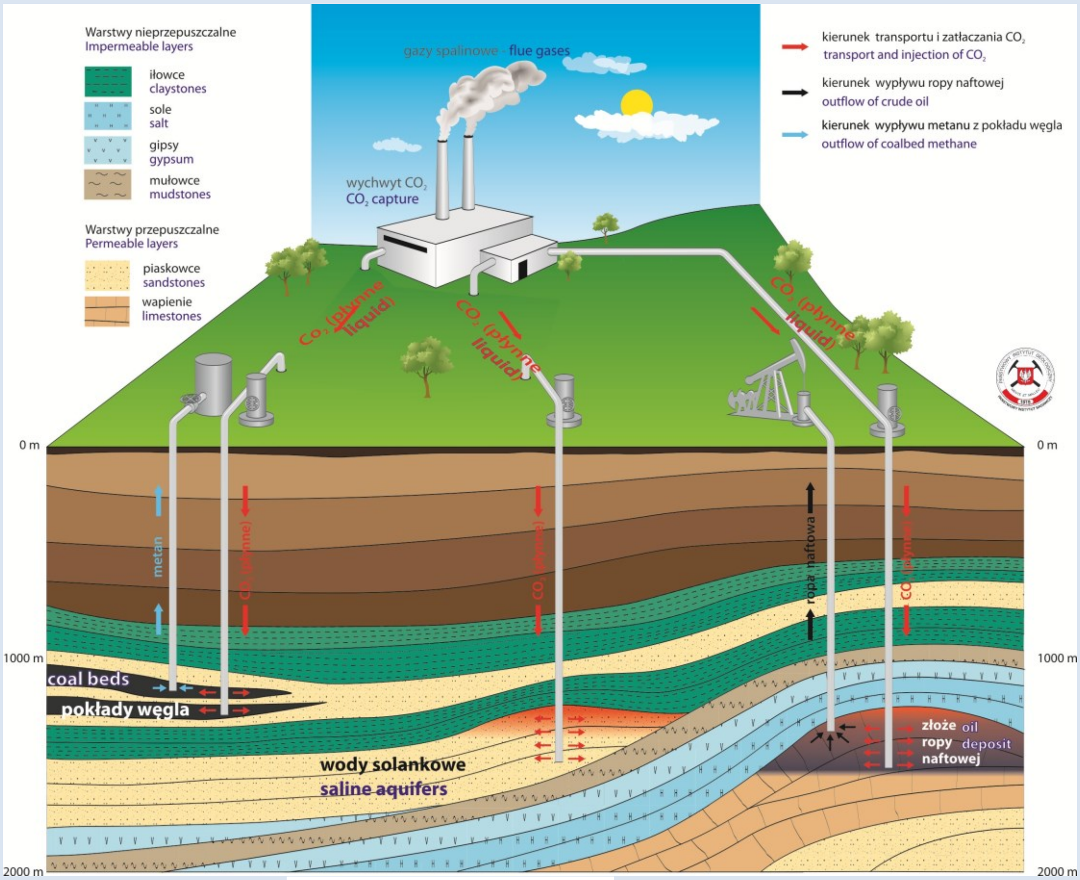
ASSESSMENT OF FORMATIONS AND STRUCTURES SUITABLE FOR SAFE CO_2 GEOLOGICAL STORAGE *(IN POLAND)* INCLUDING THE MONITORING PLANS

(SUMMARY)



MINISTERSTWO
ŚRODOWISKA

ORDERED BY MINISTRY OF ENVIRONMENT,
FINANCED BY NATIONAL FUND OF ENVIRONMENT
PROTECTION AND WATER MANAGEMENT

Warsaw 2014

MINISTERSTWO
ŚRODOWISKA

ORDERED BY MINISTRY OF ENVIRONMENT,
FINANCED BY NATIONAL FUND
OF ENVIRONMENT PROTECTION
AND WATER MANAGEMENT

ASSESSMENT OF FORMATIONS AND STRUCTURES SUITABLE FOR SAFE CO_2 GEOLOGICAL STORAGE *(IN POLAND)* INCLUDING THE MONITORING PLANS

(SUMMARY)

THE PROJECT CONSORTIUM

Warsaw 2014

Editors:

Adam Wójcicki (PGI-NRI & overall)

Stanisław Nagy (AGH-UST)

Jan Lubaś (INiG)

Jarosław Chećko (GIG)

Radosław Tarkowski (MEERI PAS)

Review:

Jan Szewczyk (the entire final report)

Tadeusz Peryt (collaboration)

Technical elaboration:

PGI-NRI

Table of Contents

1. INTRODUCTION

The objectives of the project have been related to the state strategy of Clean Coal Technologies in the part referring to the EU directive on the geological storage of CO_2 (“the Directive of the European Parliament and of the Council 2009/31/EC of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013 / 2006” – the CCS Directive) and liabilities of our country resulting from the implementation of the Kyoto Protocol, and further steps taken by the EU towards reducing CO_2 emissions.

These objectives have been concerned in the first instance to identify and assess the geological formations and structures suitable for geological storage of CO_2 from large industrial emission sources. The results of the study were to be used for the purposes of CCS demonstration projects of zero-emission power plants till 2015 horizon (at the start of the project, in 2008, two such projects had been planned in Poland - PGE Belchatów and PKE & ZAK Kędzierzyn, then only PGE project started), entities applying for permission to build new "CCS ready" power blocks, required to identify potential CO_2 storage sites and provide pre-feasibility studies, commercial CCS installations planned for construction after 2020+, and by research institutions.

The subject of this project included:

- Summary of the current state of knowledge on the geological sequestration of CO_2, taking into account previous studies and projects (in Poland, Europe and world-wide);

- Consulting for the Ministry of the Environment regarding the implementation of the CCS Directive;

- Assessment of geological formations and structures suitable for geological storage of CO_2 from industrial emission sources with an estimate of national needs and capabilities of geological storage of CO_2;

- Integration of results and plans for research and development in the field of geological CO_2 sequestration conducted in Poland and the cooperation with European geological surveys and other key stakeholders in this field in Europe and around the world;

- Development of multi-variant (alternative) scenarios of geological sequestration of CO_2 for the purposes of CCS demonstration projects of power plants with reduced CO_2 emissions and possibly other CCS installations;

- Development of monitoring programs for selected geological structures.

Geological storage of carbon dioxide

(Adam Wójcicki)

CO_2 injection into the geological formations is used for nearly 40 years in the oil industry, such as enhanced oil or gas recovery (Lake & Walsh, 2008). New is rather a combination of capture of CO_2 from the combustion of fossil fuels in power plants or other large industrial installations and transport for storage in geological formations and structures of adequate capacity (hence the acronym **CCS** - called Carbon Capture and Storage, or capture and storage of carbon dioxide).

Carbon dioxide is present in the natural geological accumulations or "storage sites" millions of years of age, like oil and natural gas fields, which may contain dozens or even hundreds of millions of tons of CO_2, and are sometimes exploited for commercial purposes (e.g., in the food industry). As examples from Europe one can provide CO_2 fields Vichy St. Parize and Montmiral in France, Vorrderhoehn in Germany, Florina in Greece, Latera in Italy and Mihályi in Hungary. The largest such fields, containing hundreds of millions of tons of carbon dioxide are present in the United States: McElmo Dome, Sheep Mt., Bravo Dome, Jackson Dome, LaBarge and StJohns-Springville (SRCCS IPCC, 2007). This demonstrates the stability of the natural "storage sites" of carbon dioxide, which exist for millions of years.

With the present state of knowledge in the field of reservoir geology, we know what geological structures may be suitable for the storage of anthropogenic carbon dioxide. Above all, they must be natural traps, which means a system of geological layers to prevent the escape of the injected fluid - usually these are structural highs, so called anticlines. The IPCC SRCCS report, 2007 shows the three main types of geological structures (options of geological storage of carbon dioxide) suitable for this purpose, in order of their potential for geological storage of CO_2 (this situation also applies to our country - Wójcicki, 2008):

- Deep-saline aquifers (depth> 800-1000 m), where reservoir rocks (reservoirs) are mostly sandstones. Large structures of this type are also found in Poland, and their storage potential is huge, enough to "accommodate" emissions of biggest power plants over the life of the installation (reaching even hundreds of millions of tons for individual structures). Unfortunately, since they were not the subject of exploration for oil, gas and other raw materials, they are often poorly explored. In addition, there is virtually no different uses for these structures, and the potential conflicts of interest in connection with their use can occur practically only in the event a geothermal plant is planned for the same location as the geological storage of CO_2.

- Fully or partially depleted oil and gas fields. These structures are generally well explored and considered safe traps for the storage of carbon dioxide, as they retained oil, gas, and sometimes accompanying CO_2 for millions of years. In the case of oil fields, production by standard techniques usually leaves most of the resources in the reservoir and hence the injection of carbon dioxide is to be applied for enhanced oil recovery (EOR - Enhanced Oil Recovery), which gives a substantial economic effect, or in case of gas (EGR - Enhanced Gas Recovery). This technology is particularly well developed in the U.S., where about 3,000 km of pipelines are used to transfer CO_2 to assist in oil recovery processes. In Poland such fields are generally too small for the needs of power plants and other large emittants, while some of the fields may be appropriate to the needs of medium-sized emittants.

- Deep un-mineable coal seams containing methane. Carbon dioxide injected into these beds is absorbed better by coal than methane and as a result the natural methane gas is released. The effectiveness of this method of production of methane from coal beds is much higher than the classical methods, and hence we talk about production enhancement (CO2 - ECBMR - Enhanced Coalbed Methane Recovery), which is of significant economic importance. Particularly favorable geological and reservoir conditions are in the San Juan coal basin in New Mexico, USA, where this technology has been deployed in small-scale demonstration projects (Davis et al., 2004). In Poland, one can practically take into account only the seams in the Upper Silesian Coal Basin, but in our geological conditions (different from those in the U.S.), this technology is currently too immature in terms of commercial application and can bring conflicts of interest (on exploitation/gasification of deep, currently un-mined coal beds).

Carbon dioxide is a gas under normal conditions, with a density of about 2 kg/m^3. In the deeper geological formations its properties change significantly, depending on the reservoir temperature and pressure occurring there. From hitherto experiences we know that for geological storage high-density supercritical phase is preferred (**Fig. 1_1**), or liquid phase (liquid under supercritical pressure > 7.38 MPa), but in any case it cannot be two-phase area or gas phase, because then dioxide carbon has a much higher volatility and mobility.

For the temperature of 31.1 °C and a pressure of 7.38 MPa, so called critical point can be distinguished on the diagram (**Fig. 1_1**) where four states (phases) of CO_2 meet.

Depending on the reservoir temperature and pressure that occur in the storage formation, it is assumed that the minimum depth of location of the saline aquifer or hydrocarbon field, suitable for geological storage of CO_2 is 800-1000 meters, because at this depth the density of the injected carbon dioxide is hundreds of times higher than in normal conditions (i.e., it is present in the supercritical phase, or possibly a liquid, if the local geothermal gradient is low, but we prefer the supercritical phase; in both cases the pressure exceeds 7.38 MPa). In the case of coal beds, this criterion can also be used, although sometimes shallower layers, for which the mining operation is unprofitable, are considered (in China). Maximum depth is related to the reservoir properties of the storage formation – it is generally accepted that for depths greater than 3000 meters injection is unprofitable (in the case of depleted gas fields, for which we can use the existing wells, the lower limit of the geological storage is only determined by reservoir properties - in some cases this depth may even be greater than 3000 meters). Of course, for the poorer reservoir properties (including permeability) this depth will be less, even up to 2000 meters.

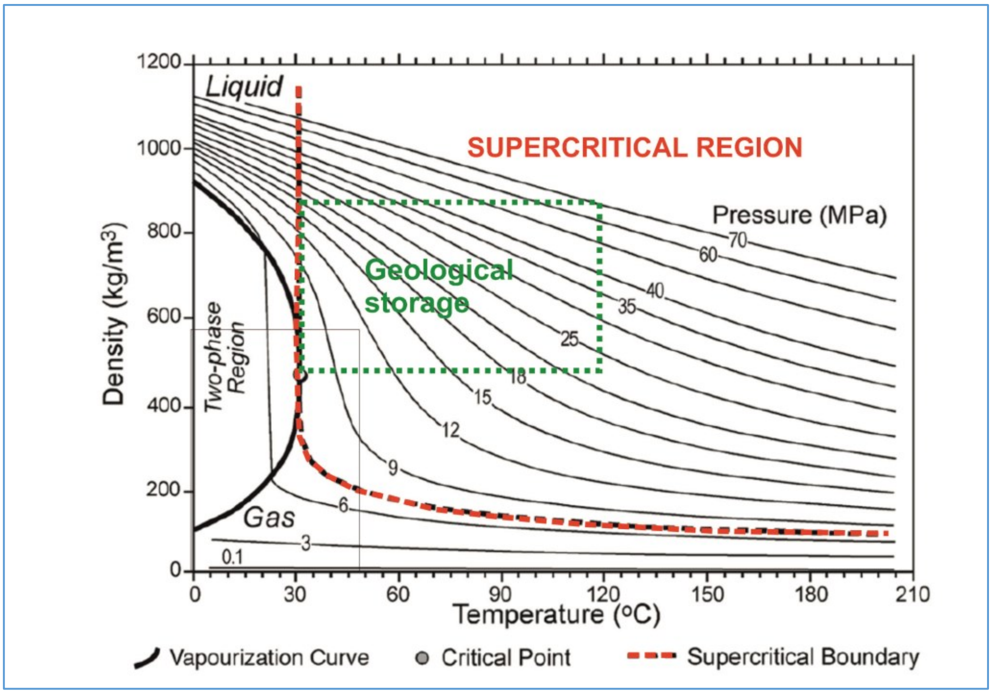


Fig. 1_1 Physical properties of carbon dioxide important for geological storage (based on IPCC SRCCS report, 2007)

For typical values of the geothermal gradient (i.e., the rate of increasing temperature with respect to increasing depth in the Earth's interior), the depth range in question corresponds roughly to the reservoir temperatures from 30 to 120 °C (**Fig. 1_1**). The density of carbon dioxide is in this case from 500 to 900 kg/m^3, depending on the reservoir pressure. It should be noted that the rectangle corresponding to the intervals of both physical parameters indicated in **Fig. 1_1**, is purely indicative, often due to the significant differences in the reservoir pressure and temperature within the structures occurring at similar depths.

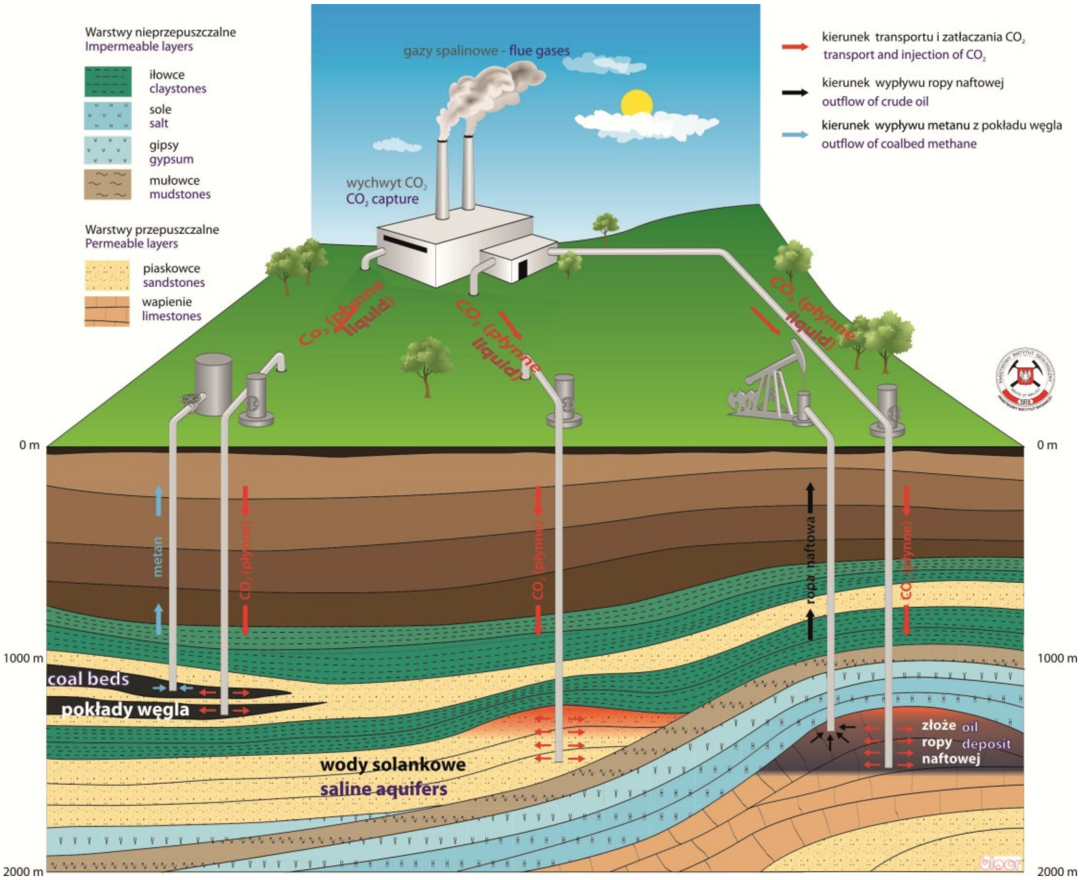


Fig. 1_2 Options of CO_2 geological storage - the most important option is saline aquifers, the second - hydrocarbon fields (oil and/or natural gas), the third - the deep coal seams containing methane (PGI-NRI, 2009 - "Climate and coal" exhibition).

In summary, the structures like either saline aquifers or depleted hydrocarbon fields and the deep un-mineable coal seams containing methane (in Poland, to a lesser extent), may be suitable for geological storage of anthropogenic carbon dioxide (**Fig 1_2**). For saline aquifer structures the reservoirs should be present in an indicative range of depths from 800-1000 m to 2000-3000 m (depending on the geological and reservoir conditions). Obviously this is not the only criterion. Very important are the parameters of the storage formation (thickness, permeability, porosity or fracturing), and - the quality of the seal, i.e. the integrity and thickness of the caprock (see also next chapter).

In case of depleted (depleting) hydrocarbon fields, most of these criteria is fulfilled by definition, because if the exploitation of the field was possible, it must have locally good reservoir properties, including porosity, permeability and thickness of the reservoir. The hydrocarbons are generally accompanied by brine (underlying formation water), and the presence and quality of the caprock is a principal condition for the existence of the oil or gas field. However, in Poland there are no fields large enough to accommodate largest power plant emissions in a single hydrocarbon field - this is only possible for smaller industrial plants and possibly (smaller) single blocks of big power plants.

Carbon dioxide storage in saline aquifers and depleted hydrocarbon fields is associated with the following physico-chemical mechanisms (Chadwick et al., 2008; SRCCS IPCC, 2007 report – **Fig. 1_3**):

- migration of CO_2 due to pressure increase caused by the injection, natural hydraulic gradient within the reservoir and in response to its buoyancy (because it is less dense than the formation water – Archimedes law) is prevented by structural and stratigraphic barriers (*structural & stratigraphic trapping*),

- trapping of CO_2 in pore space by capillary forces and adsorption onto the surfaces of mineral grains (*residual CO_2 trapping*),

- dissolution of CO_2 in formation waters (*solubility trapping*),

- geochemical trapping of CO_2 dissolved in brine (formation water) which reacts with the minerals making up the rock matrix of the reservoir (*mineral trapping*),

- diffusion and dispersion of CO_2 (not presented in **Fig. 1_3**; takes millions of years and covers a small percentage of the injected CO_2).

In practice, the calculation of the CO_2 storage capacity mostly takes into account the first mechanism, due to the fact that the other occur within a much longer period of time, and their contribution is much lower. During operation of the power plant with CCS (and shortly after the CO_2 injection stops), i.e., for decades, only a third mechanism - dissolving in the formation waters - can noticeably increase the efficiency of sequestration. It is estimated that this mechanism gives about 5 - 20 % more storage capacity in saline aquifers (for the formation waters with high salinity, i.e., with salinity of up to hundreds of g/l, it provides a smaller contribution than for the less saline formation waters, i.e., of salinity of up to tens of g/l). The residual CO_2 trapping has scarcely a significant share until many years after the injection stops. Other mechanisms (mineral trapping, diffusion and dispersion) provide contributions of further orders of magnitude smaller, in ever longer time periods.

It should be noted that considerable amounts of carbon dioxide are dissolved in the formation waters (i.e., occurring there naturally, among other substances, mainly sodium chloride). For example, in saline aquifers of Polish Lowlands, between depths of 1-2 km, according to the information collected in the hydrogeological atlas (Bojarski, 1996), the average CO_2 content in the brine is of about 0.5 g/l, which gives for the entire area of Polish Lowlands many billions of tons of carbon dioxide. However, the amount of carbon dioxide trapped in carbonate rocks and minerals within this depth range is far greater. In turn, just below the ground surface the carbon dioxide concentration in soil (soil gas) exceeds tens and hundreds of times the atmospheric concentration (IPCC SRCCS, 2007) and significantly fluctuates from season to season, which is caused by biochemical processes (vegetation, microbial activity, etc.).

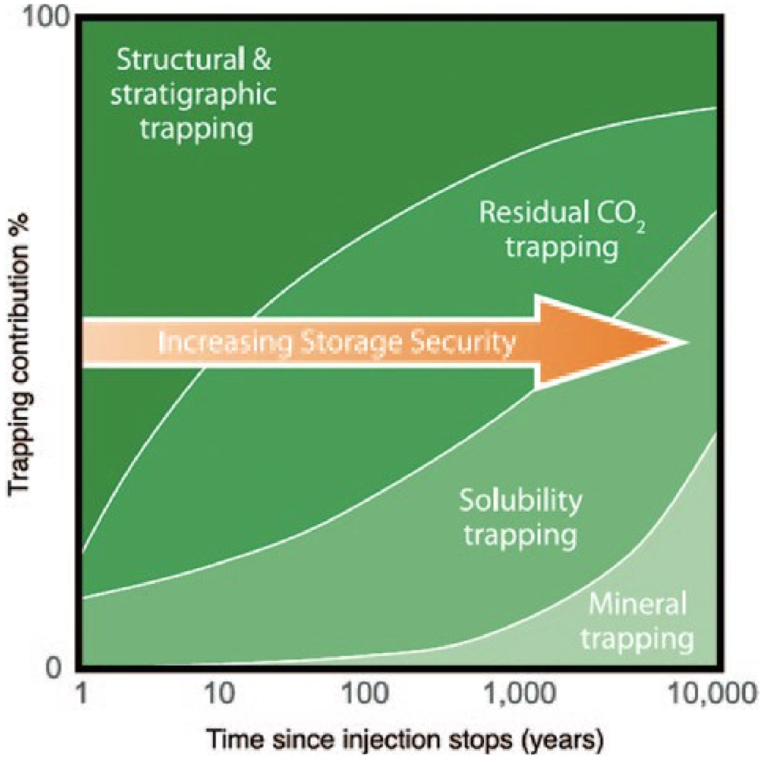
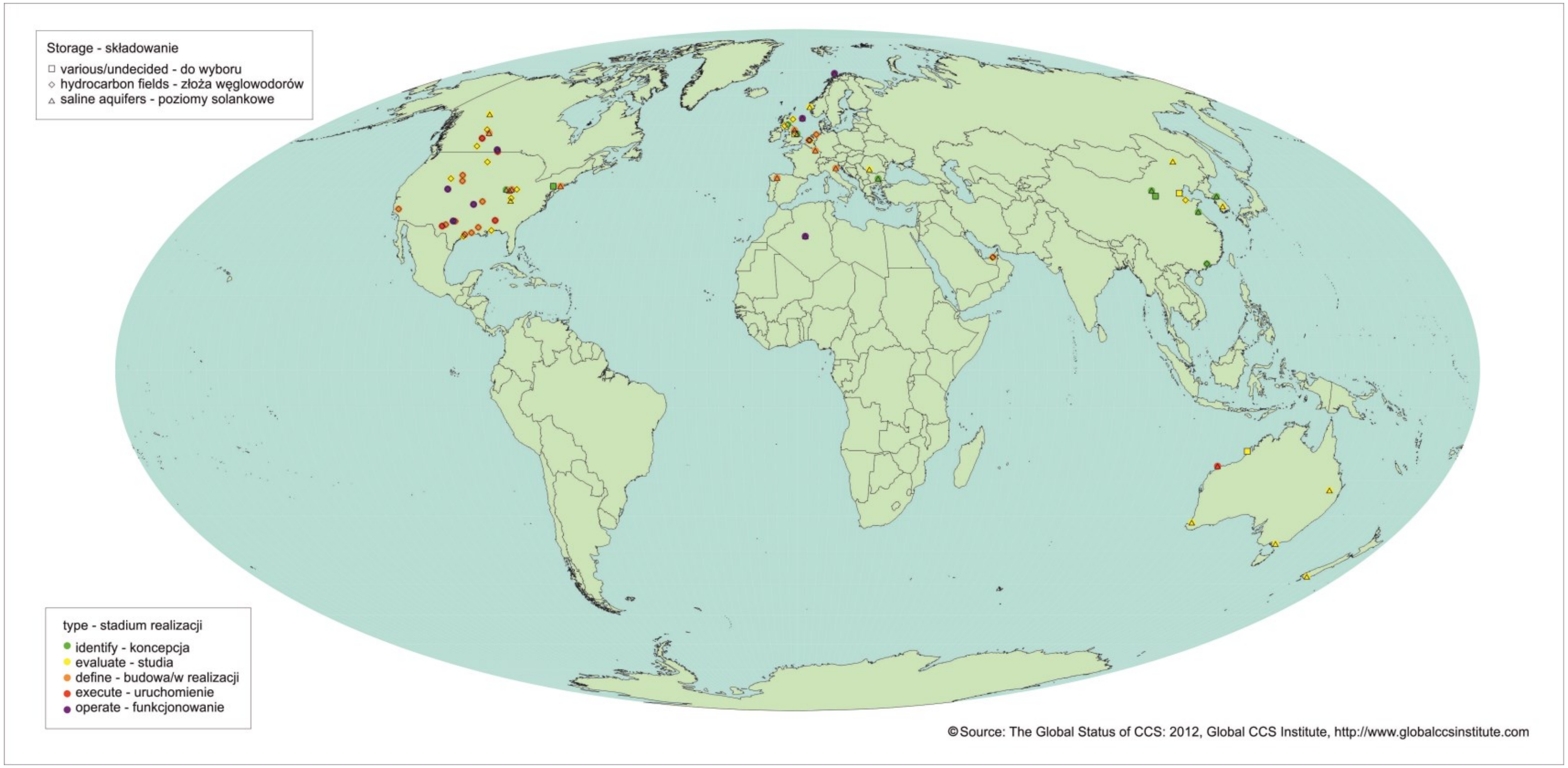


Fig. 1_3 Evolution of CO_2 trapping mechanisms – their share over time (vertical axis) since injection stops (IPCC SRCCS, 2007 report); see also explanations above.

Regarding the progress of CCS in the world, according to the Global CCS Institute in 2012 more than 70 major projects have been listed (injection of the order of 1 million tons per year), being in various stages of development (**Fig. 1-4**). Of these 8 are fully operational (5 of them are EOR projects - including the Weyburn-Midale and 3 include storage in saline aquifers - Sleipner and Snøhvit under the North Sea and the Barents Sea and In Salah in the Sahara), and 7 is in the start-up or execution phase (5 EOR projects and two in saline aquifers - in the U.S. and Australia onshore). In Poland the initial phase of the CCS demo project of PGE Bełchatów was carried out (2009-12; canceled in 2013), as one of six projects funded by EEPR (European Energy Programme for Recovery) and the project of a polygeneration plant in Kędzierzyn was planned (till 2010).

Moreover, in Europe and all over the world operates a number of pilot projects of CO_2 injection into geological structures onshore (e.g., Ketzin in Germany, Lacq in France, Otway in Australia; GCCSI, 2012).

Polish experiences in the field of pilot projects include the injection of acid gas (60% of CO_2, 15% H_2S, the rest is heavier hydrocarbons; in the period 1995-2010 several thousand tons of acid gas was injected) which was a product of the purification of natural gas in Borzęcin gas field near Trzebnica in Lower Silesia (Lubaś & Szott, 2010) and the experiment of injection of a few hundred tons of CO_2 into coal seams, together with a comprehensive monitoring (2004-2008), in the region of Kaniów near Bielsko-Biała in Upper Silesia (Jura et al., 2007; Pagnier et al. 2003).



©Source: The Global Status of CCS: 2012, Global CCS Institute, http://www.globalccsinstitute.com

Fig. 1_4 Status of CCS worldwide - large integrated projects (injection of CO_2 in the order of 1 million tons per year) after Global CCS Institute, 2012, updated

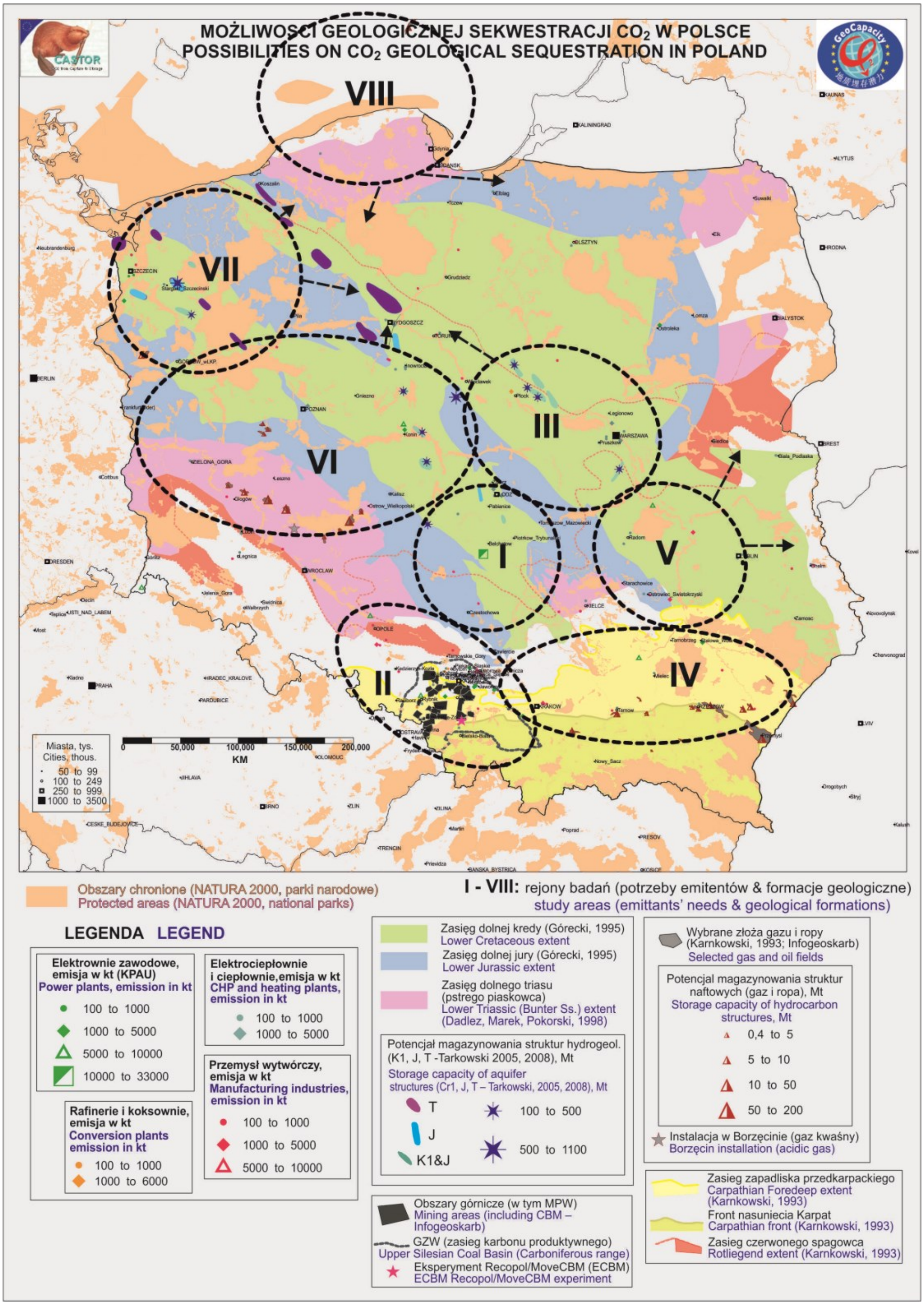


Fig. 1_5 State of knowledge about possibilities of CO_2 geological storage in Poland at the beginning of the project

2. THE SCOPE AND METHODOLOGY

(Adam Wójcicki)

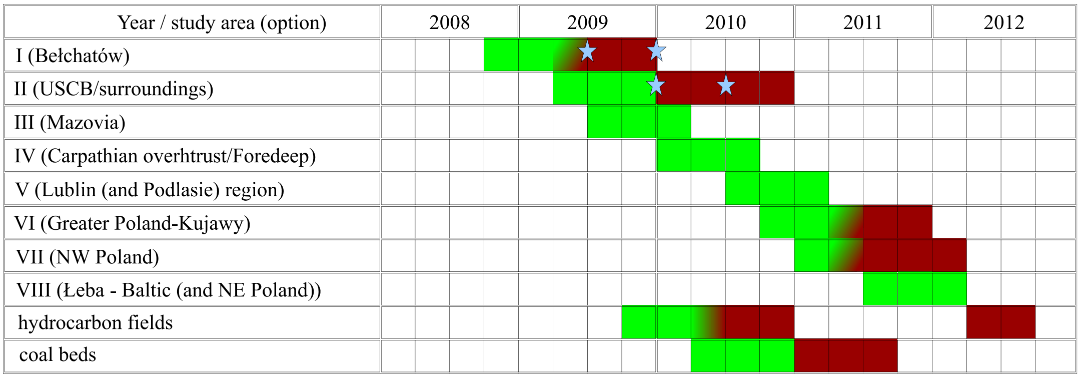
The scope of work covered by the contract has been essentially composed of two mutually overlapping segments (regional studies and case studies, see also **Fig 2_1** and **2**).

Due to the size, objectives, level of complexity and participation of institutions representing various domains, having some experience about the geological storage of CO_2 and related issues, this project was a subject to prolonged consultations between the contractors and the customer (Ministry of Environment, but also energy companies associated with the Ministry of Economy were interested in the project implementation). Its workplan had been amended several times, in relation to the needs of the two Polish demonstration projects (PGE Bełchatów and PKE-ZAK Kędzierzyn) supported then by the Polish government.

The regional studies covered the entire territory of Poland (**Fig. 1_5**); in particular the studies for saline aquifers in eight regions of the country (marked with Roman numerals I-VIII in **Fig. 1_5**; Permian-Mesozoic formations in four study areas: Bełchatów, Warsaw (Mazovia), Greater Poland-Kujawy and NW Poland; Paleozoic formations of USCB and its surroundings; Paleozoic formations of Lublin (and Podlasie) region; Paleozoic formations of Łeba elevation, together with the neighboring area of the Polish economic zone of the Baltic Sea and **a part of NE Poland**; Mesozoic and Paleozoic formations of the basement of the marginal zone of the Carpathian overthrust and the Carpathian Foredeep) and the other two options of CO_2 geological storage (depleted and uneconomic hydrocarbon fields, mainly in the west and SE Poland; deep un-mineable coal beds, mainly in the Upper Silesian Coal Basin).

The case studies included the development of multi-variant (alternative) scenarios of geological sequestration of CO_2 for potential underground storage sites (located within a radius of 80 km from existing or planned energy installations) in saline aquifers - in the region of Bełchatów, the region of Upper Silesia and the region of Greater Poland and NW Poland; in depleted gas and oil fields - a gas field in western Poland and an oil field and a gas field in the SE part of Poland; and a site in coal beds in the southern part of Upper Silesia; in total 8 scenarios (see also **(Fig. 2_3**, where localization of the potential storage sites selected for the case studies is indicated, as well as the other selected structures and geological formations are presented). As a priority two scenarios for the purposes of the zero-emission demonstration power plants, whose projects were submitted in 2008 to the Ministry of Economy by Polish energy companies (BOT/PGE Bełchatów for the Bełchatów region and PKE for the region of Upper Silesia) were implemented.

The scope of work provided for the case studies was referring to the requirements of the Directive on the geological storage of carbon dioxide (**2009**). It imposes very strict requirements regarding the assessment of possibility of using geological formations or structures as potential storage sites (i.e., construction of static and dynamic models, risk analysis, monitoring plans), not only for the purpose of obtaining a storage permit, but even in case of an exploration permit. According to Annex 1 of the Directive, for the potential storage site an assessment must be made, using results of new surveys at the potential storage site and / or any available archive materials, specifying in particular the impact of geological storage of CO_2 on the environment.



light green color denotes regional studies, **brown** - case studies
☆ implementation (interim) reports

Fig. 2_1 The indicative timetable for the project

According to the indicative schedule (**Fig. 2_1**) the regional studies were carried out for various areas and options. In the first half of the project the implementation (interim) reports were required, due to the then needs of national demo projects (Bełchatów, Kędzierzyn), to be used by those projects that applied or intended to apply for EU funds. The CCS demo project of PGE Bełchatów was being implemented by the end of this study (due to financial problems, the board of PGE tried by all means to withdraw from the project, which took place at the end in March 2013) and on the basis of a cooperation agreement, PGE was supplied with all the information and data they needed.

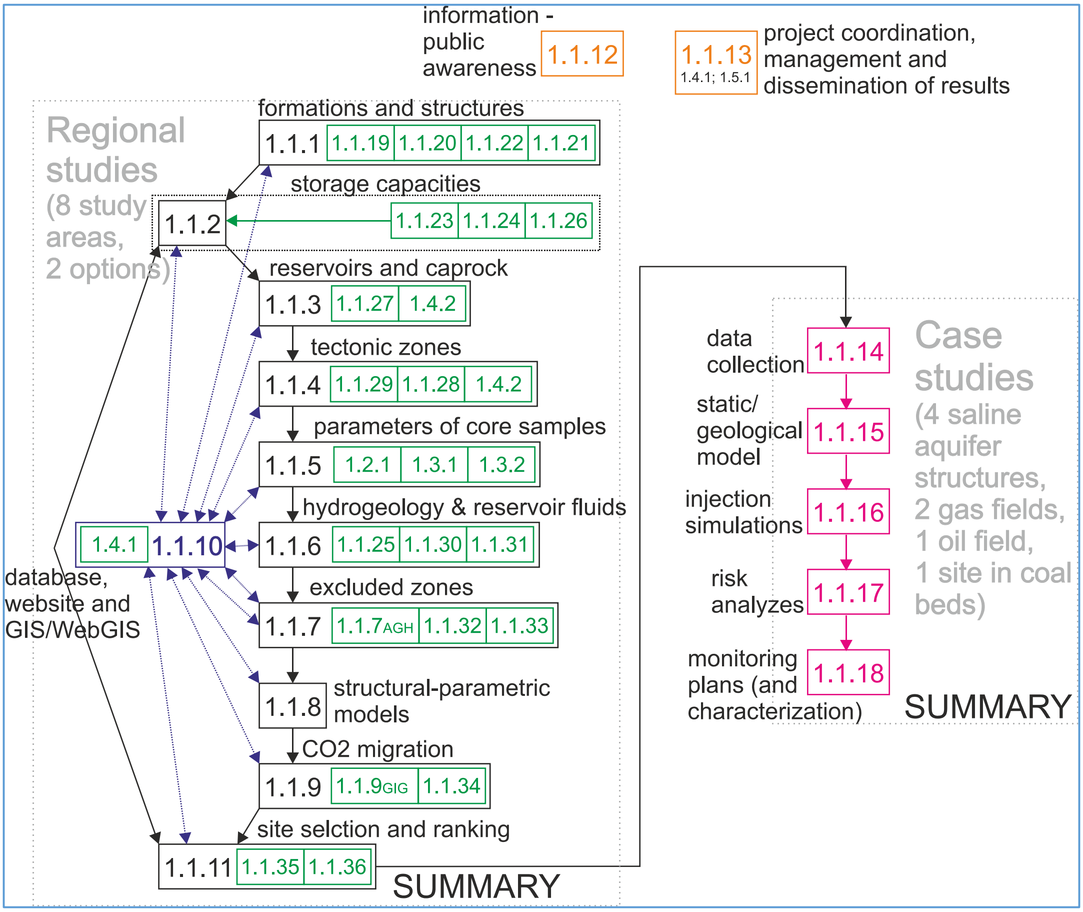


Fig. 2_2 The project structure

In **Fig. 2_2** the structure of the project is shown, implicating general principles of the methodology of the regional studies and the case studies, including the following work packages:

1.1.1 Inventory of the current state of knowledge regarding the formations and structures which can be used for CO_2 sequestration, a preliminary verification (using the CO_2STORE criteria, for saline aquifers, as well as assumptions for other storage options). In the case of saline aquifers MEERI studies (1.1.19, 1.1.23) served as a preliminary step in this and the next work package.

1.1.2 Storage capacity assessment for Poland (updating/verification of the initial state of knowledge - 1.1.1, while new information provided by other work packages is gathered, however this work package was concluded simultaneously with the entire scope of the regional studies).

1.1.3 Facies - reservoirs and seals/caprock. This included the well correlations for prospective formations and structures (selected in 1.1.1), the interpretation of seismic data (correlation of horizons, and a limited number of analysis of seismic attributes, due to a poor quality of the most of the available seismic data).

1.1.4 Tectonic zones - analysis of integrity, i.e. the answer to the question whether the fault zones may be CO_2 escape paths out of the storage complex.

1.1.5 Petrological (mineralogical composition, including the cement/rock matrix) and petrophysical parameters (porosity, permeability, and integrated analyzes - CO_2 viscosity, brine displacement within the reservoir model). A quite extensive laboratory analyzes of the available core samples were carried out and useful archive date were collected (for this project and possible further research).

1.1.6 The hydrogeological parameters, including the composition of formation water - for example, the share of individual ions, as an indicator of the possibility of brine - freshwater contact (e.g., whether infiltration within the structure took place recently, or many thousands of years ago, or whether the mixing of fresh waters and brines took place in the framework of flows within the regional aquifer), especially in the case of regional potable aquifers, and mineralization of formation water. In addition, this work packed covers the problem of formation fluid/CO2-rock reactivity.

1.1.7 This is a summary of sorts, where available information on possible contraindications to the use of the structure or the formation for sequestration, because of various reasons (geological and reservoir conditions, protected areas, potable aquifers, exploration and production licenses for the subsurface resources, population centers) is analyzed. The presence of old wells requires, in turn, to assess whether they need to be re-cemented (but as there are no wells within the structure, we do not know much about the subsurface there).

1.1.8 The structural-parametric models of the formations of the particular study areas - depending on the available data, the quality and human resources, models of varying complexity were constructed.

1.1.9 Hydrogeological models of regional propagation of CO_2 - depending on the available data and their quality, models of varying complexity were constructed. For example, in the area of the northern Poland (the study areas VII and VIII) the work was limited to the construction of the model of Lower Triassic reservoir, and the Cambrian aquifer onshore has been so far very poorly explored by seismic, though the exploration of unconventional hydrocarbons is slowly changing this.

1.1.10 The database and the GIS/WebGIS application (the latest on the project website). The database was used for the needs of contractors implementing the project.

1.1.11 Site selection and ranking of structures - which structures would be better suitable, which worse, or not at all, for the potential CO2 storage sites (in the light of current knowledge) and why. A summary of the results of the entire regional studies is also included there.

1.1.12 Elaboration of information for the purposes of public awareness of CCS, participation in seminars with representatives of local communities.

1.1.13 Co-ordination, project management, dissemination of results, including contacts with domestic and abroad R&D actors, and industrial partners, consultations with the Ministry of Environment on the implementation of the CCS Directive, etc.

1.1.14 (Case studies) Data collection for the site and its surroundings, i.e. storage complex, essential for the construction of detailed geological models and simulations of injection.

1.1.15 The static characteristics of the storage complex, i.e. building its three-dimensional structural-parametric model of geological reservoirs, caprock and the hydraulically connected areas (WP 1.1.14 and 15 are analogous to WPs 1.1.1-1.1.8 of regional studies).

1.1.16 Computer models (simulations) of the dynamic processes of injecting carbon dioxide into the storage site using the above, static models, characterizing effectiveness and safety of storage (and trapping) in the short and long-term perspective.

1.1.17 Risk management for CO_2 geological storage, including sensitivity of the simulation results to changes in various input parameters, the risk assessment for geological storage of carbon dioxide and the associated hazards and effects for humans and the environment, together with proposing scenarios of their minimization (after Quintessa FEP database or requirements of the NER300 program).

1.1.18 Monitoring plans for the storage complex of carbon dioxide (baseline/storage site characterization, during and after injection), referring to the risk analyzes, including proposals of geophysical and (bio)geochemical surveys, as well as assumptions for the CO_2 test injection. This work package also includes a summary of the outcomes of the case studies.

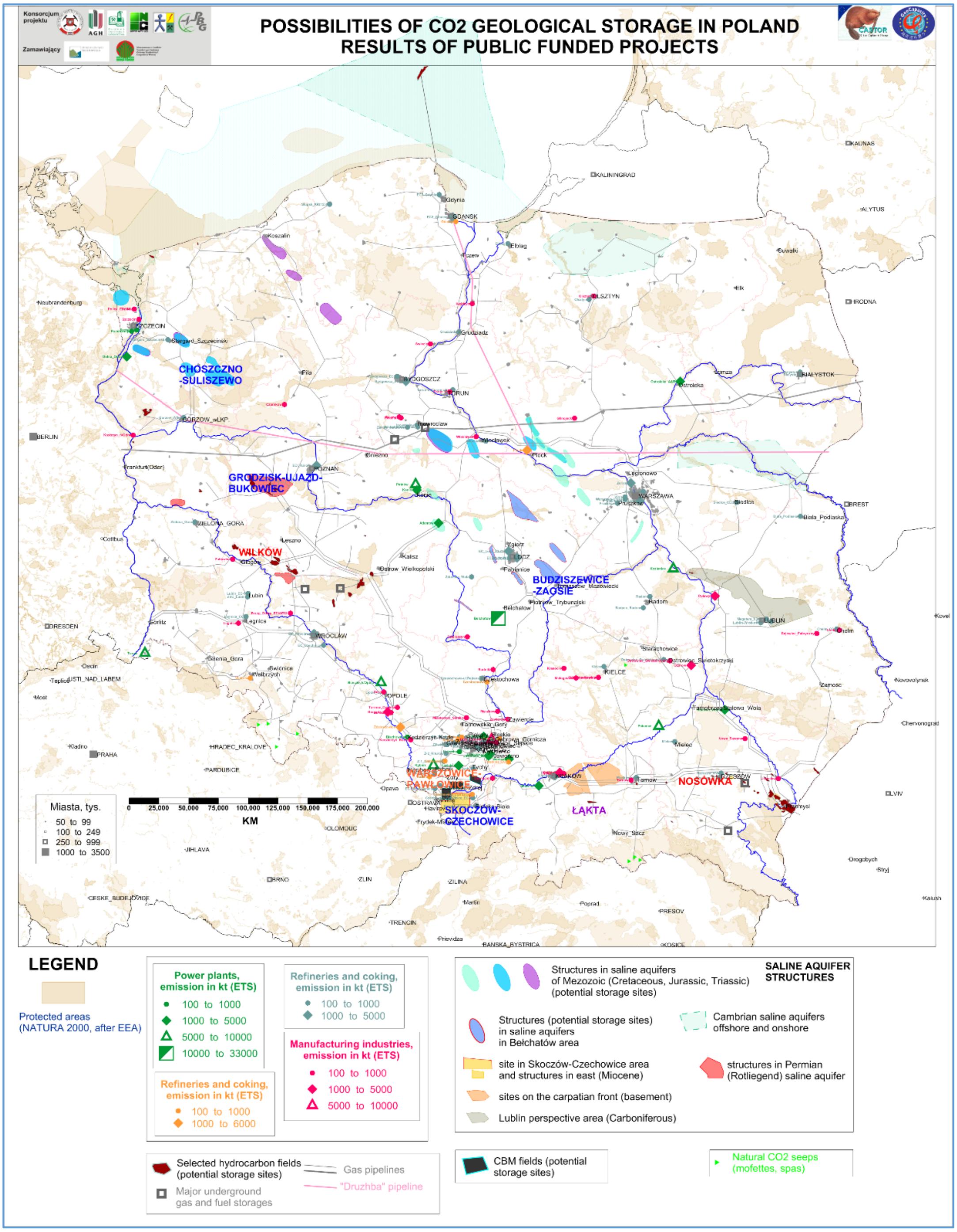


Fig. 2_3 The potential storage sites selected for the case studies (saline aquifer structures Budziszewice-Zaosie, Skoczów-Czechowice, Grodzisk-Ujazd-Bukowiec, Choszczno-Suliszewo; Nosówka oil field, Wilków and Łąkta gas fields; Warszowice-Pawłowice coal bed site), on the background of emittants, protected areas, pipelines and other sites analyzed in the frames of the regional studies.

Site selection and storage capacity assessment

(Adam Wójcicki, Janusz Jureczka, Radosław Tarkowski, Barbara Uliasz-Misiak, Robert Warzecha, Tadeusz Bromek, Jarosław Chećko, Jan Lubaś, Sławomir Szuflita, Stanisław Nagy, Bartosz Papiernik)

For these regional studies fundamentally the methodological assumptions of the FP6 EU GeoCapacity project (Vangkilde-Pedersen et al., 2009) were used, the scope of which included the assessment of the possibility of geological storage of CO_2 in Europe, together with the preliminary estimate of the potential of geological storage for formations and structures in saline aquifers, hydrocarbon fields and coal beds. This project has utilized and recommended methodologies developed under several previous projects. On the other hand, the basis for the case studies were the requirements of the CCS Directive (specifically Annex 1 and part of Annex 2).

Structures and formations in saline aquifers

Based on the Best Practice Manual for the geological storage of CO_2 in saline aquifers (CO_2STORE project - Chadwick et al., 2008), it was assumed the following optimal criteria are to be met by the geological structures - potential storage sites for large CCS projects, i.e. of the stream of CO2 injected of order of magnitude of million tons per year:

1. Storage Capacity of the structure much larger than the total emissions of the industrial plant.

2. Reservoir depth; the minimum depth of 800 m (CO_2 does not occur in the supercritical/liquid phase above), the maximum depending on the reservoir properties - up to 3000 m.

3. Reservoir thickness (net); a minimum of 20 m, better at least 30 m or more.

4. Reservoir porosity; a minimum of 10% (in case of a porous-fractured reservoir wherein hydrocarbon fields occur in the same formation, confirming reservoir properties are sufficient, it may be less), ideal 20% or more.

5. Reservoir permeability; a minimum of 10-100 mD, better at least 300 mD.

6. Salinity (TDS), a minimum of 30 g/l (= the lack of contact of brine with freshwater; if we know from other evidence that no such a contact takes place, the minimum value may be lower).

7. Caprock (seal) unfaulted, impermeable, with a thickness of at least 50 m, optimally more than 100 m (the value is 50 meters for the primary seal above the reservoir is

safe; the integrity of the seal is very important, and the occurrence of secondary sealing complexes above is desirable).

In addition to the mentioned above geological and reservoir conditions, the selection and ranking of structures and formations in saline aquifers depended on whether protected areas, potable aquifers, licenses for exploration and production of the subsurface resources and population centers occur in their areas as well as the presence of CO_2 emitters in the vicinity of the structure.

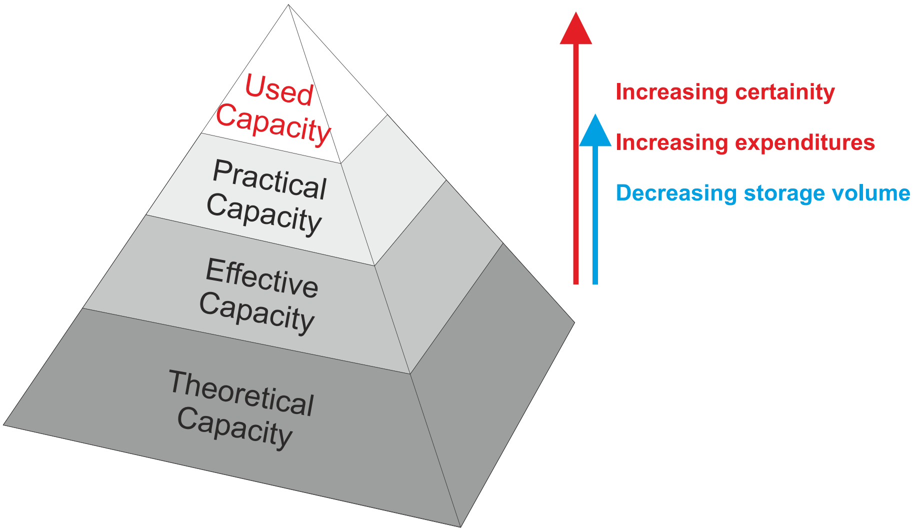


Fig. 2_4 Storage potential pyramid for the key storage option - saline aquifers (based on Bachu & Adams, 2003 and CSLF - see also Vangkilde-Pedersen et al., 2009)

As in the case of assessment of energy, mineral or thermal water resources, there are also different categories of "resources" - storage capacity/potential in case of CO_2 sequestration. After the EC funded EU GeoCapacity project (Vangkilde-Pedersen et al., 2009), the following categories of resources - storage capacities, depicted in **Fig. 2_4**, have been assumed:

- theoretical storage capacity is the total amount of CO_2 that can be accommodated in the entire pore volume of a given geological unit, within the considered depth range (free phase and CO_2 dissolved in the reservoir fluids until the maximum saturation is reached)

- effective storage capacity is a part of the theoretical capacity, constrained by geological and engineering cut-off limits of the estimation of storage capacity, determined generally for individual structures or areas within the geological unit (taking into account their depth, pressure, porosity, content of irreducible formation water in the pores, and in particular, the storage efficiency factor); this is the estimated, static capacity for the regional studies, comprising the volumetric CO_2 storage capacity and capacity resulting from the dissolution of CO_2 in formation water (brine);

- practical storage capacity is the capacity taking into account the technical, economic and legal criteria, and an evaluation of the emission sources relative to storage sites; the (dynamic) capacity obtained as a result of case studies, including specific scenarios for injection, is an equivalent of the practical capacity, though lacking economic analyses.

In contrast, the used capacity is the one that actually is taken by CO_2 injected into the storage site under the CCS project.

As a result of new geological-geophysical surveys the estimates of effective and practical capacity can be reevaluated, because they are based on currently available information.

Hydrocarbon structures (oil and gas fields)

When it comes to the selection and ranking of hydrocarbon structures, the matter is generally simpler than in the case of saline aquifer structures, because we know that the hydrocarbon structure is, by definition, a good trap.

In principle, there are two cases - enhanced recovery of hydrocarbons (mostly, and sometimes exclusively, oil recovery), or only storage of carbon dioxide, in a maximum quantity. The oil field should be big, if possible, moreover the depth parameters, pressure, temperature, composition of crude oil and the production history, which affect the effectiveness of enhanced oil recovery, are important. The main condition consists in the oil field is available for more or less effective enhanced recovery operations in the adequate period of its production history (and whether CO_2 will be available in sufficient quantity and at the right time). Gas field should also be as big as possible, located within a similar depth range as it was assumed for the saline aquifer structures (the depth of the structure top is important - no less than 800 meters, ensuring CO_2 will occur in the supercritical or liquid state) and characterized by good reservoir properties.

Moreover, next to the size of (primary) hydrocarbon reserves and associated storage capacity of the field, the distance from the emittant and the size of its emissions (then the time necessary for the structure to be filled) and the presence of the population centers and protected areas within the structure and its neighborhood, and - obviously - its availability and the degree of depletion are important. Because we have generally small hydrocarbon fields in Poland, after earlier studies (e.g., Wójcicki et al., 2008) an initial criterion for the oil fields has been adopted - the primary recoverable (proven) reserves of a minimum of 100,000 tons, and for the gas fields - the primary minimum recoverable reserves of 400 million m^3.

The basis for estimating the effective, or static, capacity for oil and gas fields in the regional studies was the methodology proposed in the EU GeoCapacity project (Vangkilde-Pedersen et al., 2009) and the GESTCO project (Schuppers et al. 2003), which includes the assumption that CO_2 fills the reservoir volume occupied previously by the extracted hydrocarbons (extracted using the standard technology). On the other hand, the issue of enhanced recovery of hydrocarbons, particularly oil, required rather an estimation of dynamic, or practical, capacities - obtained as a result of simulations of carbon dioxide injection into the field (which was, among others, the subject of the work on case studies for hydrocarbon fields).

Coal beds

Generally, possibilities and the potential of CO_2 storage with methane recovery (CO_2-ECBMR) in deep un-mineable coal seams in the Upper Silesian Coal Basin were analyzed. Other coal basins (Lower Silesian Coal Basin, Lublin Coal Basin) seem to be inappropriate for CO_2 storage due to safety reasons or the status of exploration of CBM resources.

The selection and ranking of prospective areas were made considering the (known) prevalence of coal bed methane (CBM) seams below a depth of 1000 m, the parameters of these seams (thickness, the methane content, permeability, water saturation), tectonics, the presence of impermeable Miocene caprock above Carboniferous, whether the CBM fields exist on large surface areas distant from the active coal mines, and a low degree of urbanization (Jureczka et al., 2011) and environmental impact (protected areas, regional potable aquifers).

In order to estimate the potential of CO_2 geological storage in deep coal beds with methane recovery the methodology used in COALSEQ (Davis et al., 2004), GESTCO (Bergen, Wildenborg, 2002; May, 2003; Tongeren, Laenen, 2001) and EU GeoCapacity (Vangkilde-Pedersen et al., 2009) projects was used, which is based on the estimation of methane content in terms of CO_2-ECBMR technology, and CH_4-CO_2 replacement factor in coal seams.

3. REGIONAL STUDIES

This chapter provides an overview of the most important results of the final report regarding regional studies (Wójcicki [ed.], 2013), including ranking and recommendations of structures of different study areas and options for CO_2 storage.

3.1 Saline aquifers

(Adam Wójcicki, Janusz Jureczka, Anna Feldman-Olszewska, Anna Becker, Józef Chowaniec, Anna Tomaś, Adam Tomaś, Maria Waksmundzka, Hubert Kiersnowski, Krzysztof Leszczyński, Jolanta Pacześna, Grzegorz Wróbel, Teresa Adamczak, Lidia Razowska-Jaworek, Zbigniew Kaczorowski, Jacek Chełmiński, Krzysztof Czuryłowicz, Marta Kuberska, Aleksandra Kozłowska, Marek Jarosiński, Grzegorz Pieńkowski, Radosław Tarkowski, Barbara Uliasz-Misiak, Robert Warzecha, Tadeusz Bromek, Jarosław Chećko, Jan Lubaś, Sławomir Szuflita, Grzegorz Leśniak, Stanisław Nagy, Bartosz Papiernik)

Regional studies included updating and verification of the information developed in the "Interactive Atlas of presenting the possibility of geological sequestration of CO2 in Poland" (Wojcicki et al., 2008), in accordance to the methodology of the EU GeoCapacity project (Vangkilde-Pedersen et al., 2009). They were initiated by MEERI PAS work (Tarkowski [ed.], 2010), as a preliminary step in the analysis (a summary of the current state of knowledge). The following final analyses (the most important results of the chapters of the final report regarding the regional studies - see previous section) included a summary of previously collected and elaborated information, storage capacity assessment, ranking and recommendation of (previously verified) formations and structures in saline aquifers.

The most important information has been included in the GIS/WebGIS application (on DVD and the project website; http://skladowanie.pgi.gov.pl/co2polska/polska.phtml). Shown in the figures below screenshots of the said application (**Fig. 3_1** - **3_49**) are characterizing the location, situation and the basic parameters of the considered formations and structures. For selected structures for which the storage complex is relatively shallow, temperature at the top of the reservoir is specified ("injection points", i.e., existing wells are usually at the top of the structure, in case of major discrepancies, the temperature is specified for the top of the structure, and not for any existing well). Moreover, at the end of this section temperature values (of reservoir tops) for all selected structures are presented in the form of the diagram (**Fig. 3_50**), as well as in **Table 3_3**, which also includes other parameters of these structures.

The section is concluded by the assessment of storage capacities for individual study areas and geological formations and the evaluation of their suitability for safe geological storage of carbon dioxide.

EXPLANATIONS

The following (Polish & English) field codes characterizing the saline aquifer structures for the GIS/WebGIS application have been adopted (for coal and hydrocarbon fields analogous annotation of the basic parameters was assumed):

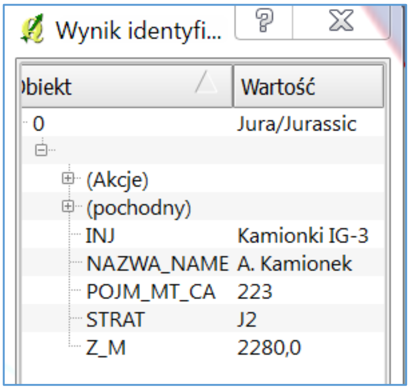
NAZWA_NAME – site/structure name;

STRAT – simplified reservoir stratigraphy;

Z_M – approximate depth of the structure top;

INJ – approximate location of the injection point (usually an existing well at the structure top);

POJM_MT_CA*(pacity)* – approximate static storage capacity (the sum of volumetric and solubility capacity) given in millions of tons (Mt).



biekt	Wartość
0	Jura/Jurassic
(Akcje)	
(pochodny)	
INJ	Kamionki IG-3
NAZWA_NAME	A. Kamionek
POJM_MT_CA	223
STRAT	J2
Z_M	2280,0

I - Bełchatów

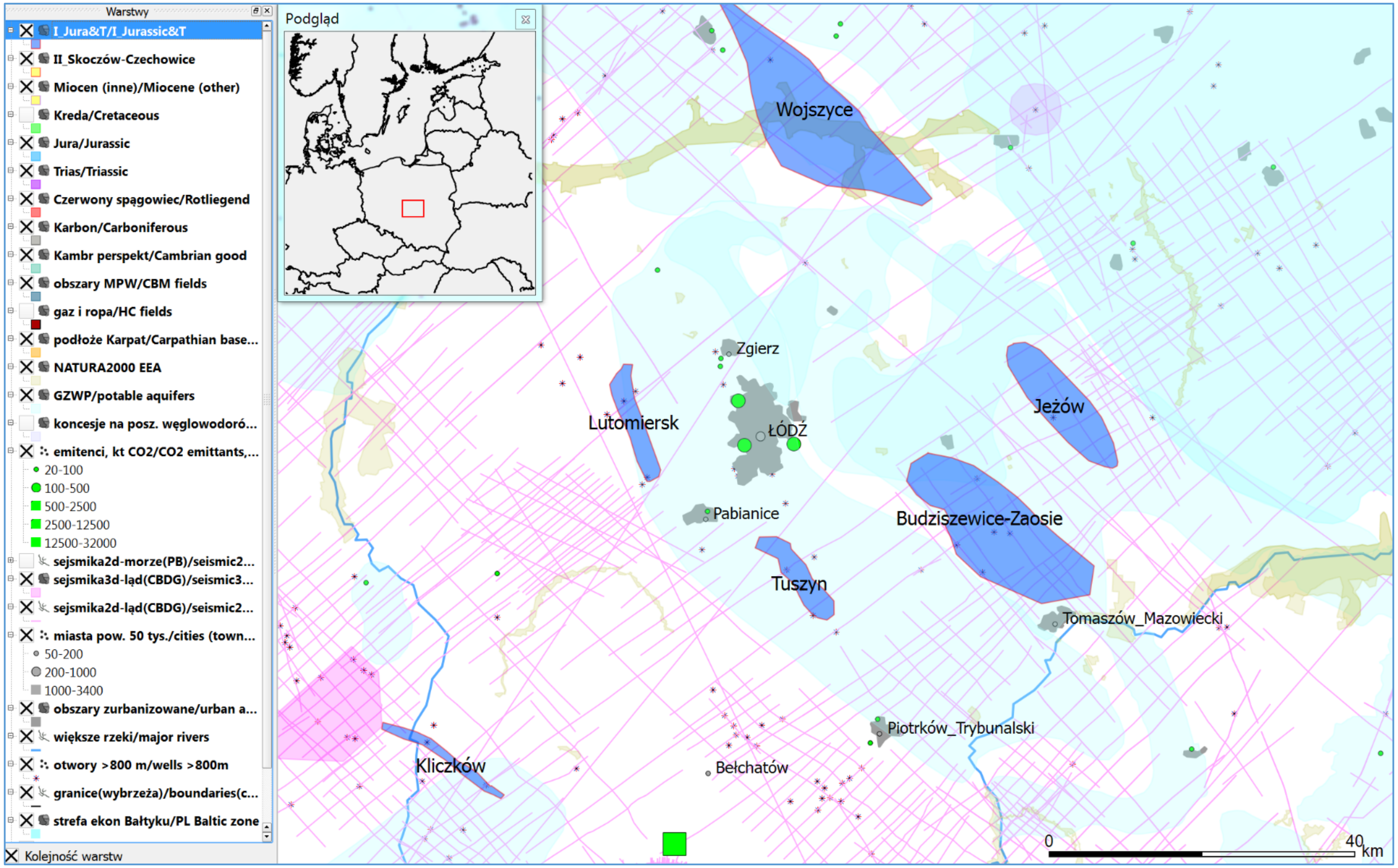
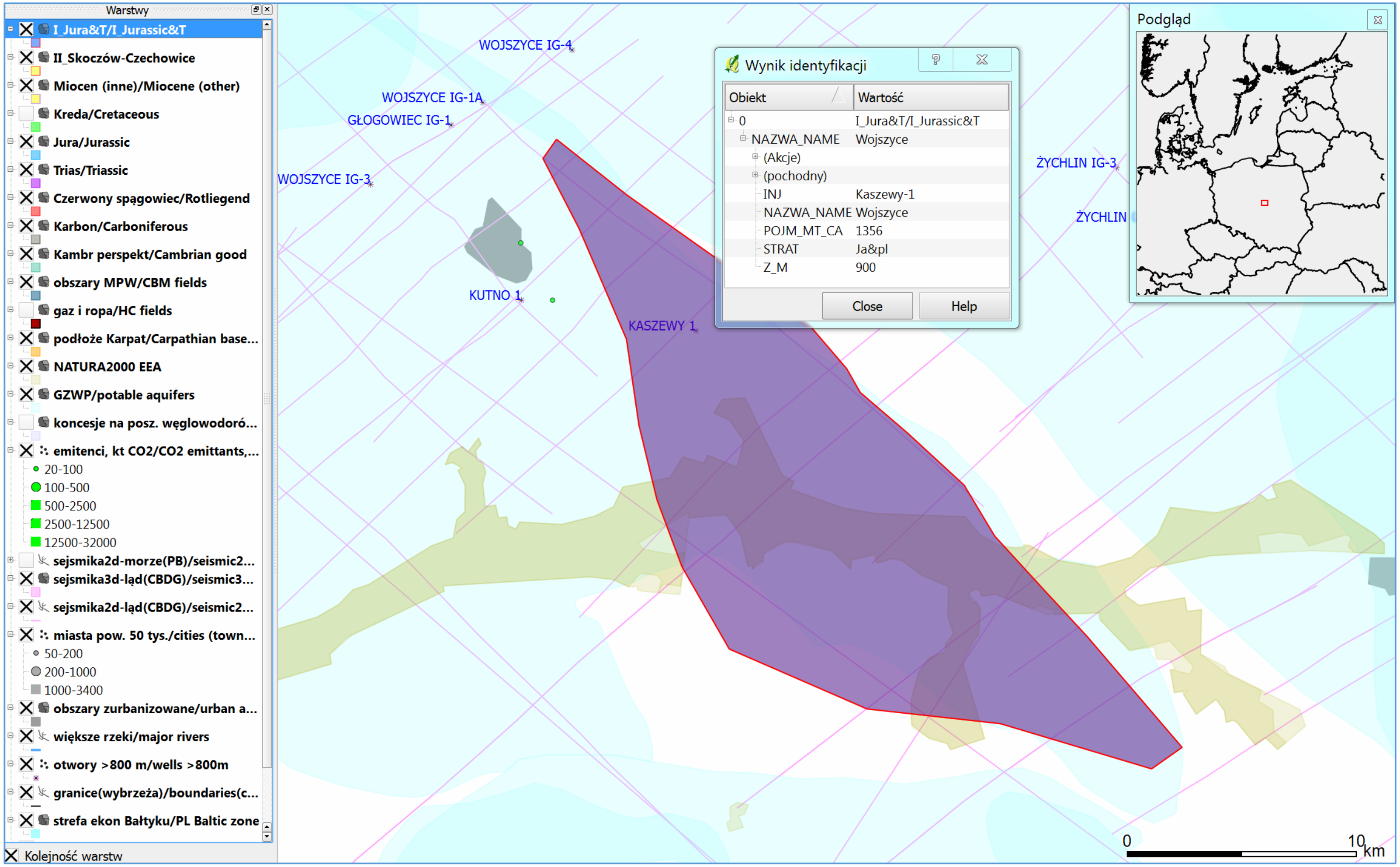
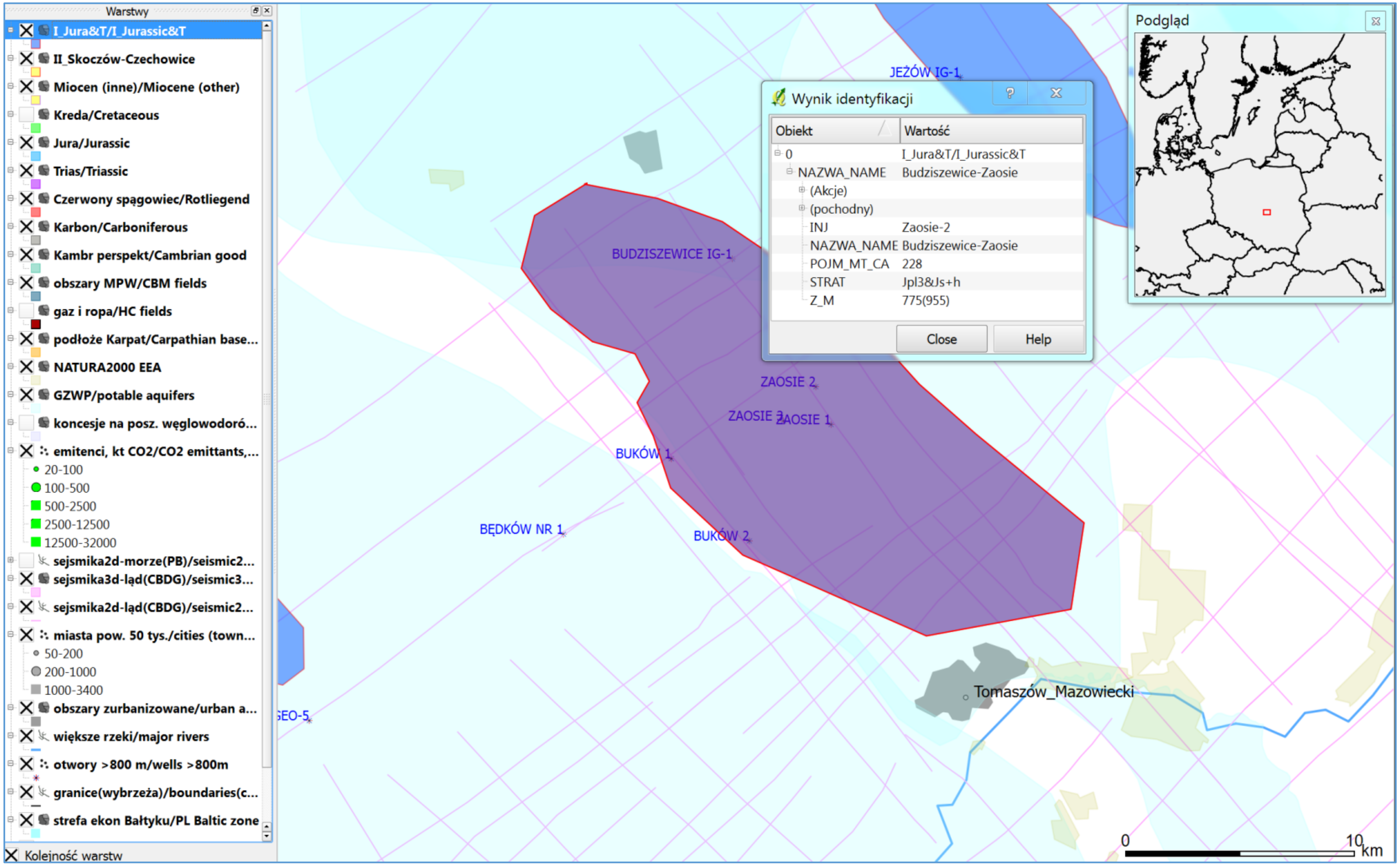


Fig. 3_1 Selected saline aquifer structures in Bełchatów study area



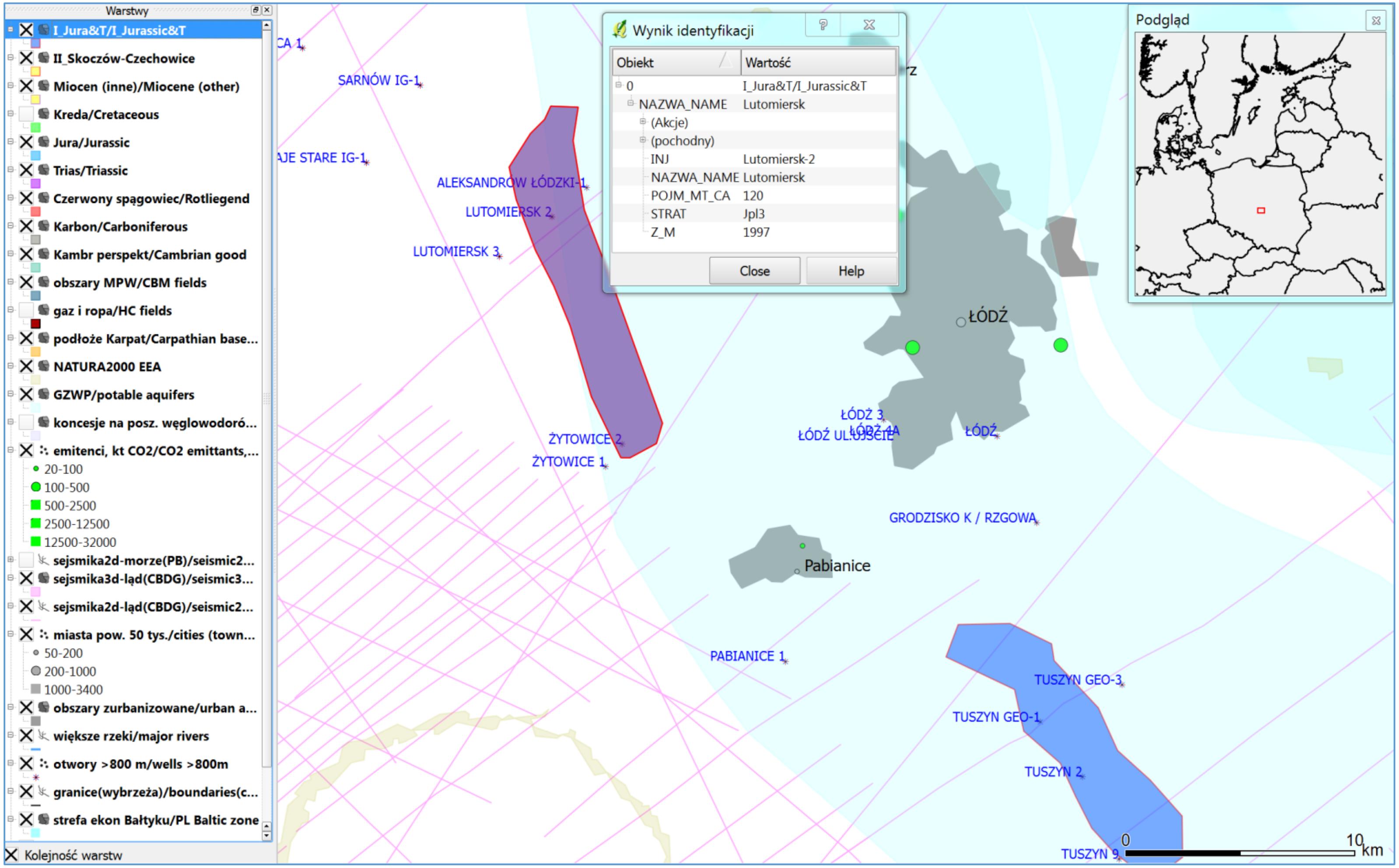
Obiekt	Wartość
0	I_Jura&T/I_Jurassic&T
NAZWA_NAME	Wojszyce
(Akcje)	
(pochodny)	
INJ	Kaszewy-1
NAZWA_NAME	Wojszyce
POJM_MT_CA	1356
STRAT	Ja&pl
Z_M	900

Fig. 3_2 Wojszyce structure (*Kaszewy well was drilled in the demo project – Posyniuk & Rosa, 2010; temperature at the top of Ja: 35 °C*)



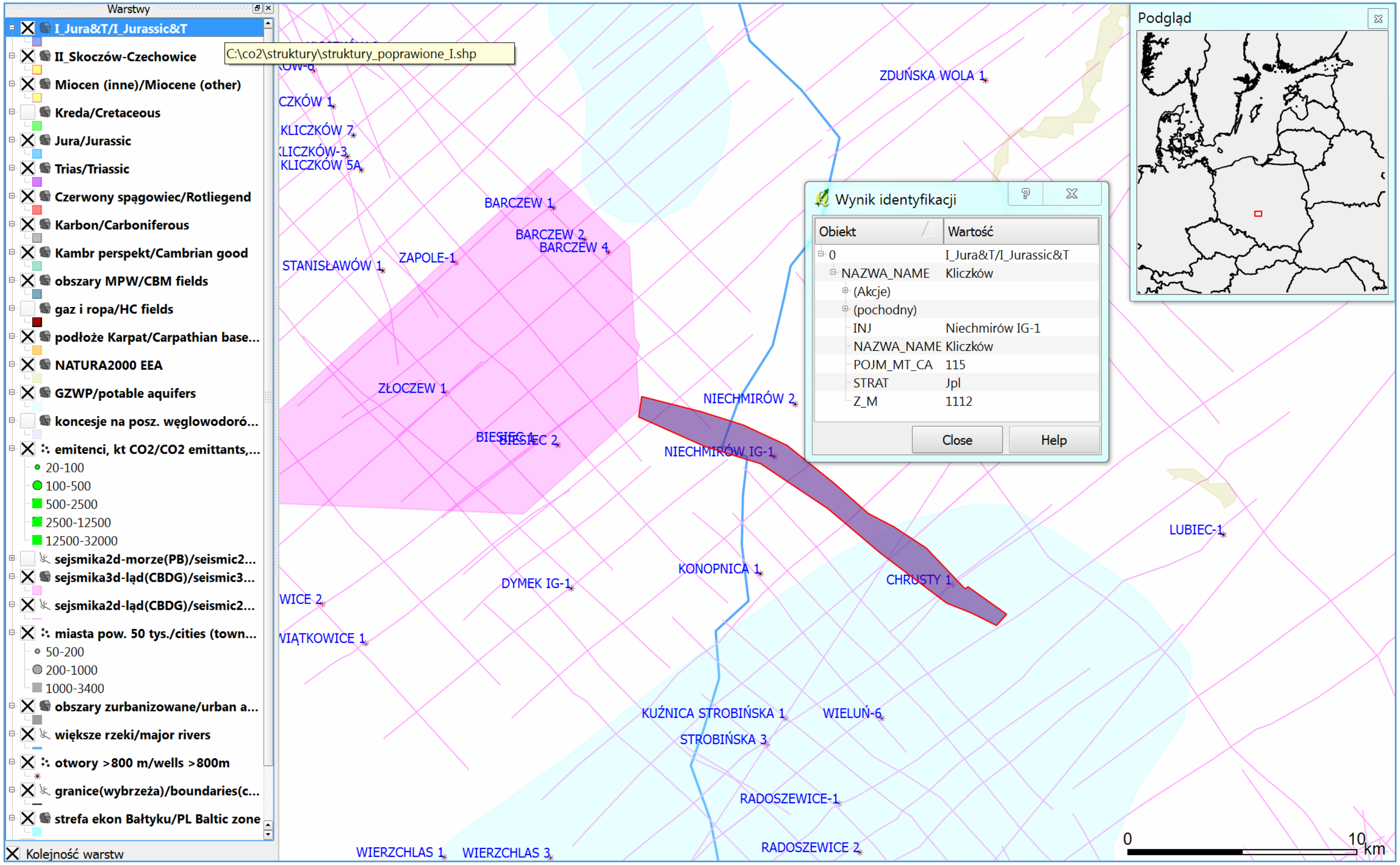
Obiekt	Wartość
0	I_Jura&T/I_Jurassic&T
NAZWA_NAME	Budziszewice-Zaosie
(Akcje)	
(pochodny)	
INJ	Zaosie-2
NAZWA_NAME	Budziszewice-Zaosie
POJM_MT_CA	228
STRAT	Jpl3&Js+h
Z_M	775(955)

Fig. 3_3 Budziszewice-Zaosie structure (CO_2 in liquid phase, under supercritical pressure)



Obiekt	Wartość
0	I_Jura&T/I_Jurassic&T
NAZWA_NAME	Lutomiersk
(Akcje)	
(pochodny)	
INJ	Lutomiersk-2
NAZWA_NAME	Lutomiersk
POJM_MT_CA	120
STRAT	Jpl3
Z_M	1997

Fig. 3_4 Lutomiersk (& Tuszyn) structure



Obiekt	Wartość
0	I_Jura&T/I_Jurassic&T
NAZWA_NAME	Kliczków
(Akcje)	
(pochodny)	
INJ	Niechmirów IG-1
NAZWA_NAME	Kliczków
POJM_MT_CA	115
STRAT	Jpl
Z_M	1112

Fig. 3_5 Kliczków – J structure

Works for the study area I (**Figure 3_1**) were performed in the first half of 2009. These structures have the storage potential enough for the demonstration project (PGE; minimum of 45 Mt over the life of the installation), and are ranked as follows;

(Wojszyce)[1] - **Fig. 3_2**

- Budziszewice-Zaosie - **Fig. 3_3**

- Lutomiersk & Tuszyn - **Fig. 3_4**

- Kliczków-J - **Fig. 3_5**

- *Jeżów* - see **Fig. 3_1**

Budziszewice - Zaosie structure (Lower Jurassic) is the best explored by seismic and wells, and mainly for this reason was selected for the case study (conditionally).

Lutomiersk structure is very poorly explored by seismic. It lies close to a major fault area - there is a possibility of migration of CO_2 and brine from Middle Jurassic reservoir to a reserve potable aquifer of Łódź agglomeration - storage in deeper reservoir is rather safe. Tuszyn structure has a similar situation as Lutomiersk.

Kliczków-J structure is actually a section of the Jurassic trench, into which probably one cannot inject too much carbon dioxide. It is not sufficiently explored (it was not attractive for petroleum prospecting).

Jeżów structure in Jurassic is too shallow and according to seismic surveys there is no good seal – storage possible only in Lower Triassic.

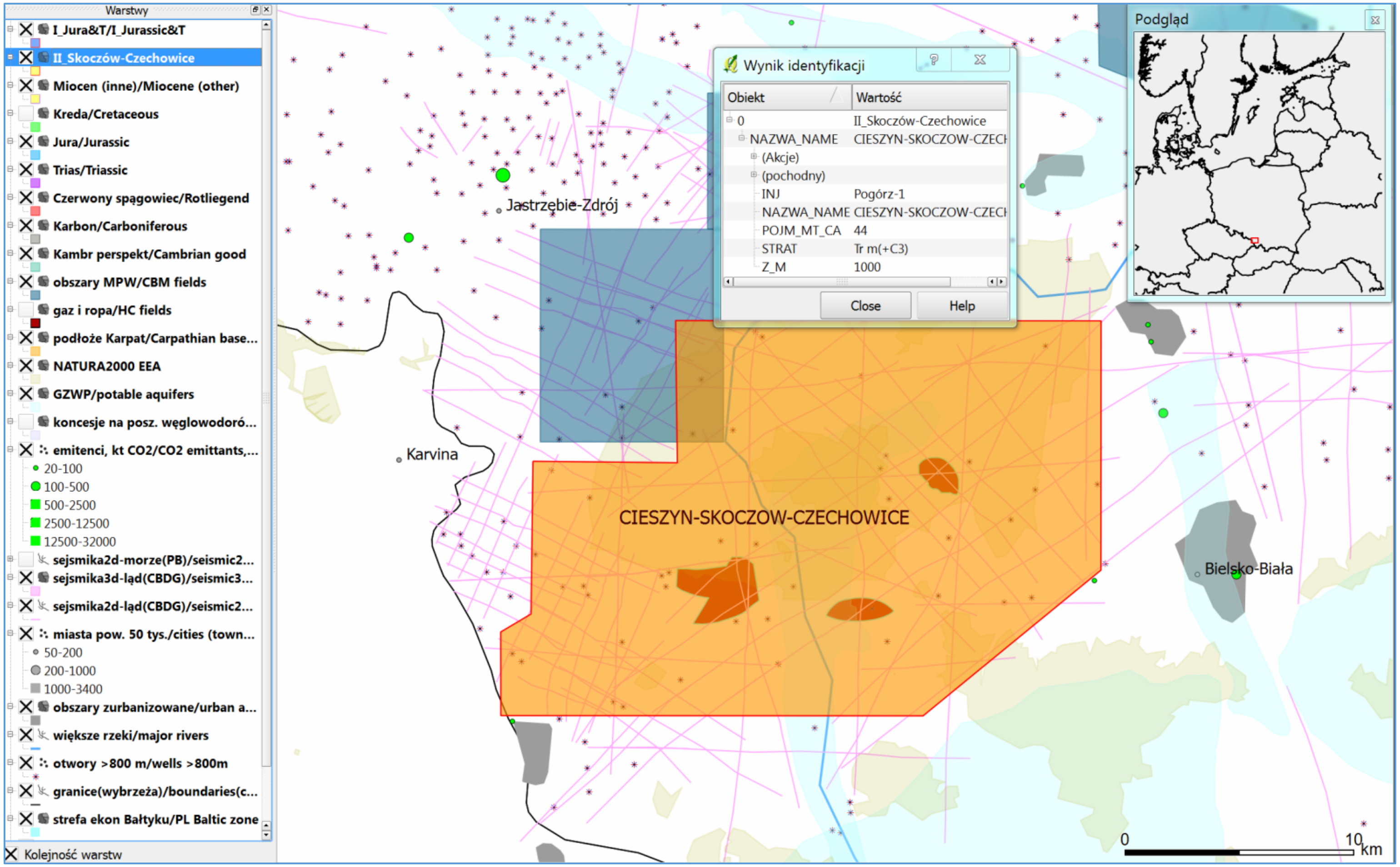
Wojszyce structure (J_2/J_1) is relatively far from the Bełchatów and had been insufficiently explored by seismic and wells, until field works under the CCS demo project of PGE Bełchatów were completed in year 2010, then turned out to be the best of all.

Except the case of Wojszyce (NATURA 2000 area in the center, tight gas exploration in the neighborhood, however failed) no substantial conflicts of interest were found for these structures when it comes to natural resources, i.e., protected areas, exploration and exploitation of raw materials and the potable aquifers (reservoirs proposed for sequestration are separated from them by hundreds of meters of sealing and saline and brackish aquifer complexes). The largest CO_2 emitters in this region are: Bełchatów power plant (where the demo CCS project was also planned) and CHP plants in Łódź.

---

[1] Wojszyce structure lies between study areas I and III. It was proposed to PGE to carry out a reconnaissance survey in the CCS demo project there (and for Lutomiersk & Tuszyn).

II – Upper Silesian Coal Basin



Obiekt	Wartość
0	II_Skoczów-Czechowice
NAZWA_NAME	CIESZYN-SKOCZOW-CZEC
(Akcje)	
(pochodny)	
INJ	Pogórz-1
NAZWA_NAME	CIESZYN-SKOCZOW-CZEC
POJM_MT_CA	44
STRAT	Tr m(+C3)
Z_M	1000

Fig. 3_6 Skoczów-Czechowice saline aquifer site (SW part of USCB)

In the area of the Upper Silesian Coal Basin (USCB) the Dębowiec beds (lower Miocene sandstones) were chosen as prospective formation, characterized by better reservoir properties than the Carboniferous formations. First, two sites located outside the active areas of coal mines, as well as outside the areas of currently planned mines, with a good seal (Skoczów-Czechowice and Kęty-Andrychów) were selected. The first site is bigger (i.e., of bigger storage potential) and better explored than the other, and in particular is characterized by better reservoir properties. Hence, it was concluded that the Cieszyn-Skoczów-Czechowice site (**Fig. 3_6**) seems to be the most suitable for geological storage, which was also chosen as the subject of case study for the region of Upper Silesia Coal Basin (Dębowiec beds, locally zamarskie beds and possibly the top part Carboniferous).

Possible conflicts of interest relating to the use of that potential storage site area affect its fragments covered by NATURA 2000 areas, urban areas or small hydrocarbon fields occurring within it. They affect not a very large part of the area of Skoczów-Czechowice site and this has been taken into account for the selection of the location of the injection wells in the case study.

Regarding the storage capacity of the site[2], unfortunately it is sufficient only for the needs of a single medium size emittant - for example, a small power block or a small CHP plant (such as CHP plants in Bielsko-Biała and Czechowice-Dziedzice in eastern part, and in Jastrzębie in NW part of the area on the map **Fig. 3_6**). This capacity is too small for the purposes of an optimal variant of the CCS demonstration project of PKE & ZAK Kędzierzyn, cancelled in 2010, for which, under the contract, this scenario and analysis for the area of the USCB was to be performed (up to 2.8 million tons/year to be captured, or at least 70 million tons over the plant lifetime). Hence, the possible needs of large emittants from the region of Upper Silesia Coal Basin, located to the north and northwest of the site, could be met in other, more remote areas of the country (saline aquifers in central Poland, gas fields in the south of Greater Poland).

---

[2] This is not a typical structure, such as the brachyanticlines of the Polish Lowlands, rather, a part of a small sedimentary basin - hence the storage efficiency factor and the volumetric storage capacity here are rather low, which on the other hand, is confirmed by the results of dynamic simulations of the case study, providing a storage capacity value corresponding to a half of the static capacity.

III - Mazovia

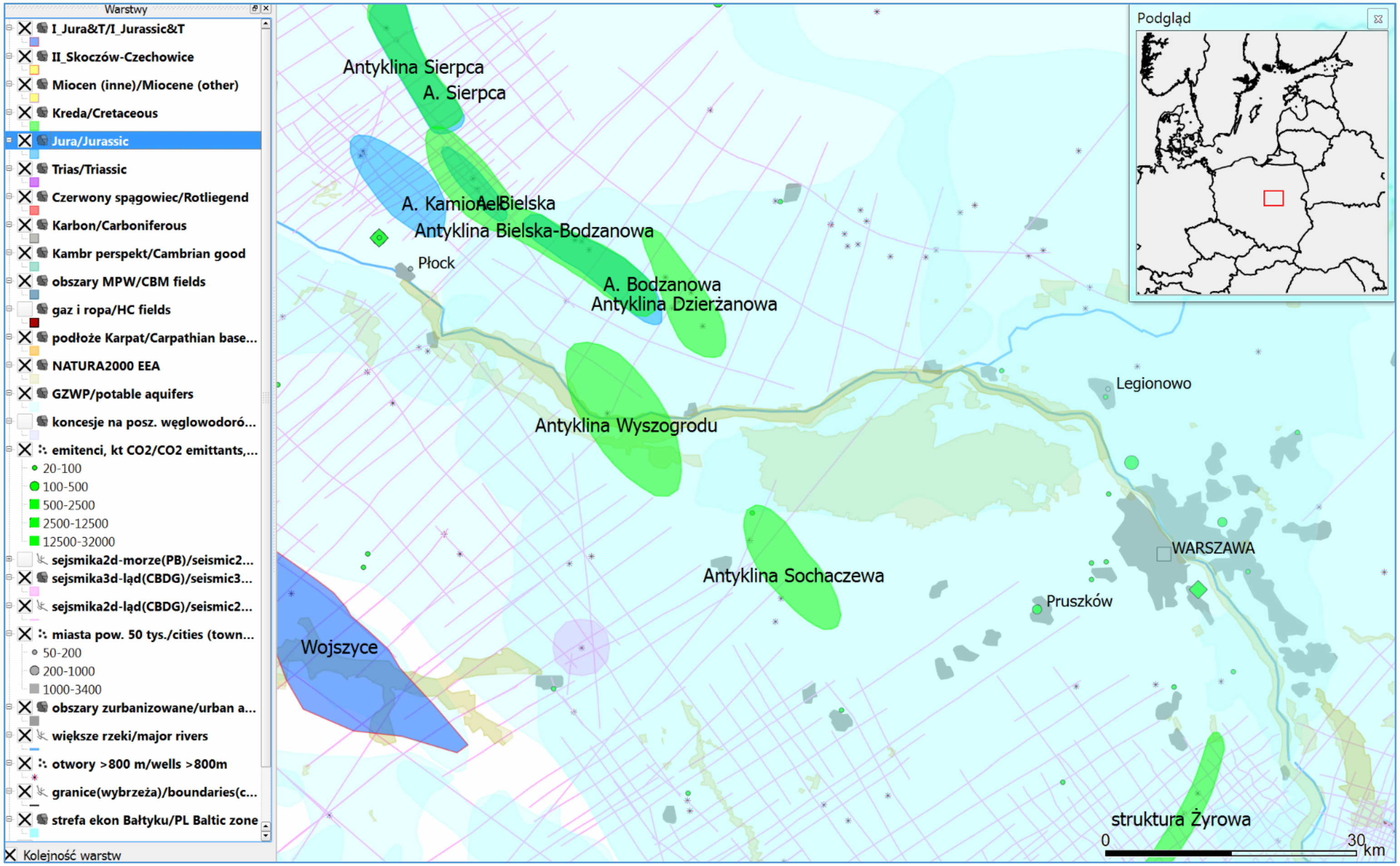
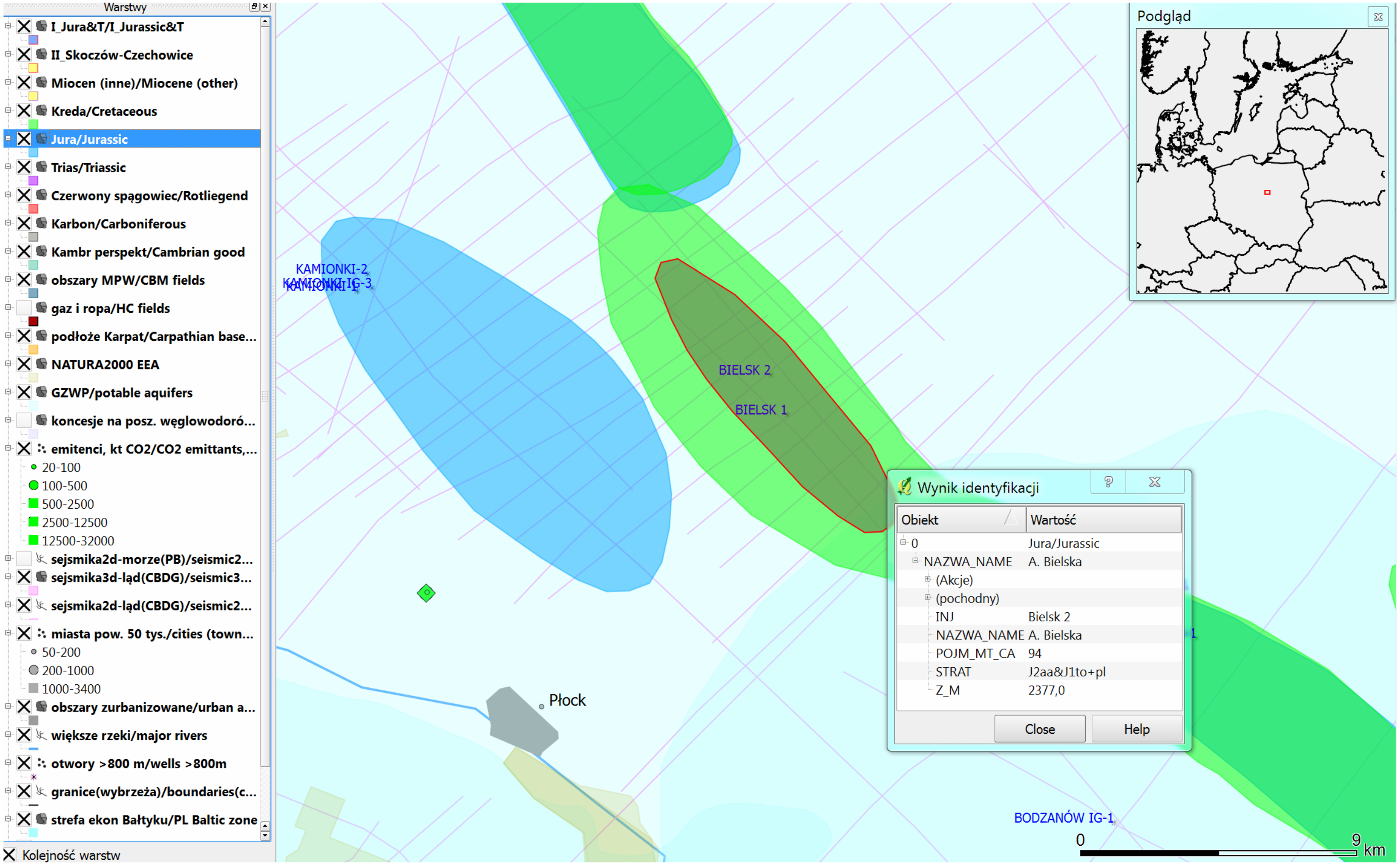
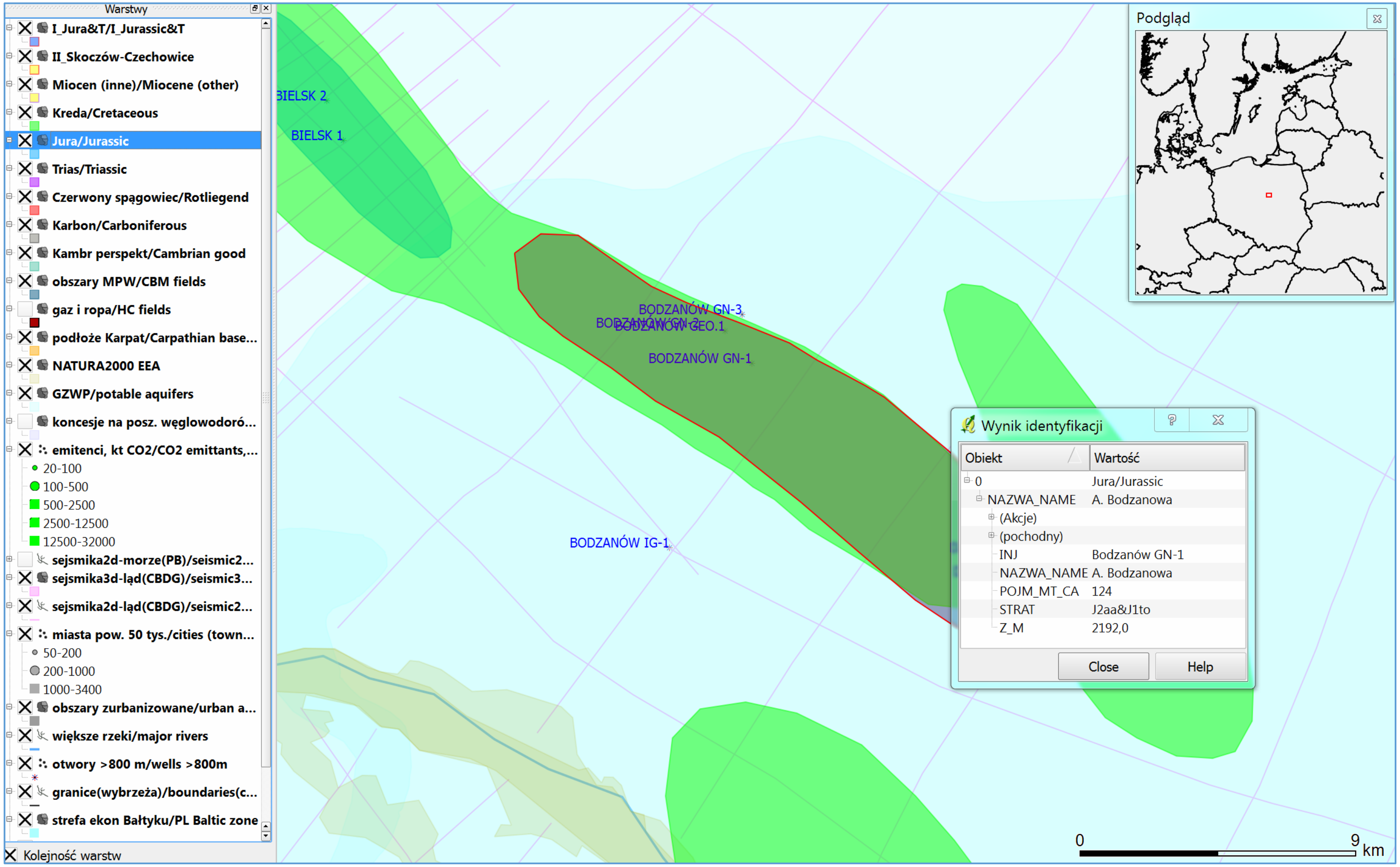


Fig. 3_7 Selected saline aquifer structures in Mazovia study area (Lower and Middle Jurassic, Lower Cretaceous)



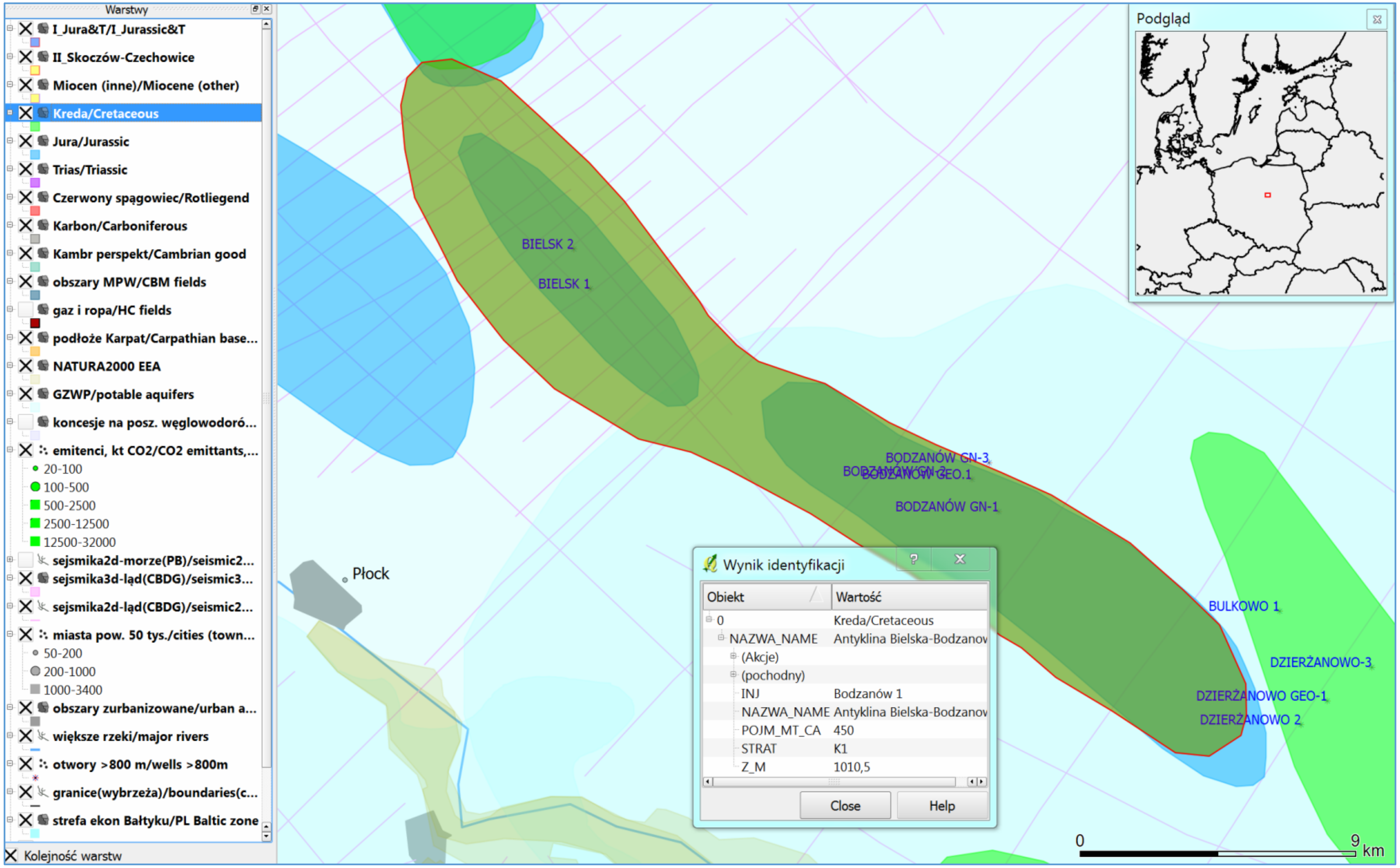
Obiekt	Wartość
0	Jura/Jurassic
NAZWA_NAME	A. Bielska
(Akcje)	
(pochodny)	
INJ	Bielsk 2
NAZWA_NAME	A. Bielska
POJM_MT_CA	94
STRAT	J2aa&J1to+pl
Z_M	2377,0

Fig. 3_8 Bielsk anticline in Jurassic



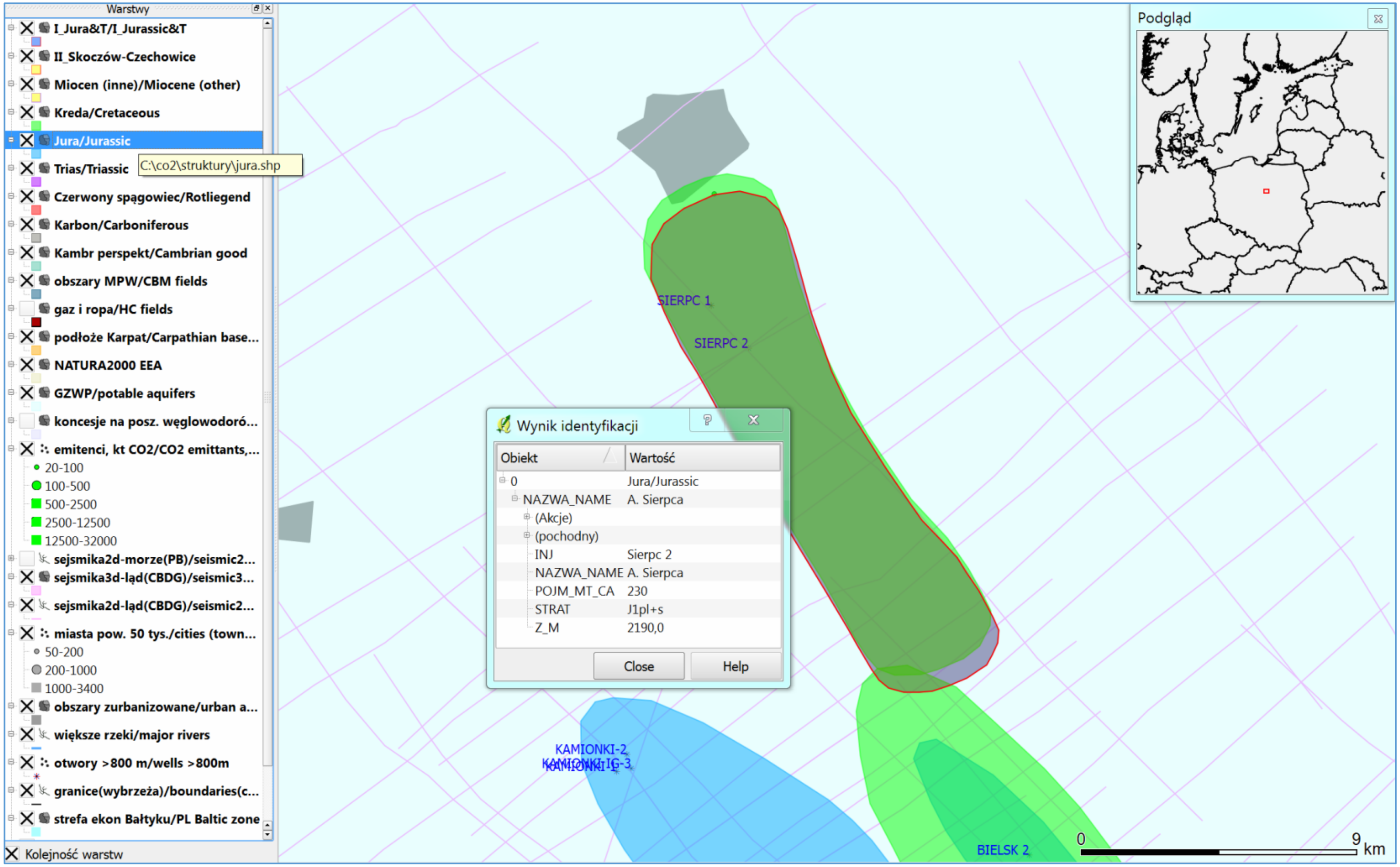
Obiekt	Wartość
0	Jura/Jurassic
NAZWA_NAME	A. Bodzanowa
(Akcje)	
(pochodny)	
INJ	Bodzanów GN-1
NAZWA_NAME	A. Bodzanowa
POJM_MT_CA	124
STRAT	J2aa&J1to
Z_M	2192,0

Fig. 3_9 Bodzanów anticline in Jurassic



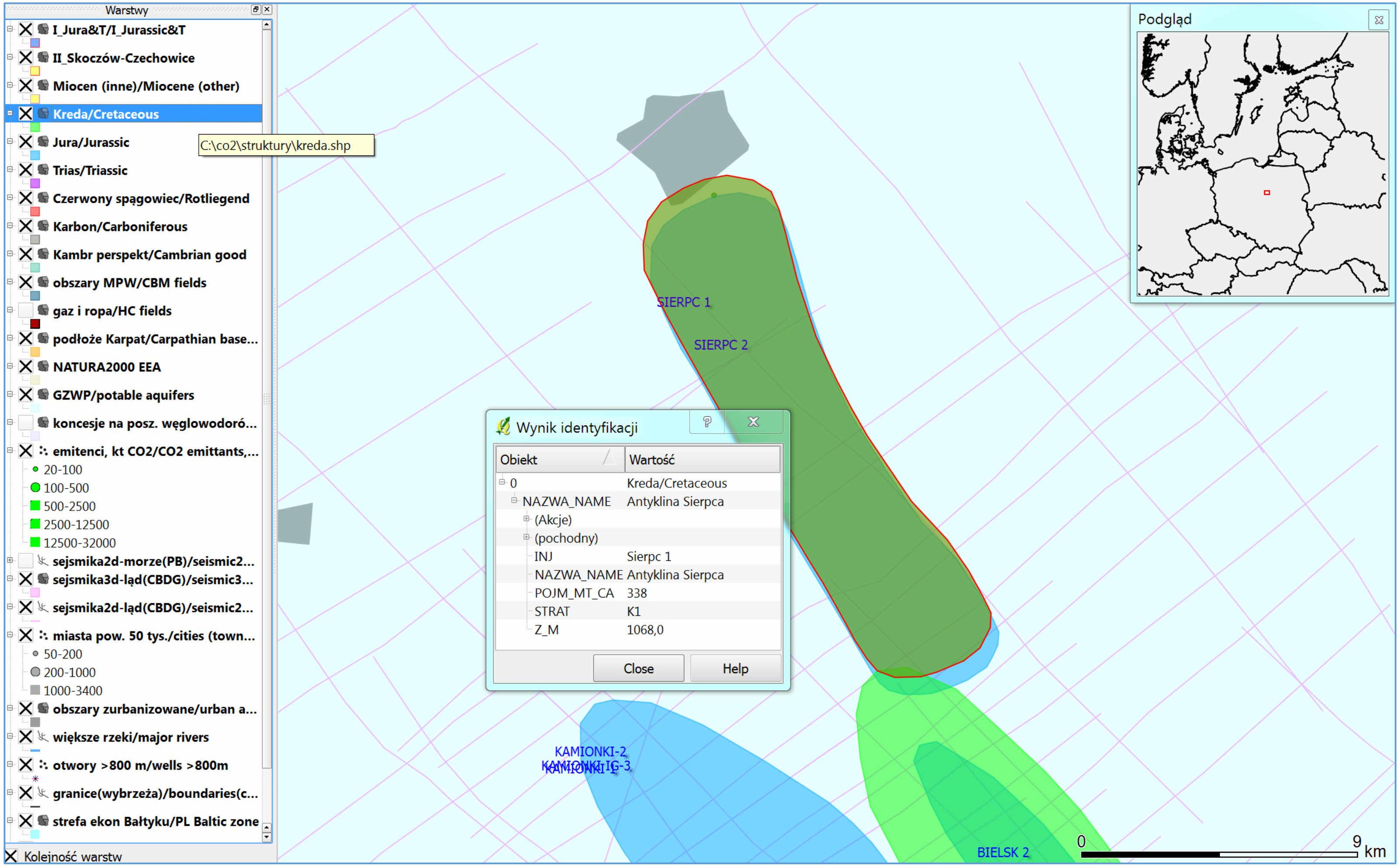
Obiekt	Wartość
0	Kreda/Cretaceous
NAZWA_NAME	Antyklina Bielska-Bodzanov
(Akcje)	
(pochodny)	
INJ	Bodzanów 1
NAZWA_NAME	Antyklina Bielska-Bodzanov
POJM_MT_CA	450
STRAT	K1
Z_M	1010,5

Fig. 3_10 Bielsk-Bodzanów anticline in Lower Cretaceous



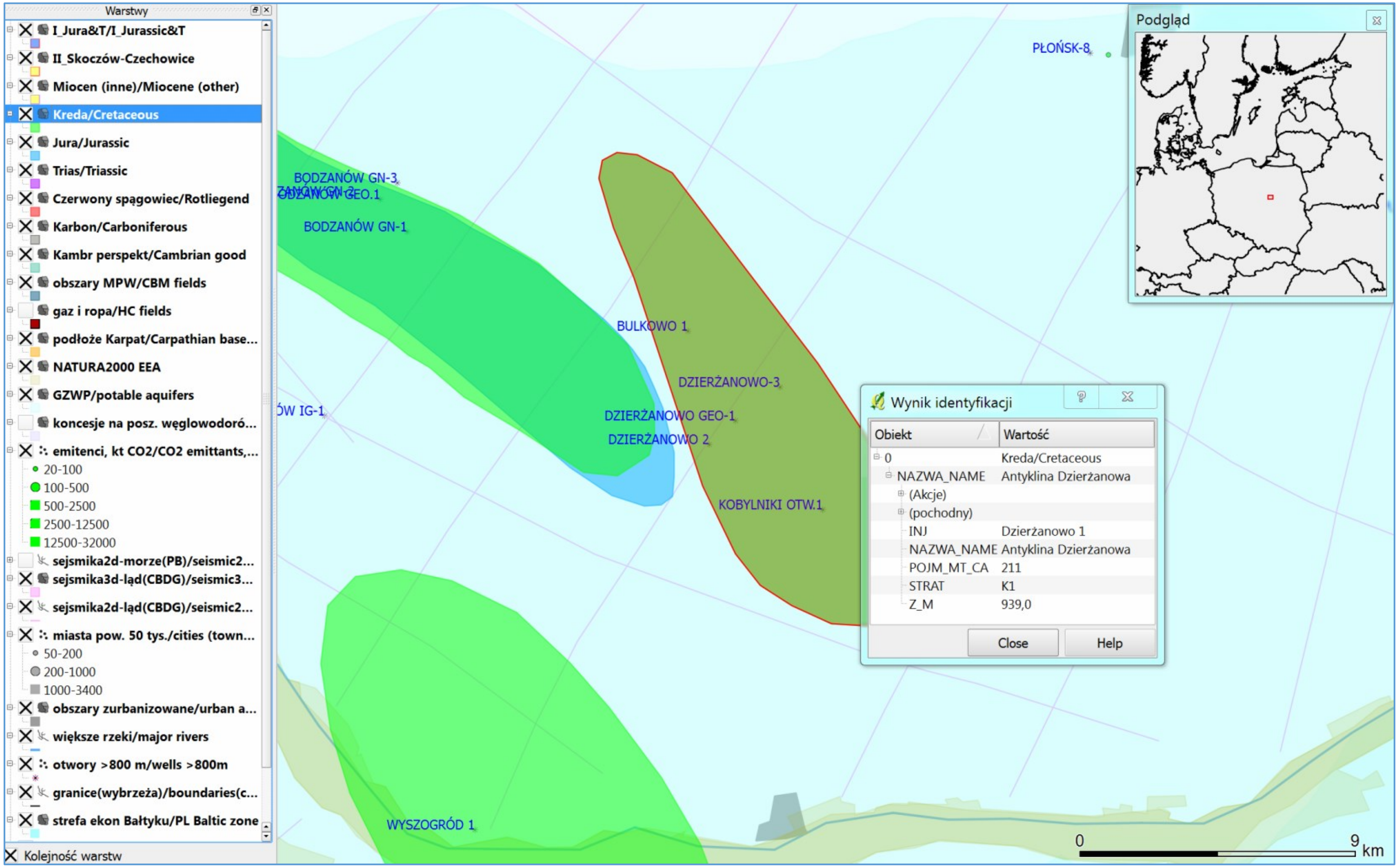
Obiekt	Wartość
0	Jura/Jurassic
NAZWA_NAME	A. Sierpca
(Akcje)	
(pochodny)	
INJ	Sierpc 2
NAZWA_NAME	A. Sierpca
POJM_MT_CA	230
STRAT	J1pl+s
Z_M	2190,0

Fig. 3_11 Sierpc anticline in Jurassic



Obiekt	Wartość
0	Kreda/Cretaceous
NAZWA_NAME	Antyklina Sierpca
(Akcje)	
(pochodny)	
INJ	Sierpc 1
NAZWA_NAME	Antyklina Sierpca
POJM_MT_CA	338
STRAT	K1
Z_M	1068,0

Fig. 3_12 Sierpc anticline in Upper Cretaceous

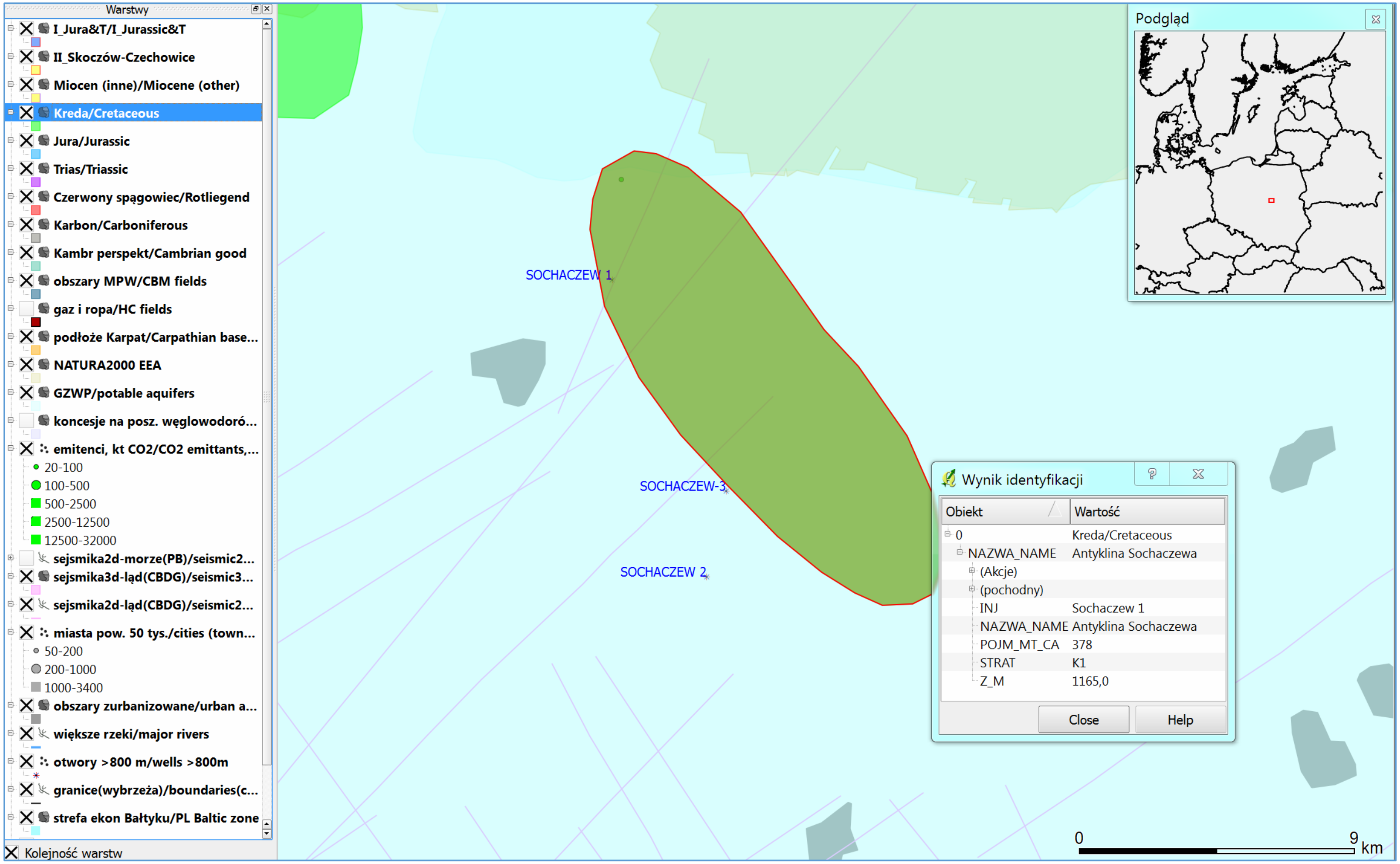


Obiekt	Wartość
0	Kreda/Cretaceous
NAZWA_NAME	Antyklina Dzierżanowa
(Akcje)	
(pochodny)	
INJ	Dzierżanowo 1
NAZWA_NAME	Antyklina Dzierżanowa
POJM_MT_CA	211
STRAT	K1
Z_M	939,0

Fig. 3_13 Dzierżanowo structure in Upper Cretaceous (*Dzierżanowo GEO-1 well – temperature 38 °C – Górecki [ed.] 2006a*)

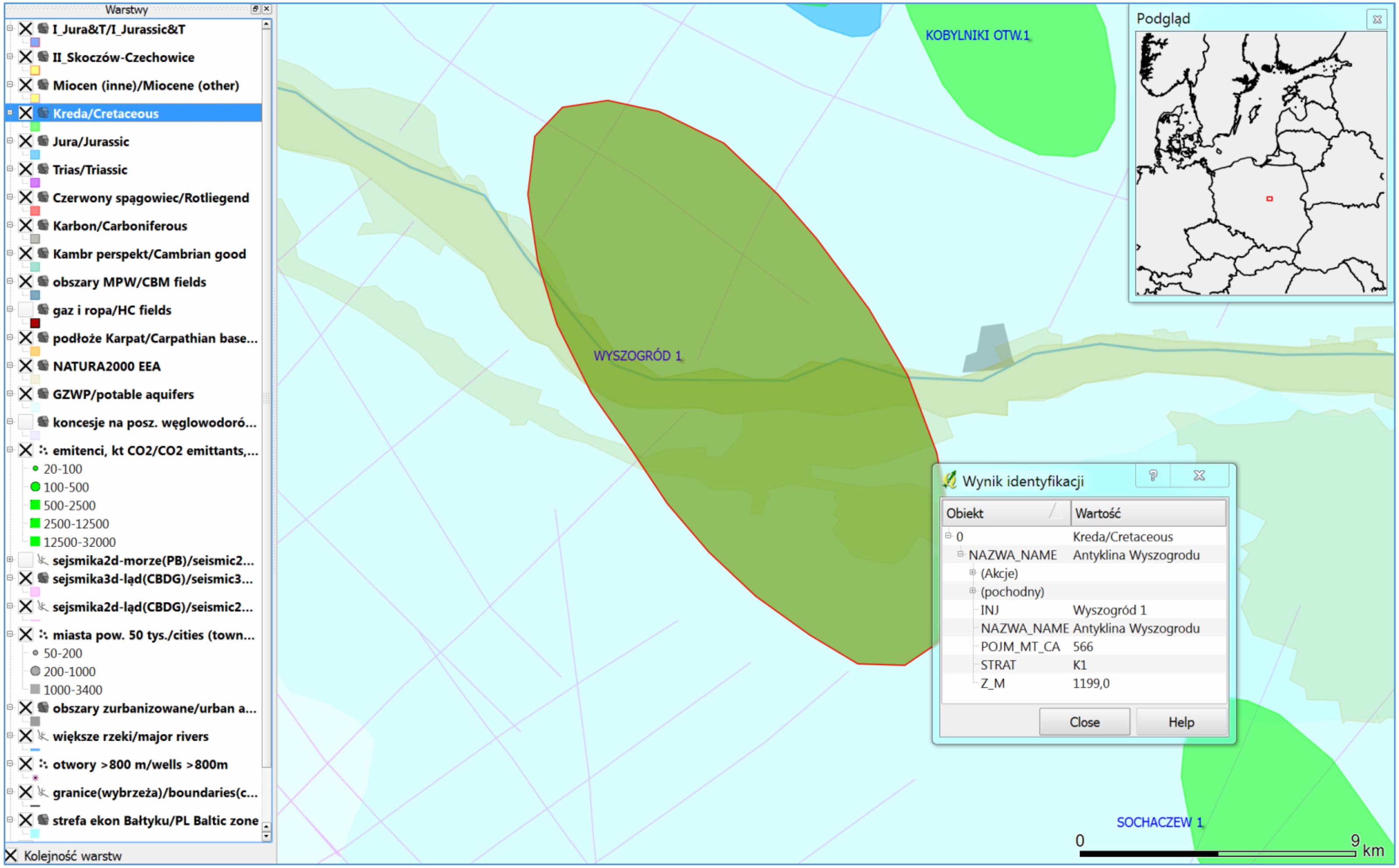
Obiekt	Wartość
0	Jura/Jurassic
NAZWA_NAME	A. Kamionek
(Akcje)	
(pochodny)	
INJ	Kamionki IG-3
NAZWA_NAME	A. Kamionek
POJM_MT_CA	223
STRAT	J1pl+s+h
Z_M	2280,0

Fig. 3_14 Kamionki anticline in Jurassic



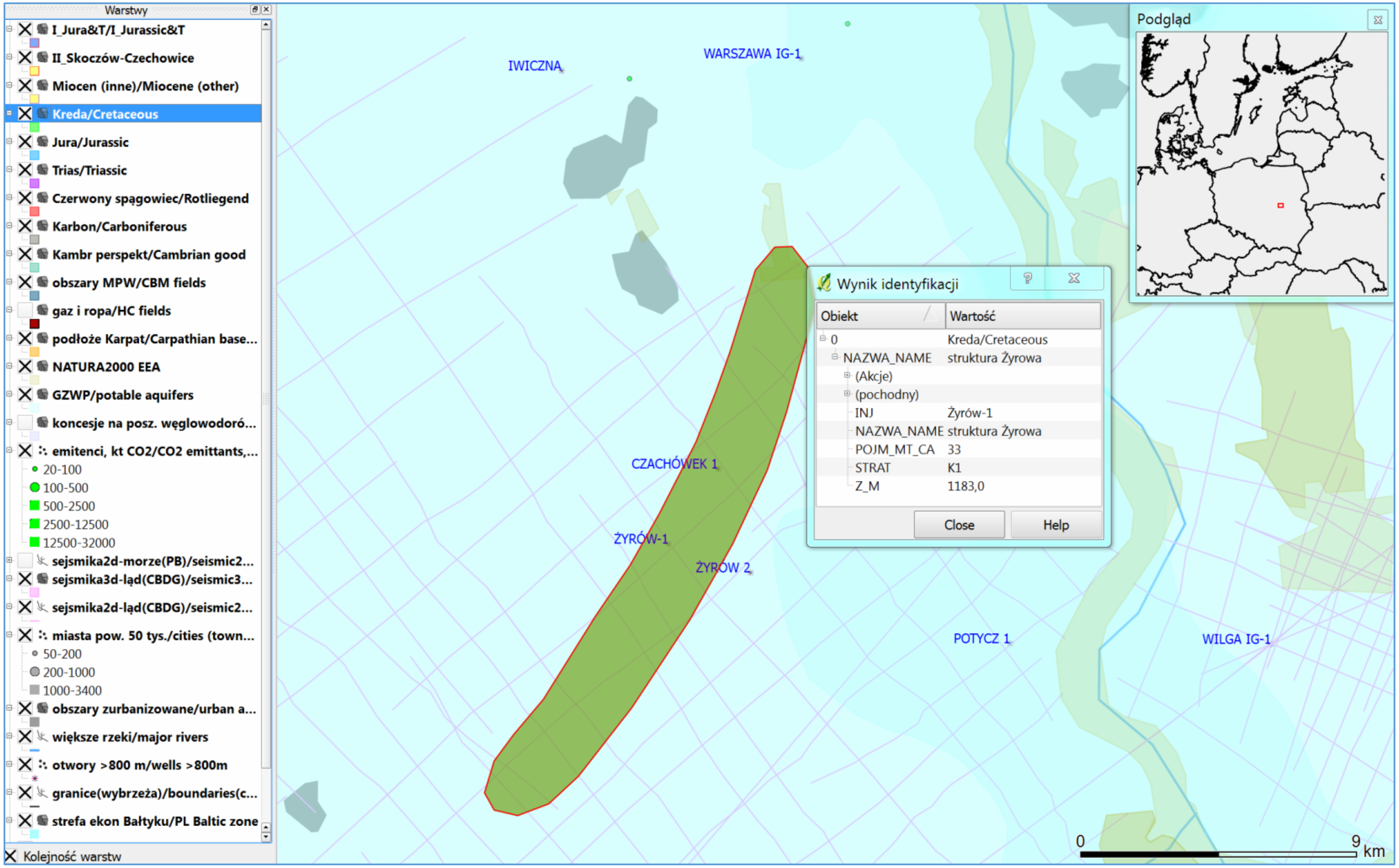
Obiekt	Wartość
0	Kreda/Cretaceous
NAZWA_NAME	Antyklina Sochaczewa
(Akcje)	
(pochodny)	
INJ	Sochaczew 1
NAZWA_NAME	Antyklina Sochaczewa
POJM_MT_CA	378
STRAT	K1
Z_M	1165,0

Fig. 3_15 Sochaczew anticline in Upper Cretaceous



Obiekt	Wartość
0	Kreda/Cretaceous
NAZWA_NAME	Antyklina Wyszogrodu
(Akcje)	
(pochodny)	
INJ	Wyszogród 1
NAZWA_NAME	Antyklina Wyszogrodu
POJM_MT_CA	566
STRAT	K1
Z_M	1199,0

Fig. 3_16 Wyszogród anticline in Upper Cretaceous



Obiekt	Wartość
0	Kreda/Cretaceous
NAZWA_NAME	struktura Żyrowa
(Akcje)	
(pochodny)	
INJ	Żyrów-1
NAZWA_NAME	struktura Żyrowa
POJM_MT_CA	33
STRAT	K1
Z_M	1183,0

Fig. 3_17 Żyrów structure in Upper Cretaceous

In the region of Mazovia saline aquifer structures in the Lower and Middle Jurassic and Lower Cretaceous formations (**Fig. 3_7**) were selected. Here we have a sequence of adjacent or overlapping structures between Warsaw and Plock, where the major emitters are: Plock refinery and power plants in Warsaw.

The main reservoirs in the Jurassic include the Borucice formation (Middle/Lower Jurassic) and the deeper Lower Jurassic formations. The latter, however, often are located at depths greater than 2500 m, so from an economic point of view, the most prospective is the borucicka formation. In the case of the Lower Cretaceous the storage is optional, after a detailed exploration of the reservoir with new geological and geophysical surveys.

For the saline aquifer structures in the region of Mazovia, from the perspective of the needs of emittants, storage capacity, safety and feasibility of storage, the following ranking and indicative storage scenarios can be proposed:

- Bielsk-Bodzanów anticlines (saline aquifers in the Jurassic - two adjacent elements of Bielsk and Bodzanów – **Fig. 3_8** and **3_9**; above them a coupled element of Bielsk-Bodzanów in the Lower Cretaceous – **Fig. 3_10**) of the highest potential in total, sufficient for the needs of Warsaw and Płock;

- Sierpc anticline (saline aquifers in the Jurassic - **Fig. 3_11** and the Lower Cretaceous - **Fig. 3_12**) of potential, in principle, sufficient for the needs of both Warsaw and Płock or Płock and other, smaller emittants located to the west (Wloclawek) or NW (Torun);

- Dzierżanowo anticline (Lower Cretaceous - **Fig. 3_13**), located not far from Warsaw, and a quite well explored, with a capacity sufficient for the needs of two CHP plants in Warsaw;

- Kamionki anticline (Jurassic - **Fig. 3_14**), located near Płock, with a capacity sufficient for the refinery in Płock;

- Sochaczew and Wyszogród anticlines (Lower Cretaceous – **Fig. 3_15** and **16**), less explored, each of them can be a backup structure for Warsaw;

- Żyrów structure (Lower Cretaceous – **Fig. 3_17**), strongly faulted and hence of a fairly low capacity, might be useful to the nearby small emittants from the Warsaw agglomeration, but its caprock integrity shall be proven by detailed surveys[3].

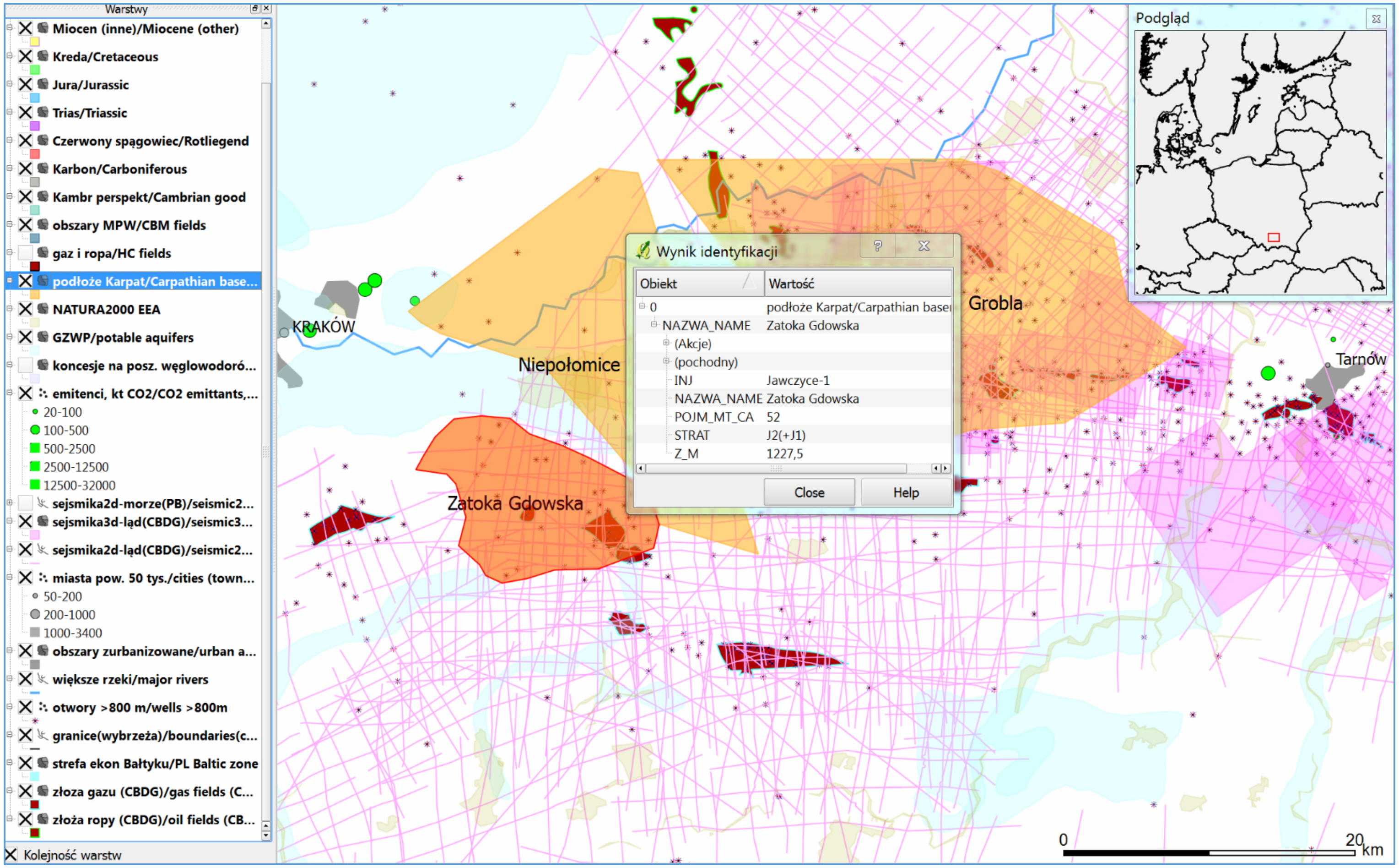
In summary, the recommended scenario for CO2 storage for large emittants of Warsaw includes the use of Dzierżanowo structure, or structures Bielsk-Bodzanów or, for example,

---

[3] The reviewer (J. Szewczyk, 2013) found that certainly there is a hydraulic connection between the Lower Cretaceous and the Jurassic aquifers (but potable aquifers occur in the Paleogene).

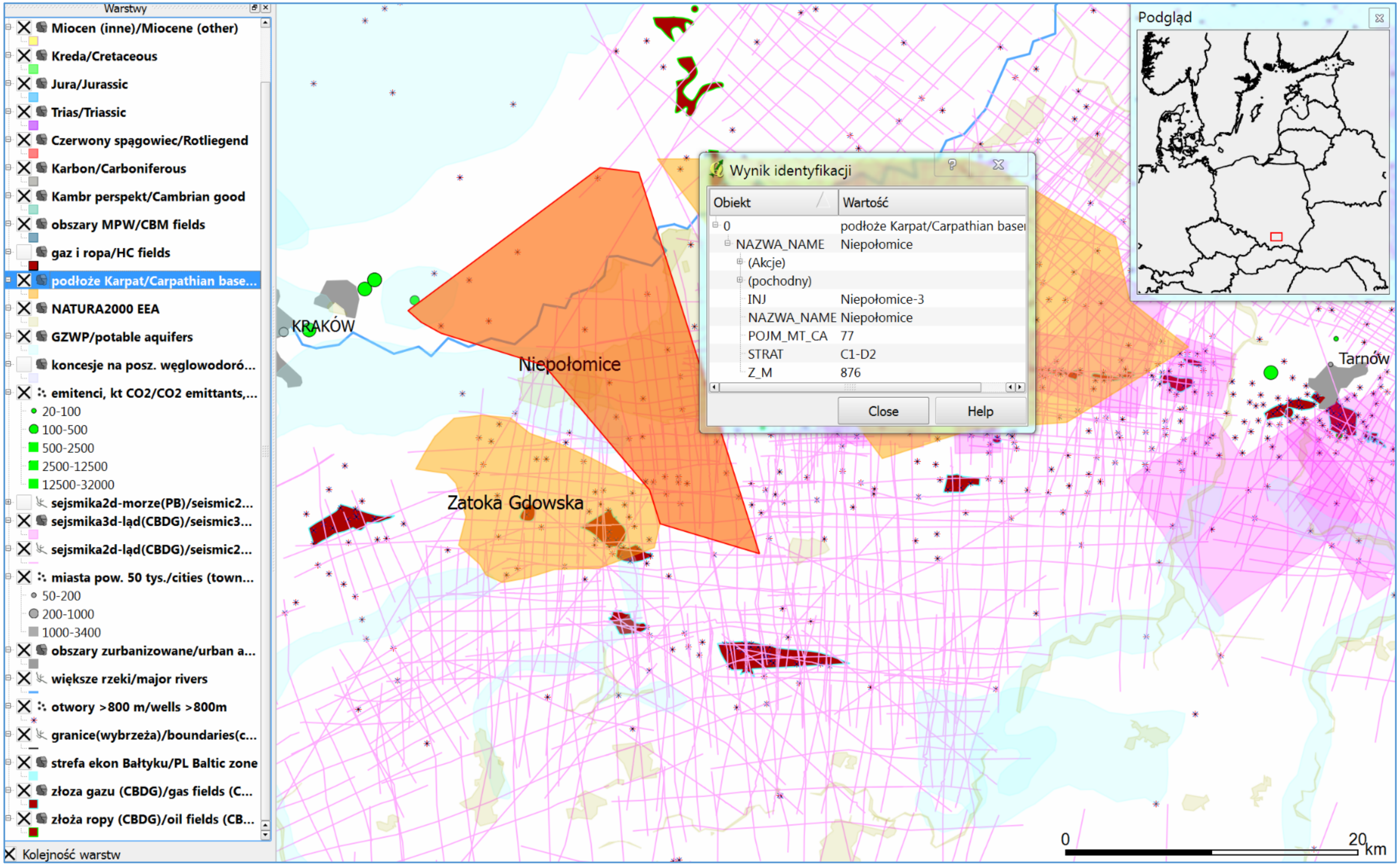
Sochaczew structure. For Płock it would be appropriate to use Bielsk-Bodzanów structures, or Sierpc or Kamionki structure.

When it comes to conflicts of interest on the use of natural resources for the study area III, there is no significant threat to the potable aquifers, and NATURA 2000 areas are found only within a single structure (Wyszogród anticline), and the prospects for shale gas discovery in the area of selected structures appear to be negligible (PGI-NRI report, 2012).



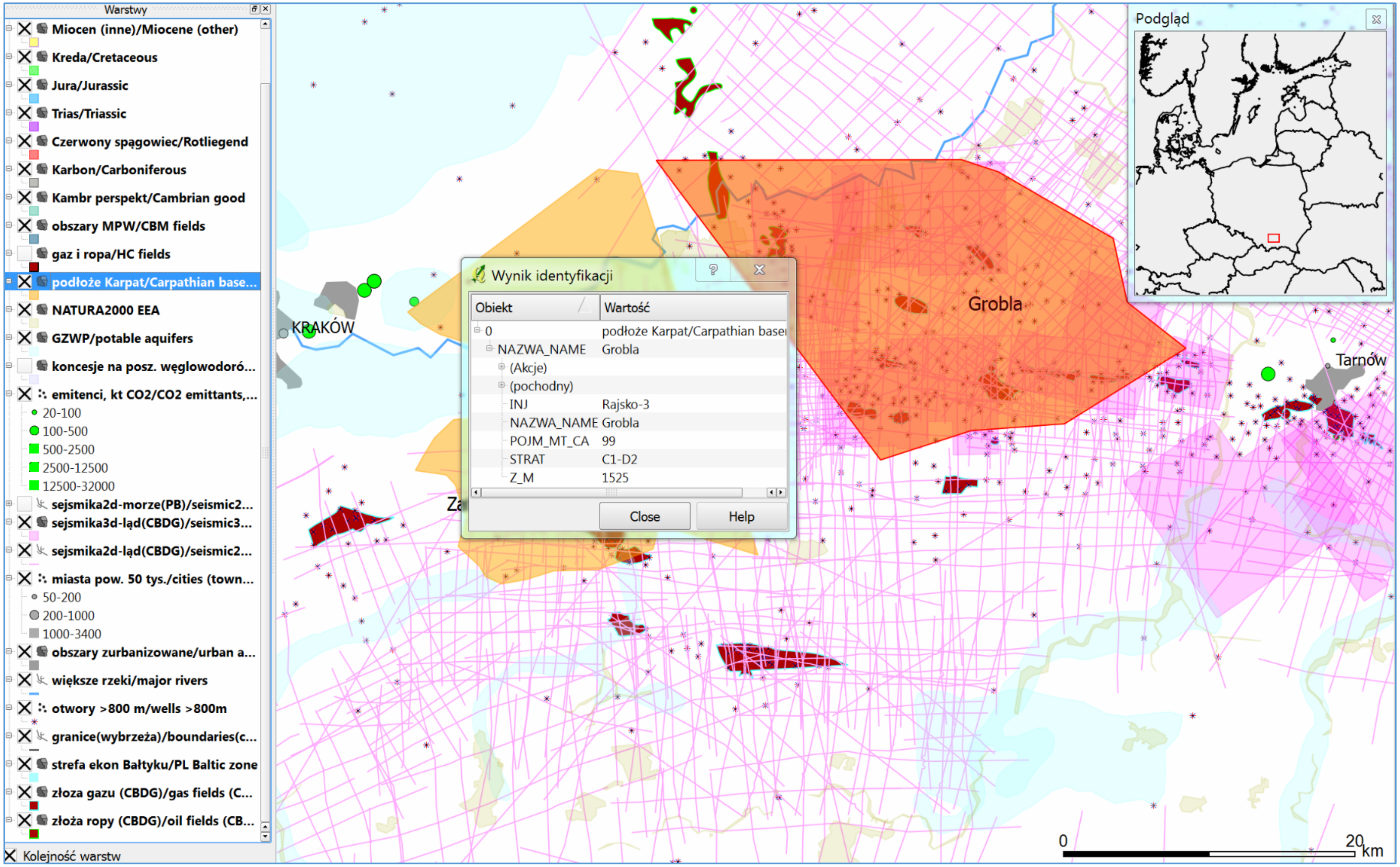
Obiekt	Wartość
0	podłoże Karpat/Carpathian base
NAZWA_NAME	Zatoka Gdowska
(Akcje)	
(pochodny)	
INJ	Jawczyce-1
NAZWA_NAME	Zatoka Gdowska
POJM_MT_CA	52
STRAT	J2(+J1)
Z_M	1227,5

Fig. 3_18 Zatoka Gdowska saline aquifer site (Jurassic, clastic)



Obiekt	Wartość
0	podłoże Karpat/Carpathian base
NAZWA_NAME	Niepołomice
(Akcje)	
(pochodny)	
INJ	Niepołomice-3
NAZWA_NAME	Niepołomice
POJM_MT_CA	77
STRAT	C1-D2
Z_M	876

Fig. 3_19 Niepołomice saline aquifer site (Carboniferous-Devonian carbonate complex)



Wynik identyfikacji

Obiekt	Wartość
0	podłoże Karpat/Carpathian base
NAZWA_NAME	Grobla
(Akcje)	
(pochodny)	
INJ	Rajsko-3
NAZWA_NAME	Grobla
POJM_MT_CA	99
STRAT	C1-D2
Z_M	1525

Fig. 3_20 Grobla saline aquifer site (Carboniferous-Devonian carbonate complex)

In the western area IVA (generally between Kraków [Cracow] and Tarnów) two sites in the Carboniferous-Devonian carbonate complex were selected, taking into account environmental aspects and the population density: "Niepołomice aquifer" (**Fig. 3_19**) and "Grobla aquifer" (**Fig. 3_20**). Impermeable overburden of these saline aquifers is a series of several hundred meters of clayey Miocene, and additionally in the southern part, the flysch complex, which - apart from the existence of hydrocarbon fields - in this case demonstrates the possibility of safe storage of CO_2 in carbonates (all other saline aquifer structures occur in clastic formations, mainly sandstones).

In addition, in the area IVA the Zatoka Gdowska site was analyzed (**Fig. 3_18**), overlapping in part of the area of the Niepołomice site discussed above. The reservoirs in the Zatoka Gdowska site are sandstones and conglomerates of clastic (mainly Middle) Jurassic.

Potential storage sites in the area IVA are not the typical anticline structures as in Polish Lowlands, but rather sites/areas, as in the region of Upper Silesian Coal Basin (the Skoczów-Czechowice site), i.e. parts of a regional reservoir - a geological formation, limited by the dislocation zones. The efficiency of storage is thus rather low.

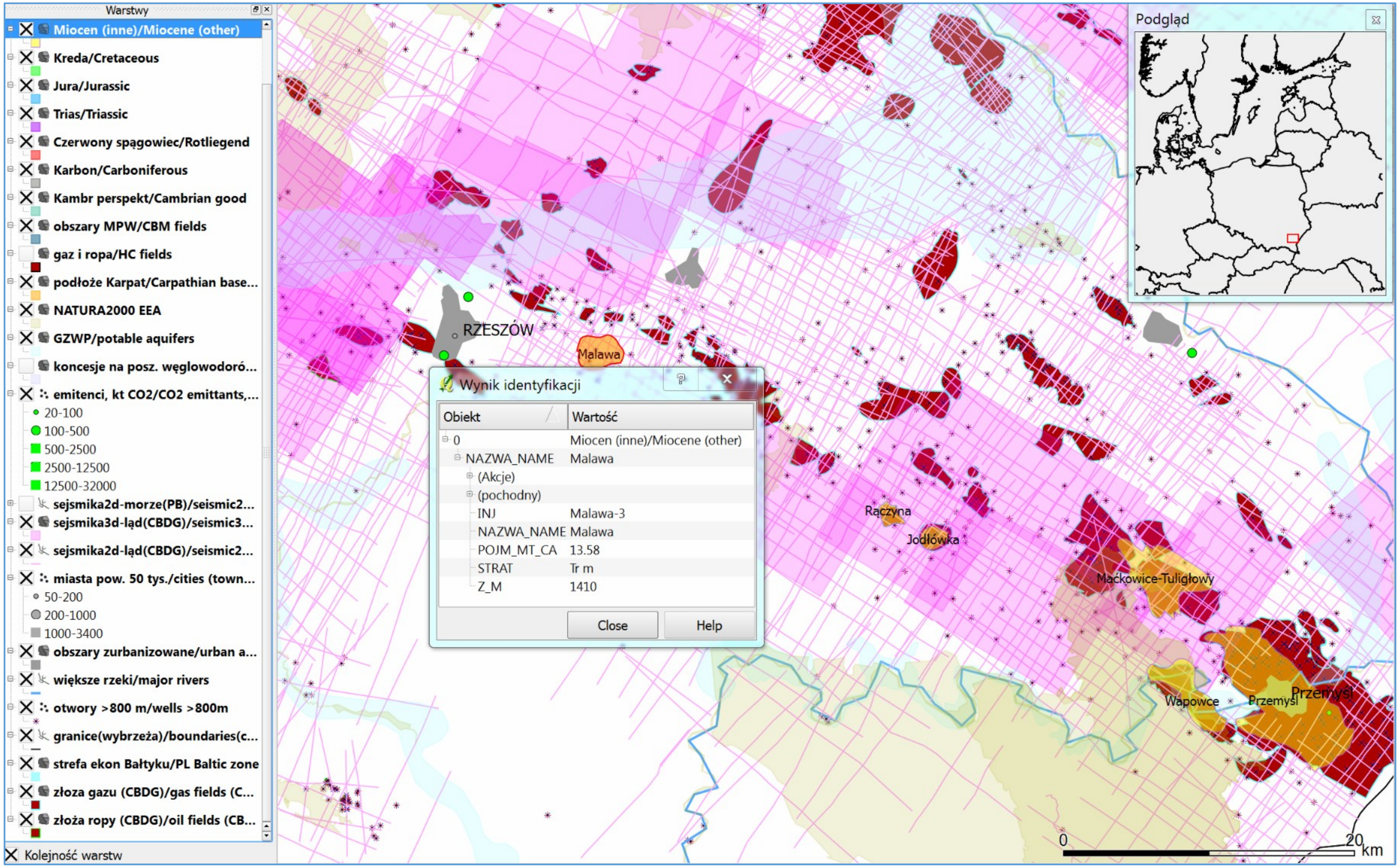
Suggested ranking of the sites:

- Zatoka Gdowska (**Fig. 3_18** - clastic Jurassic, more predictable in terms of reservoir parameters and the behavior of CO_2 injected into the reservoir than carbonate reservoirs);

- Niepołomice (**Fig. 3_19**) and Grobla carbonate reservoirs (**Fig. 3_20**) (an equivalent position; Niepołomice has more protected areas and Grobla – more gas deposits on its territory, the first is easily accessible from Cracow and the second – from Tarnów), in the case of fracture-porous reservoirs, which are carbonates, reservoir properties are highly variable and generally low (but then injection of CO_2 and associated CO_2-brine-rock reactivity phenomena can cause improvements in the properties of reservoir - as in the instance of Nosówka oil field, analyzed in case studies).

Maximum feasible scenario for the Cracow agglomeration is the use of the Niepołomice and Zatoka Gdowska sites together, and possibly a small, nearby gas field Łąkta, for the needs of Arcelor Mittal steelworks in Nowa Huta (which include a power plant, blast furnace and cement plant) and a CHP plant in Cracow, but it is also possible that the detailed geological and geophysical surveys would prove that both objects are sufficient only for the purpose of Nowa Huta (and for the needs of the municipal CHP plant in Krakow, one will need to use Grobla site). However, in the case of Grobla site it will not be a problem to meet the needs of the installations of the nitrogen plant in Tarnów.

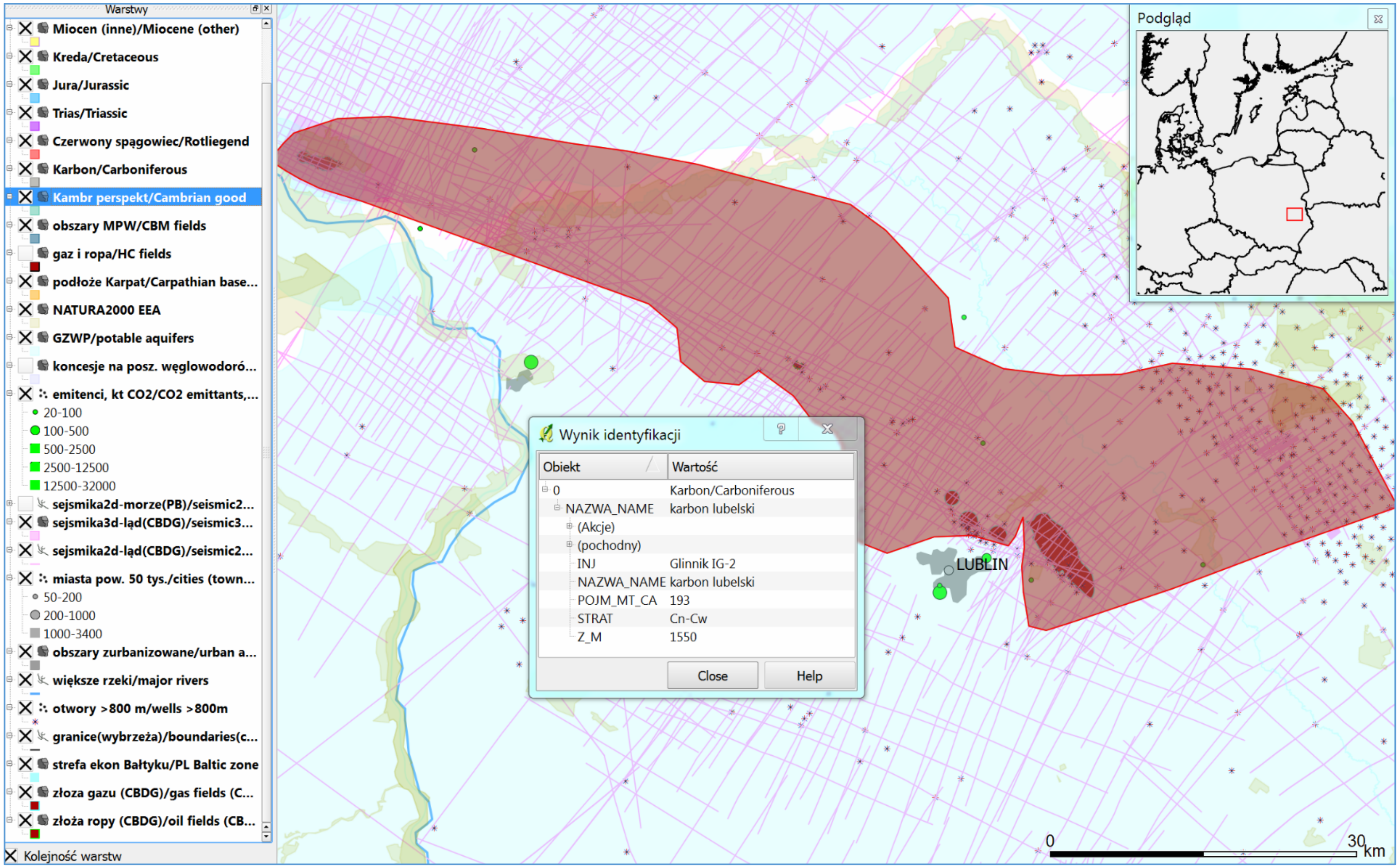
The eastern area (IVB), including small structures in the Miocene formations east of Rzeszów in the vicinity of the gas fields has been described as not prospective for geological storage of CO_2 in saline aquifers. Although locally, close to the gas fields, reservoir properties of Miocene aquifers are relatively good, due to the small thickness of these reservoirs, the resulting storage capacities are very small - the largest for Malawa structure (**Fig. 3_21**). From the viewpoint of CO_2 sequestration they are irrelevant unless they would be considered together with the adjacent gas fields (Malawa structure is adjacent to the gas fields Husów-Albigowa-Krasne).



Obiekt	Wartość
0	Miocen (inne)/Miocene (other)
NAZWA_NAME	Malawa
(Akcje)	
(pochodny)	
INJ	Malawa-3
NAZWA_NAME	Malawa
POJM_MT_CA	13.58
STRAT	Tr m
Z_M	1410

Fig. 3_21 Saline aquifer structures in Miocene in eastern part of the Carpathian overthrust front

V – Lublin (and Podlasie) region



Wynik identyfikacji

Obiekt	Wartość
0	Karbon/Carboniferous
NAZWA_NAME	karbon lubelski
(Akcje)	
(pochodny)	
INJ	Glinnik IG-2
NAZWA_NAME	karbon lubelski
POJM_MT_CA	193
STRAT	Cn-Cw
Z_M	1550

Fig. 3_22 Prospective area for CO_2 geological storage in Carboniferous, in Lublin region

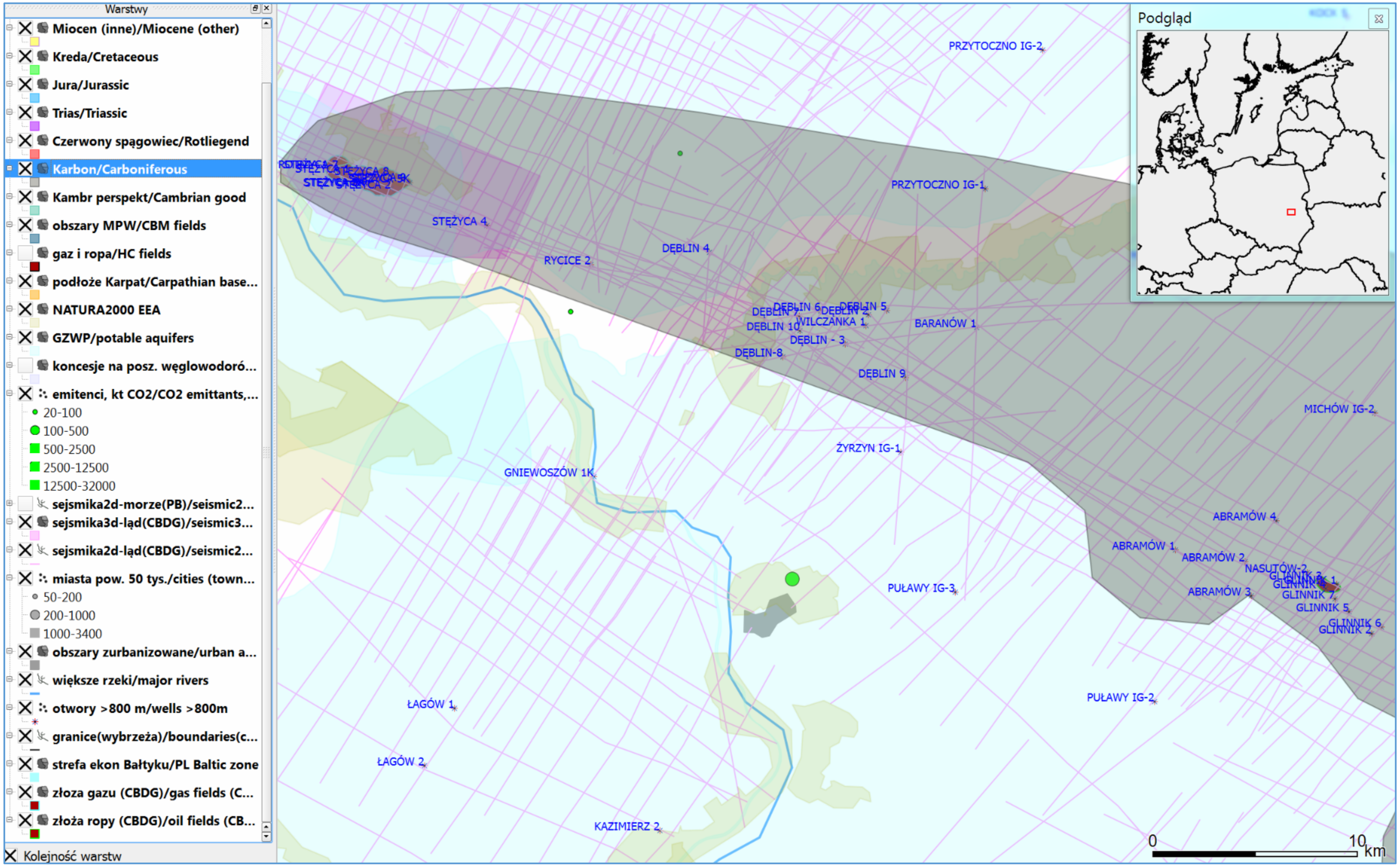


Fig. 3_22A NW part

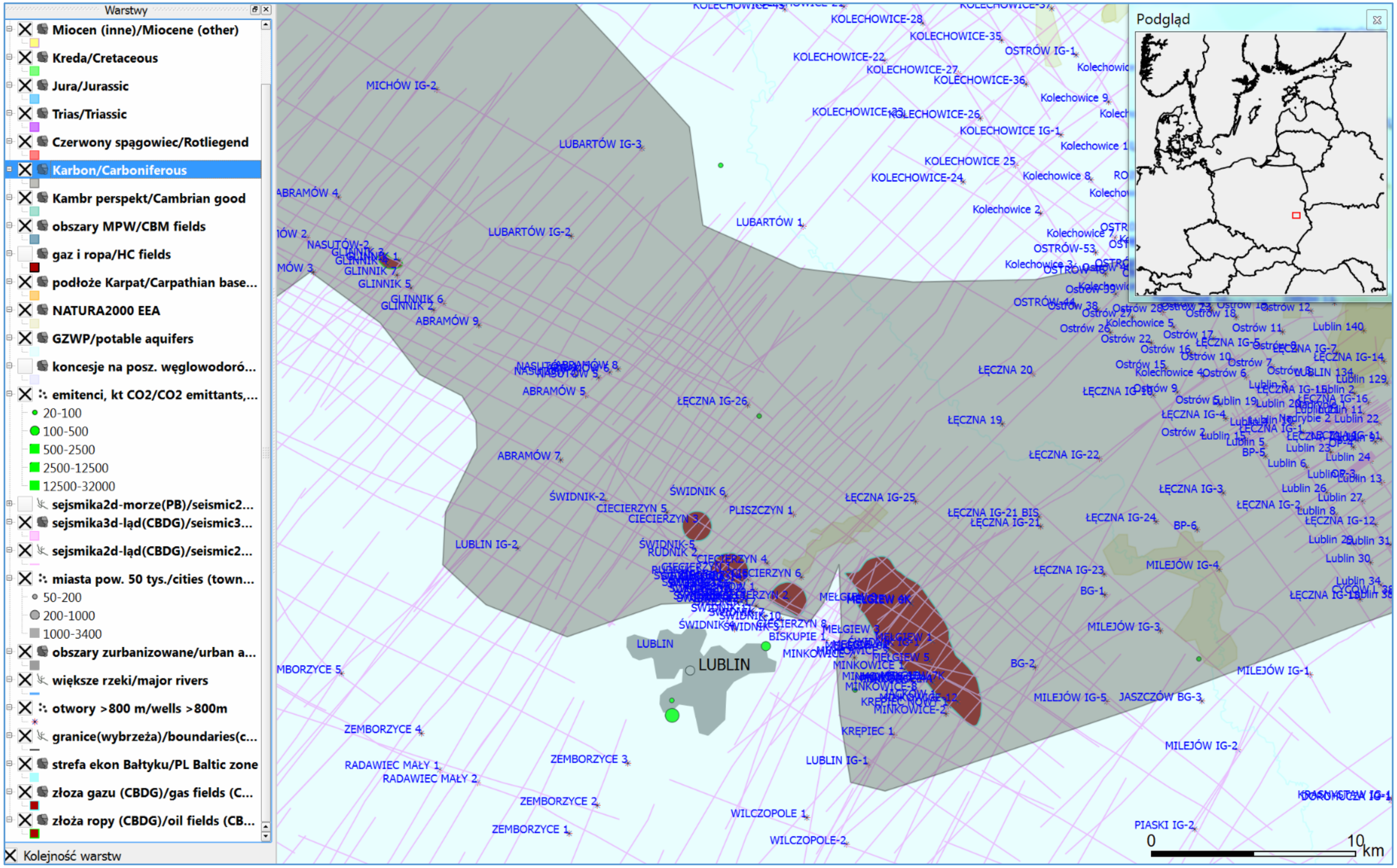


Fig. 3_22B SE part

In the Lublin region a prospective area was specified, in which there are adequate reservoir and seal facies within the Upper Carboniferous (Namurian-Westphalian). This area extends from Stężyca to Lublin and further east/northeast (**Fig. 3_22**). The problem is that a large horizontal and vertical variability of reservoir parameters occurs within the Namurian-Westphalian complex and multiple reservoir horizons of small thickness exist there.

As a result, the estimated storage capacity for the regional aquifer (C3) is indicative in nature and relates more to the lower limit of storage capacity of the whole prospective zone (**Fig. 3_22**). Therefore, we cannot propose the ranking of structures, but only possible scenarios for the area prospective for sequestration in the region of Lublin.

In this area, one can specify multiple potential injection points, depending on recipients (the CHP plants of Lublin, or installations of the nitrogen plant in Puławy): Stężyca 1, 2; Rycice 2; Deblin 7; Wilczanka 1; Abramów 1; Kock 2; Glinnik 2; Lubartów IG-3; Nasutów 1; Lublin IG-2; Łęczna IG-25; Świdnik IG-1; Lublin IG-1, Piaski IG-2; Łęczna IG-13; Busówno IG-1; Łęczna IG-9. We can say indicatively that the wells of Stężyca 1 to Glinnik 2 and Nasutów 1 inclusive may be suitable for Puławy (western part of the map in **Fig. 3_22**, see **Fig. 3_22A**) and from Glinnik 2 and Nasutów 1 to Łęczna IG-9 - for the CHP plants in Lublin (**Fig 3_22B**).

When it comes to conflicts of interest on the use of natural resources in the Lublin region, there is no significant threat to the potable aquifers or NATURA 2000 areas, and the prospects for the discovery of shale gas in the selected area seem to be faint (PGI-NRI Report, 2012).

However, in the Podlasie region two reservoir horizons of Cambrian sandstones with good reservoir properties were found in several wells, but this area (**Fig. 3_23**) is poorly explored by seismic surveys (with the exception of the westernmost part), and hence the only reliable information about the structural setting of the Cambrian is derived from extrapolation of data acquired in several wells. We have, therefore a regional aquifer, and in fact several smaller areas around the wells Tłuszcz IG-1, Łochów IG-1, Łochów IG-2, Wrotnów IG-1, Stadniki IG-1 and Mielnik IG-1; probably within the zones of troughs and horsts of the Pre-Cambrian basement. The estimated storage capacity for the regional aquifer (**Fig. 3_23**) is a very approximate (moderately pessimistic) and the sweep (storage) efficiency factor here is rather low.

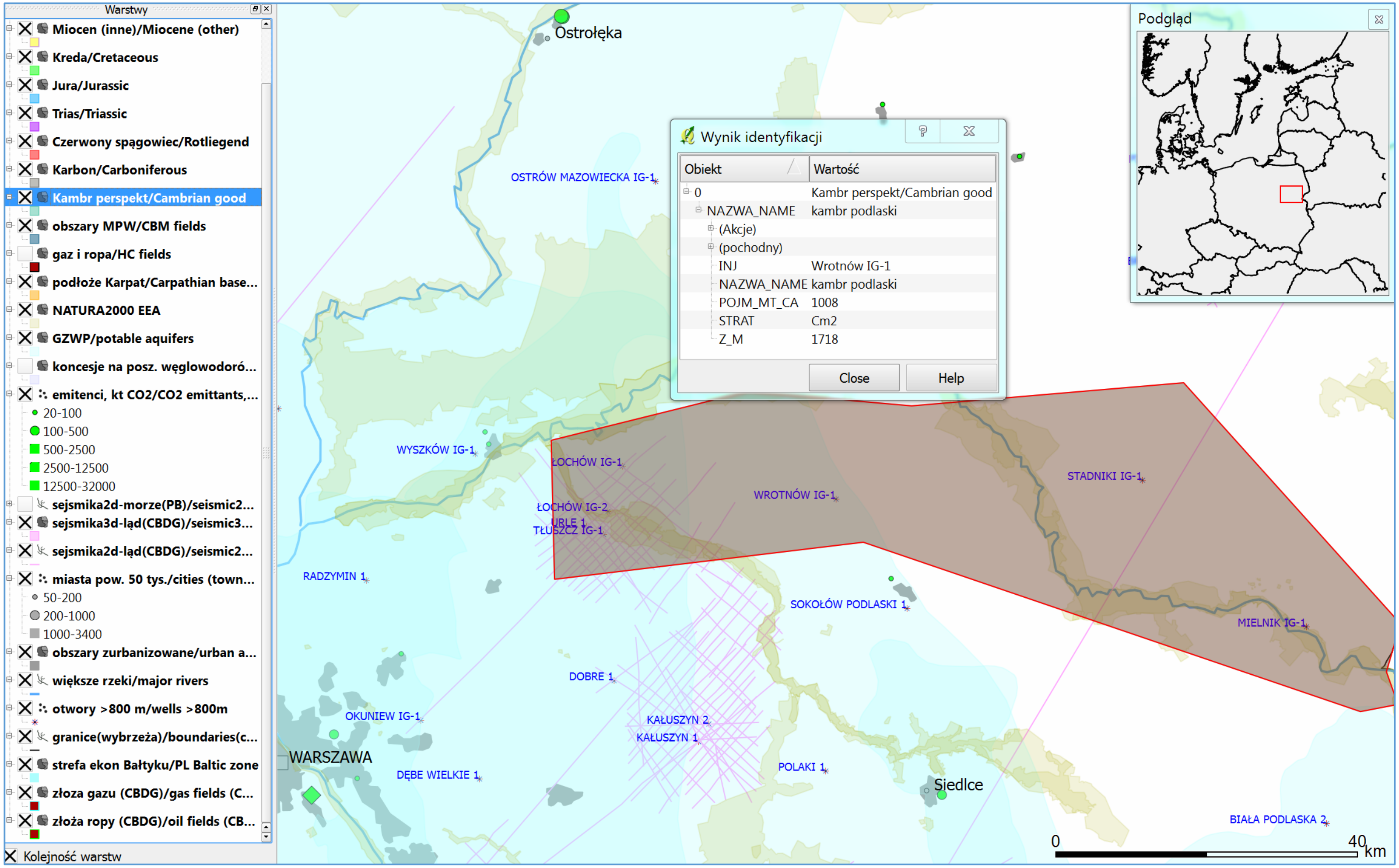
Therefore, we cannot propose the ranking of structures, but only possible scenarios for the area prospective for sequestration in the region of Podlasie.

Mentioned above wells may be taken as potential injection points for different scenarios. However, the only major emittant nearby is the power plant in Ostrołęka (about 55 km NW of the area), apart from, located at a similar distance to SW, CHP plants in Warsaw, for which sequestration scenarios have been already analyzed in the case of structures from the study area III. The other emittants in the region are small and very small municipal heating plants and CHP plants (the biggest of them is the CHP plant in Siedlce), and other small local industrial installations. Consequently, the ranking of these possible locations of injection is as follows, taking into consideration favorable reservoir properties and the occurrence of NATURA 2000 sites along the way (to the emittants):

- Stadniki IG-1;
- Wrotnów IG-1 and Mielnik IG-1;
- Tłuszcz IG1, Łochów IG1, Łochów IG 2.

Regarding conflicts of interest on use of natural resources in the region of Podlasie, there is no significant threat to the potable aquifers or NATURA 2000 protected areas, and the selected area seems to be non-perspective for the occurrence of shale gas fields (PGI-NRI Report, 2012).

.



Obiekt	Wartość
0	Kambr perspekt/Cambrian good
NAZWA_NAME	kambr podlaski
(Akcje)	
(pochodny)	
INJ	Wrotnów IG-1
NAZWA_NAME	kambr podlaski
POJM_MT_CA	1008
STRAT	Cm2
Z_M	1718

Fig. 3_23 Prospective area for CO$_2$ geological storage in Cambrian, in Podlasie region

VI – Greater Poland-Kujawy

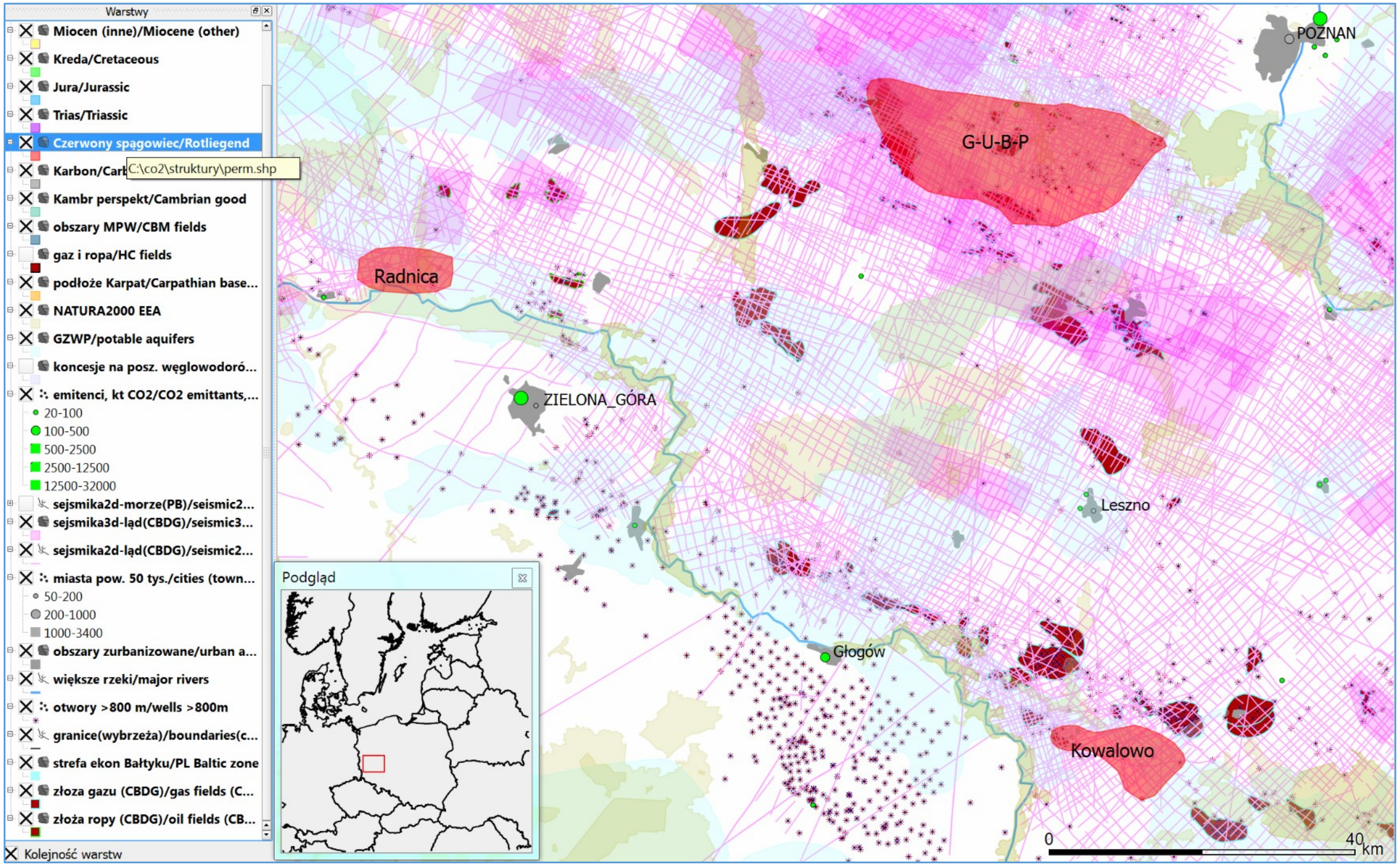


Fig. 3_24 Structures in Permian in study area VI

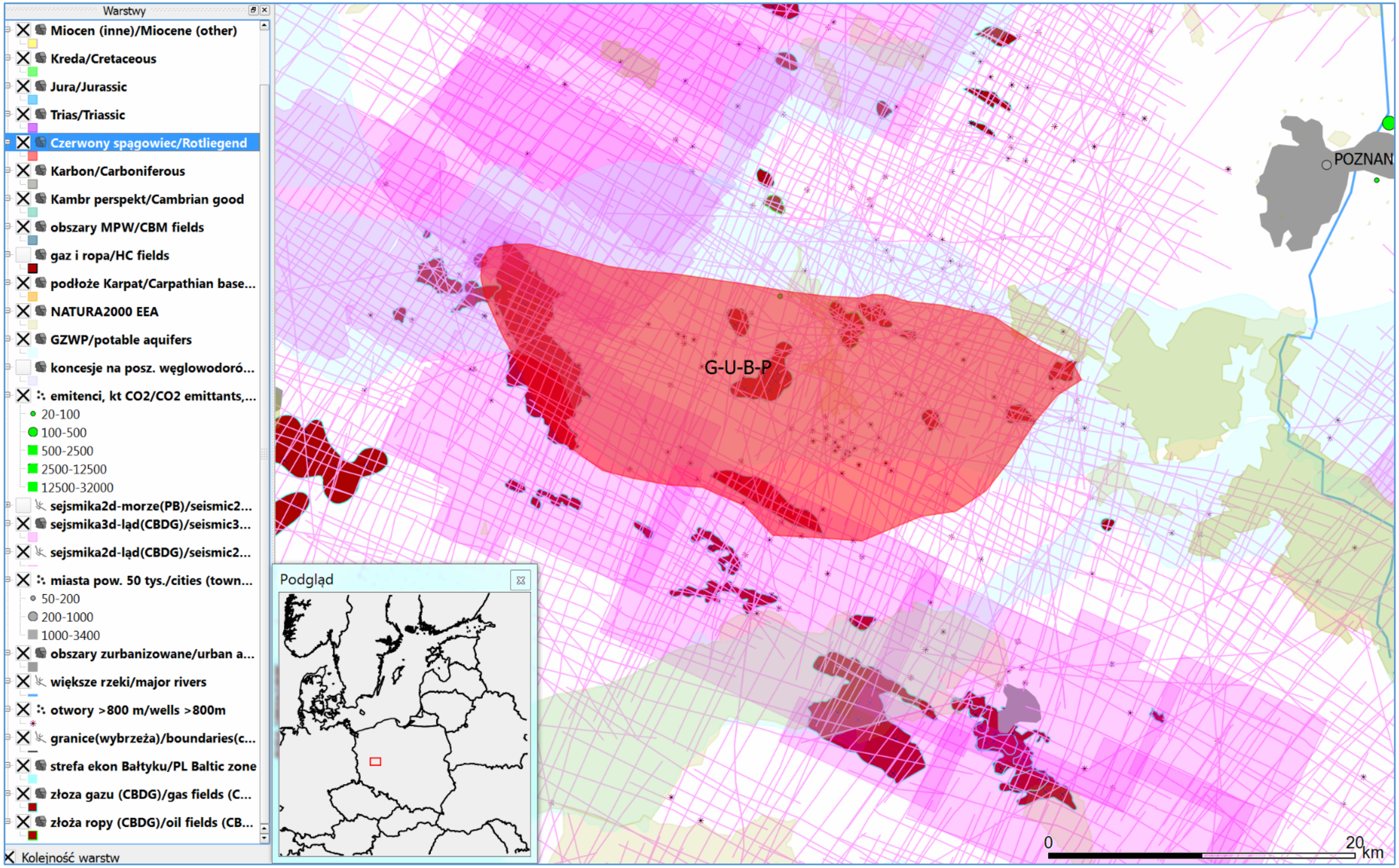
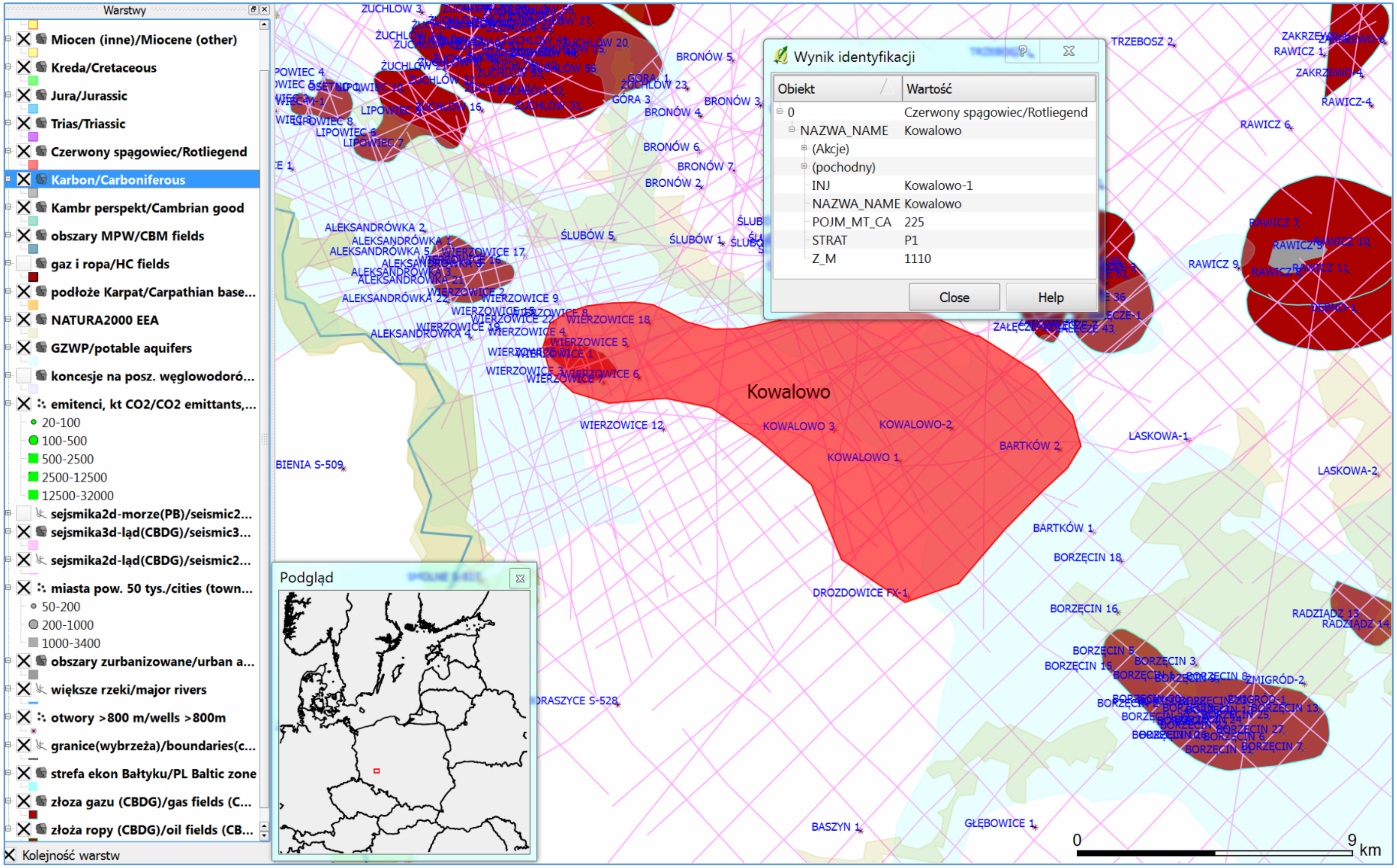
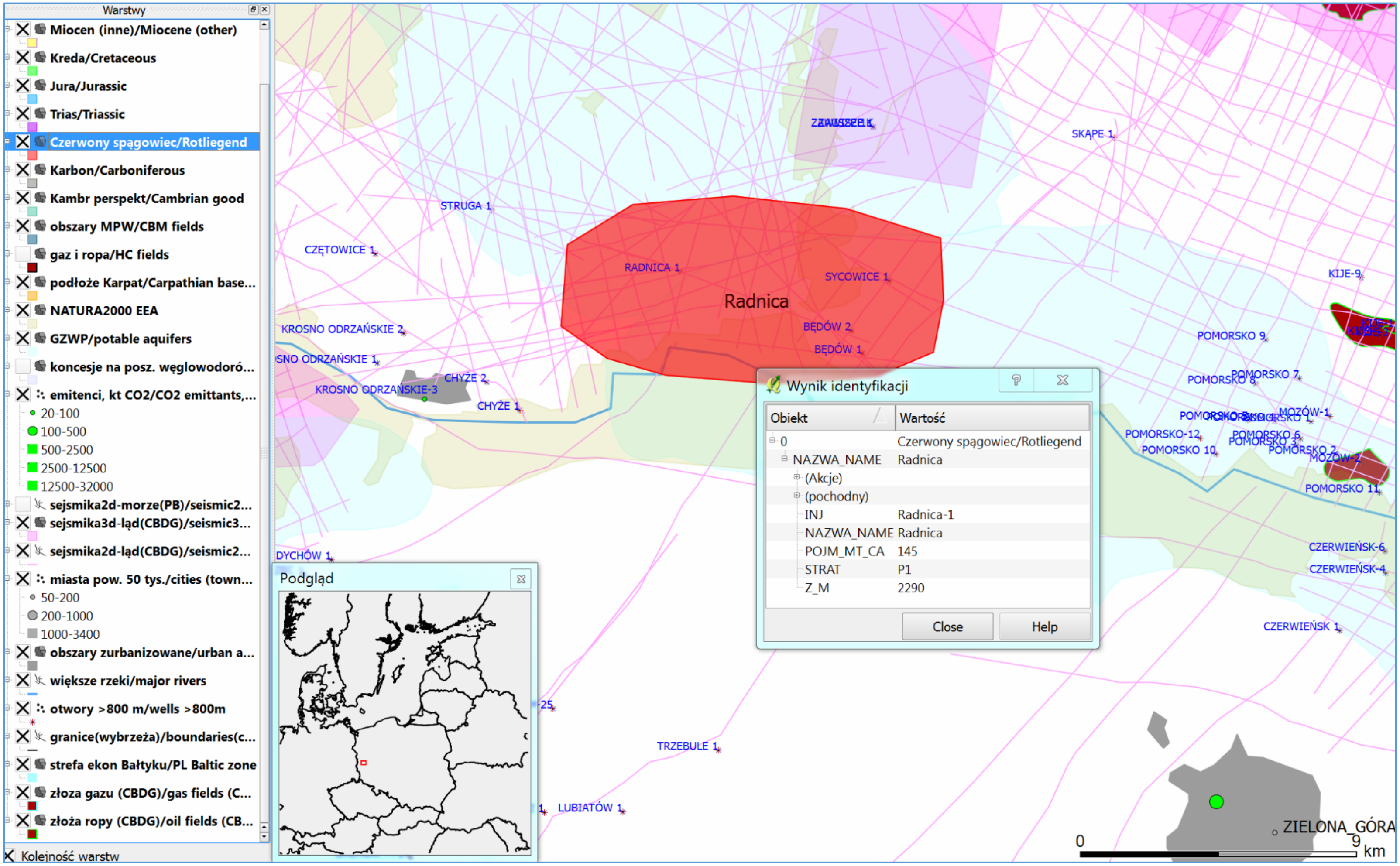


Fig. 3_25 Megastructure of Poznań trough (Grodzisk-Ujazd-Bukowiec-Paproć site) in Rotliegend



Obiekt	Wartość
0	Czerwony spągowiec/Rotliegend
NAZWA_NAME	Kowalowo
(Akcje)	
(pochodny)	
INJ	Kowalowo-1
NAZWA_NAME	Kowalowo
POJM_MT_CA	225
STRAT	P1
Z_M	1110

Fig. 3_26 Kowalowo structure in Rotliegend



Wynik identyfikacji

Obiekt	Wartość
0	Czerwony spągowiec/Rotliegend
NAZWA_NAME	Radnica
(Akcje)	
(pochodny)	
INJ	Radnica-1
NAZWA_NAME	Radnica
POJM_MT_CA	145
STRAT	P1
Z_M	2290

Fig. 3_27 Radnica site in Rotliegend

For the area of Greater Poland / Fore-Sudetic Monocline (**Fig. 3_24**) three structures in the Permian (Rotliegend) were chosen, listed below in order of their ranking, together with proposals for CCS scenarios.

- Poznań trough megastructure (Grodzisk-Ujazd-Bukowiec-Paproć - **Fig. 3_25**) is characterized by sufficient, locally rather good reservoir properties and tight caprock. It is located relatively deep, at the boundary of the recommended suitability for sequestration, but has a huge storage potential. It lies near (a distance of about 20 km) the Poznań agglomeration where we have large industrial emission sources (CHP plants) and injection of CO_2 into saline Rotliegend aquifer would improve in the long term effectiveness of the production of gas deposits located at the top of the structure (also selected for the case study).

- Kowalowo structure (**Fig. 3_26**) has a rather good reservoir properties and thick caprock of Zechstein. It is located relatively shallow, surrounded by gas fields, in the southern part of the Fore-Sudetic Monocline. In the immediate vicinity there are no major CO_2 emittants and approximately 50 km to the SE is the Wrocław agglomeration including two large CHP plants.

- Radnica site (**Fig. 3_27**) has a rather good reservoir properties (the best of the three sites under consideration here), despite the relatively large depth. This is not a typical anticlinal structure, but rather a fragment/undulation of western slope of the Fore-Sudetic Monocline. The problem may be here the presence of the NATURA 2000 protected area close to its southern edge (which means difficulties for future surveys to explore fully the site area). The nearest bigger emittant is a CHP plant in Zielona Góra (CHP).

Storage in Rotliegend is not a threat to potable aquifers in Neogene formations that occur in this area (1-2 km of rocks separates them, including hundreds of meters of impermeable Zechstein salts). Proximity of NATURA 2000 sites poses no serious conflicts of interest, as well as the presence of numerous depleted hydrocarbon fields. The problem could be the discovery and development of new hydrocarbon deposits within the considered structures.

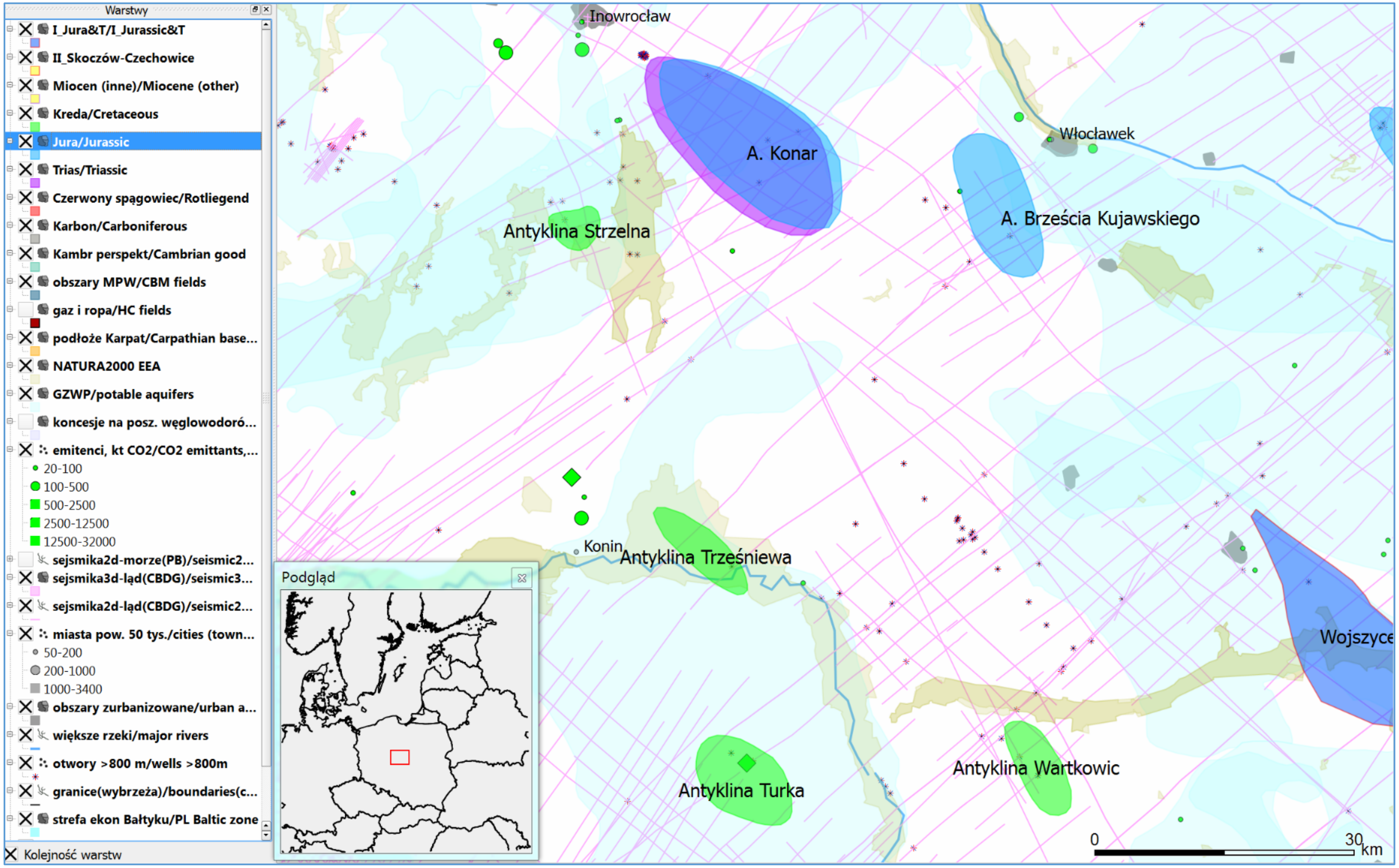
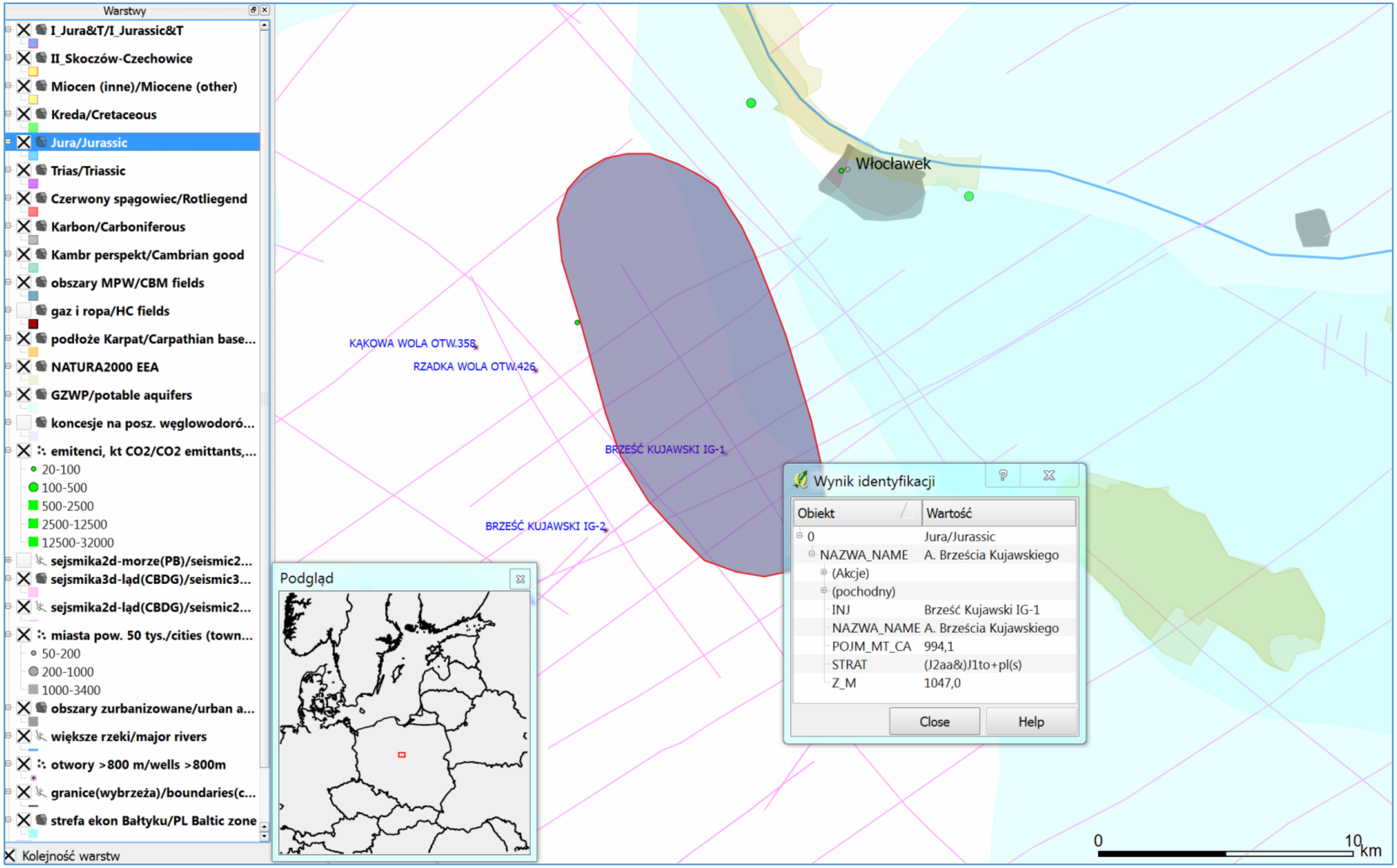


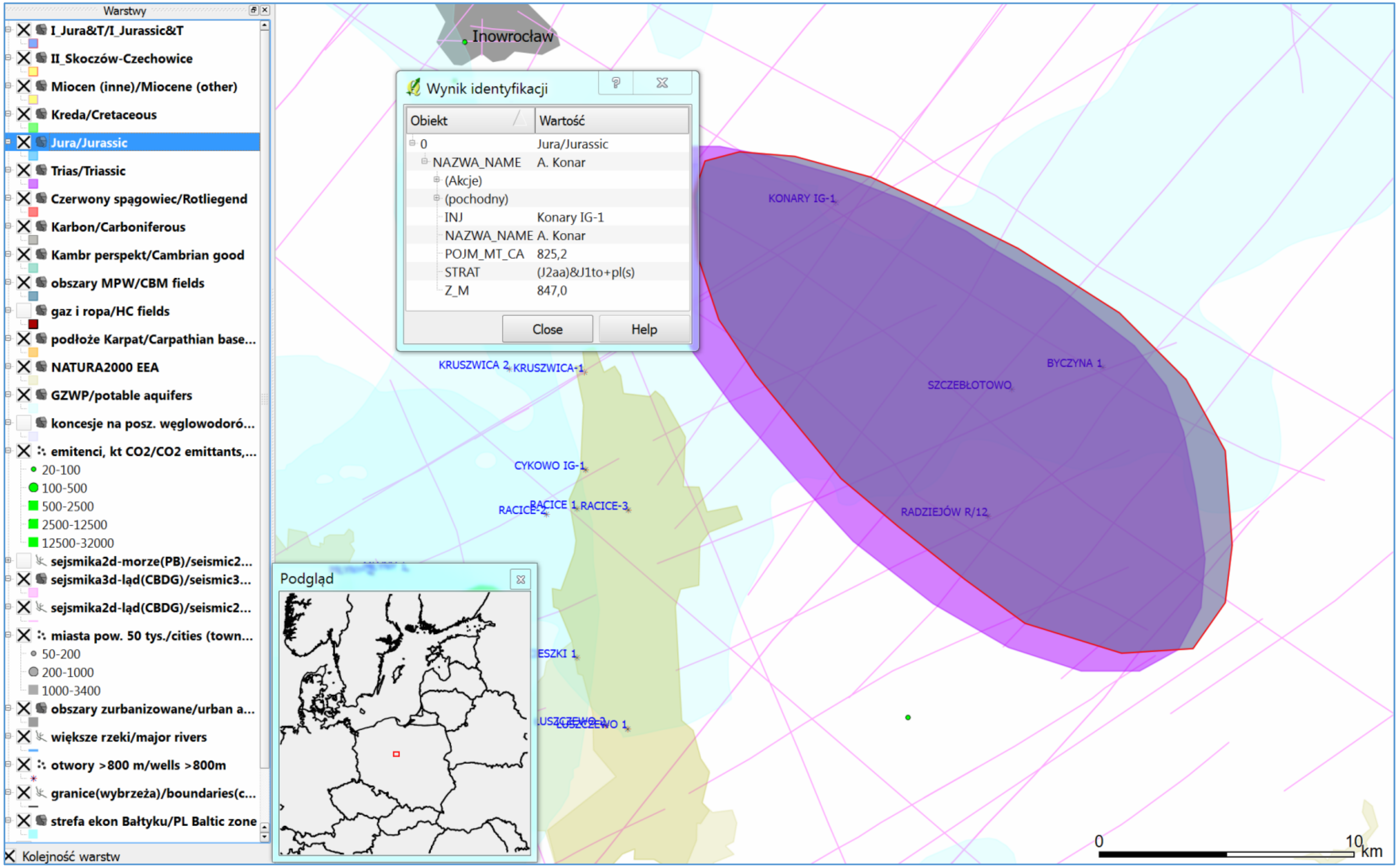
Fig. 3_28 Structures in Mesozoic in study area VI



Wynik identyfikacji

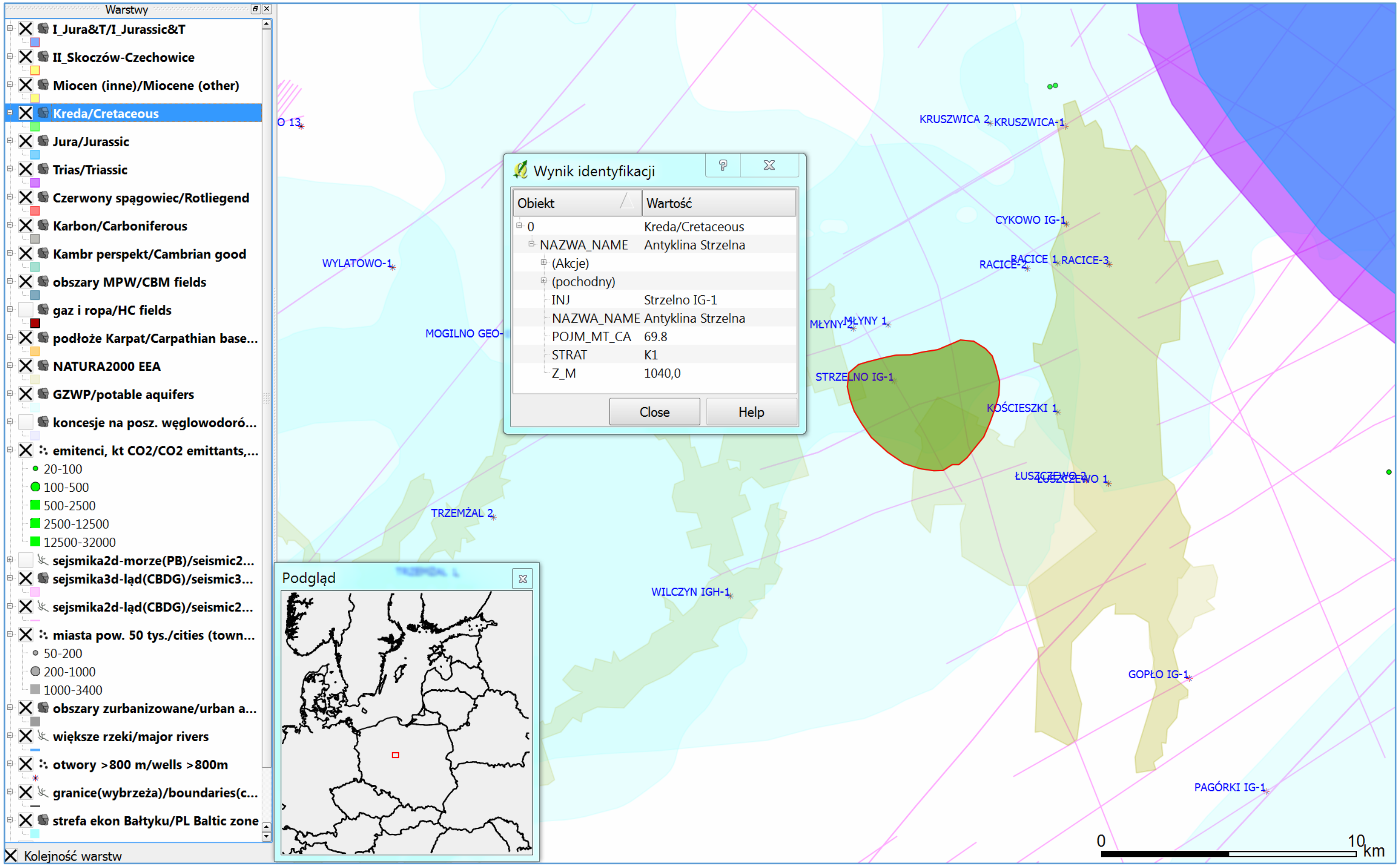
Obiekt	Wartość
0	Jura/Jurassic
NAZWA_NAME	A. Brześcia Kujawskiego
(Akcje)	
(pochodny)	
INJ	Brześć Kujawski IG-1
NAZWA_NAME	A. Brześcia Kujawskiego
POJM_MT_CA	994,1
STRAT	(J2aa&)J1to+pl(s)
Z_M	1047,0

Fig. 3_29 Brześć Kujawski anticline in Jurassic (*Brześć Kujawski IG-1 well - temperature 45 °C - Górecki [ed.] 2006a*)



Obiekt	Wartość
0	Jura/Jurassic
NAZWA_NAME	A. Konar
(Akcje)	
(pochodny)	
INJ	Konary IG-1
NAZWA_NAME	A. Konar
POJM_MT_CA	825,2
STRAT	(J2aa)&J1to+pl(s)
Z_M	847,0

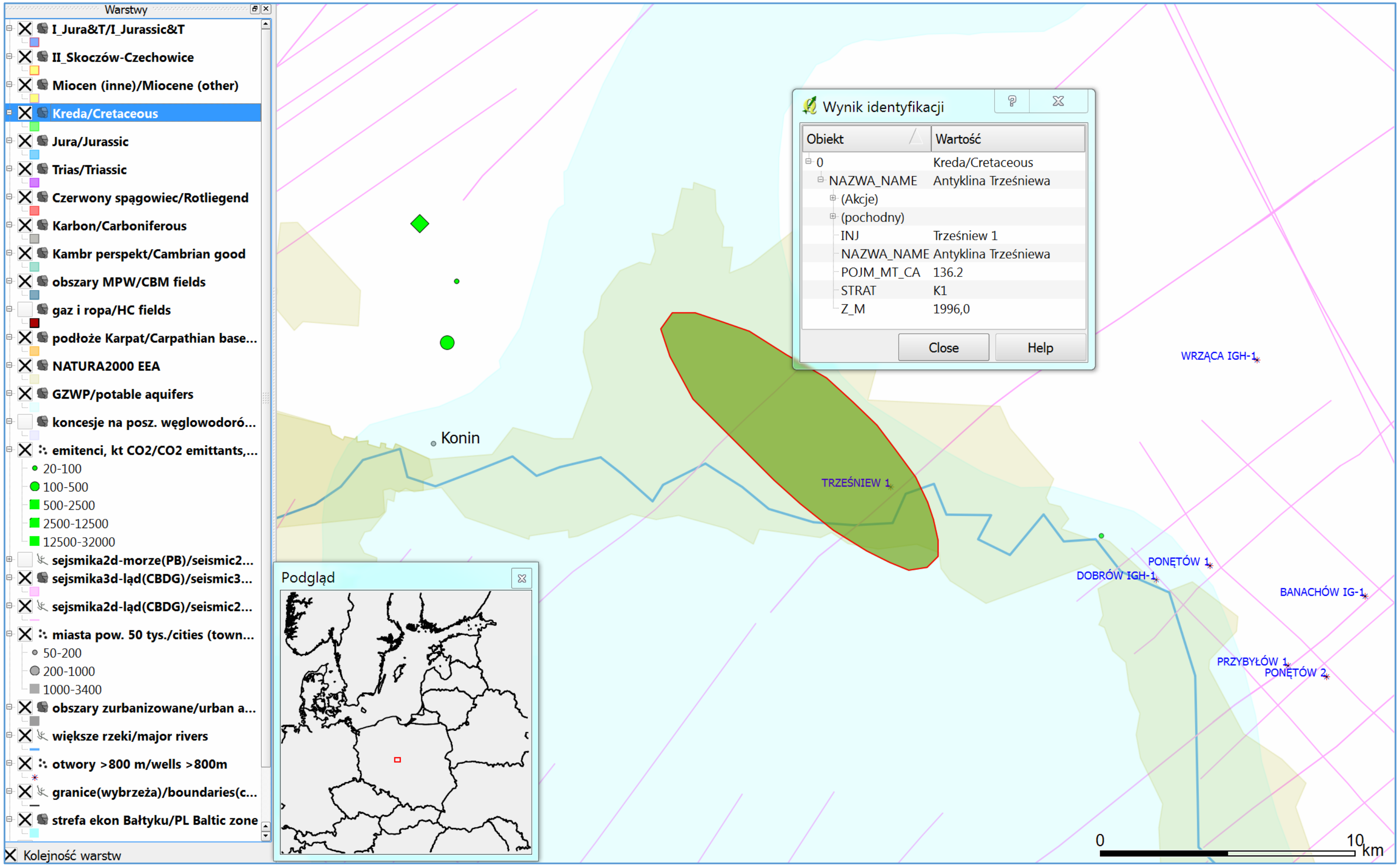
Fig. 3_30 Konary anticline in Jurassic (*Konary IG-1 well - temperature 45 °C - Górecki [ed.] 2006a*)



Wynik identyfikacji

Obiekt	Wartość
0	Kreda/Cretaceous
NAZWA_NAME	Antyklina Strzelna
(Akcje)	
(pochodny)	
INJ	Strzelno IG-1
NAZWA_NAME	Antyklina Strzelna
POJM_MT_CA	69.8
STRAT	K1
Z_M	1040,0

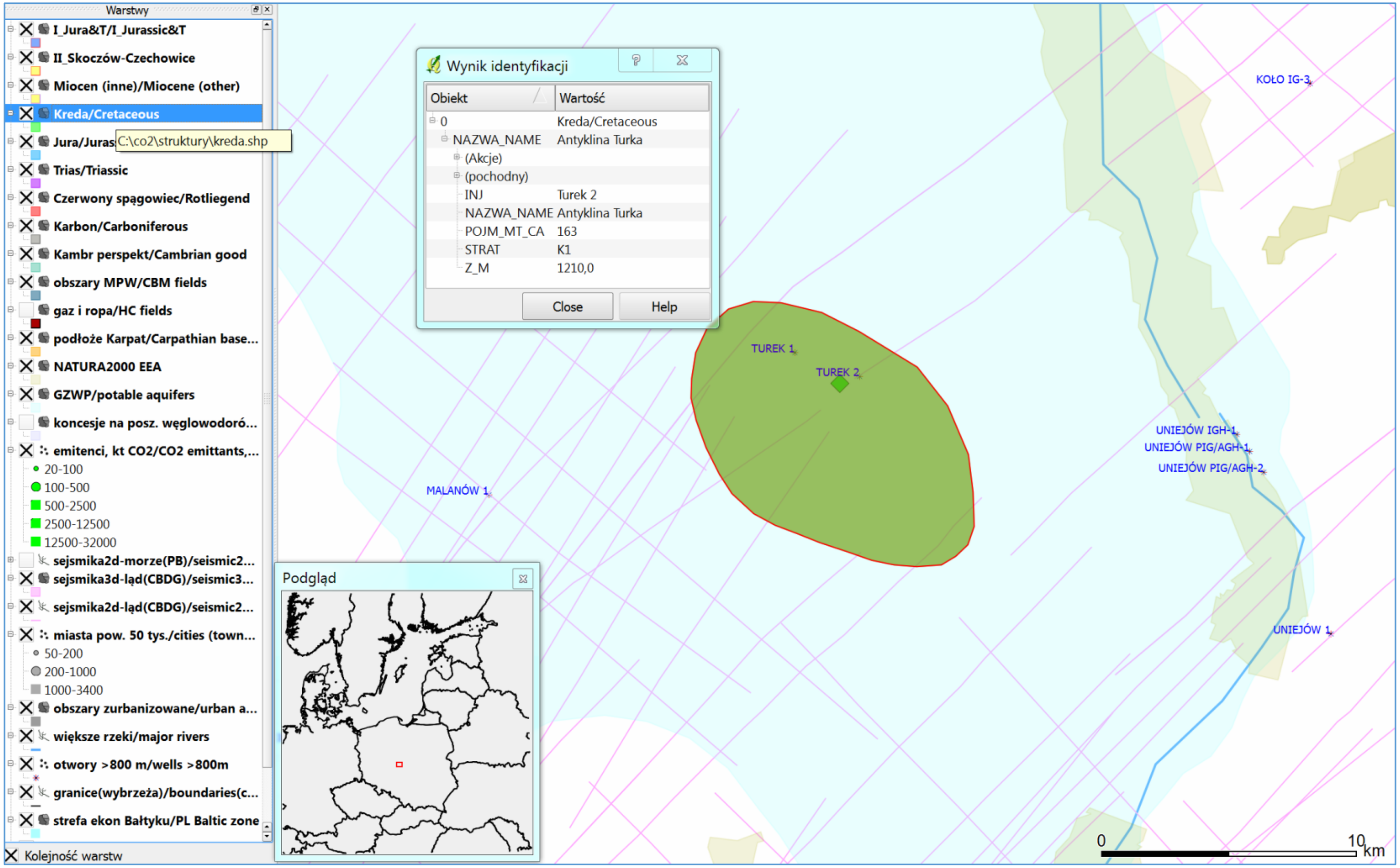
Fig. 3_31 Strzelno anticline in Lower Cretaceous



Wynik identyfikacji

Obiekt	Wartość
0	Kreda/Cretaceous
NAZWA_NAME	Antyklina Trześniewa
(Akcje)	
(pochodny)	
INJ	Trześniew 1
NAZWA_NAME	Antyklina Trześniewa
POJM_MT_CA	136.2
STRAT	K1
Z_M	1996,0

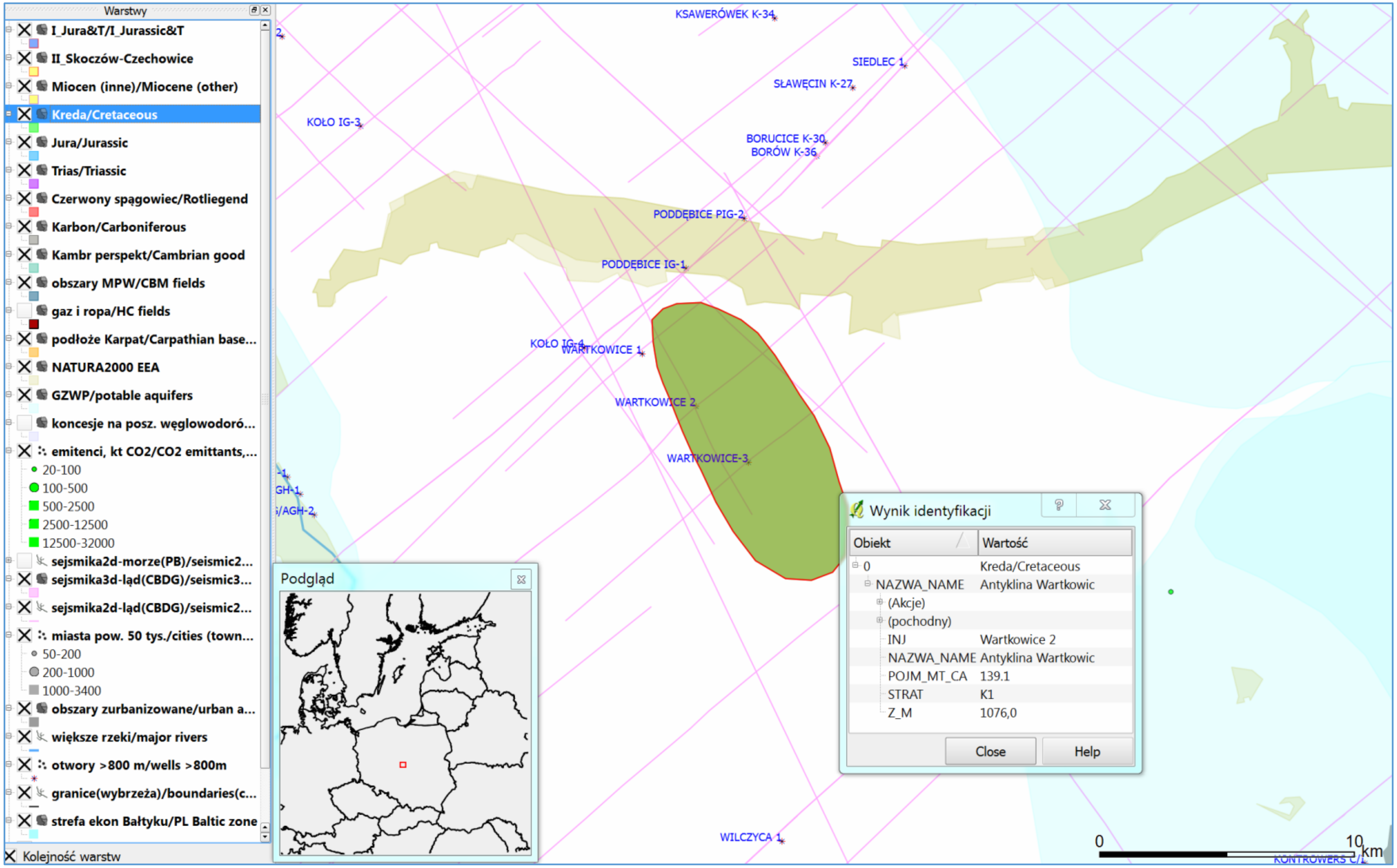
Fig. 3_32 Trześniew anticline in Lower Cretaceous



Wynik identyfikacji

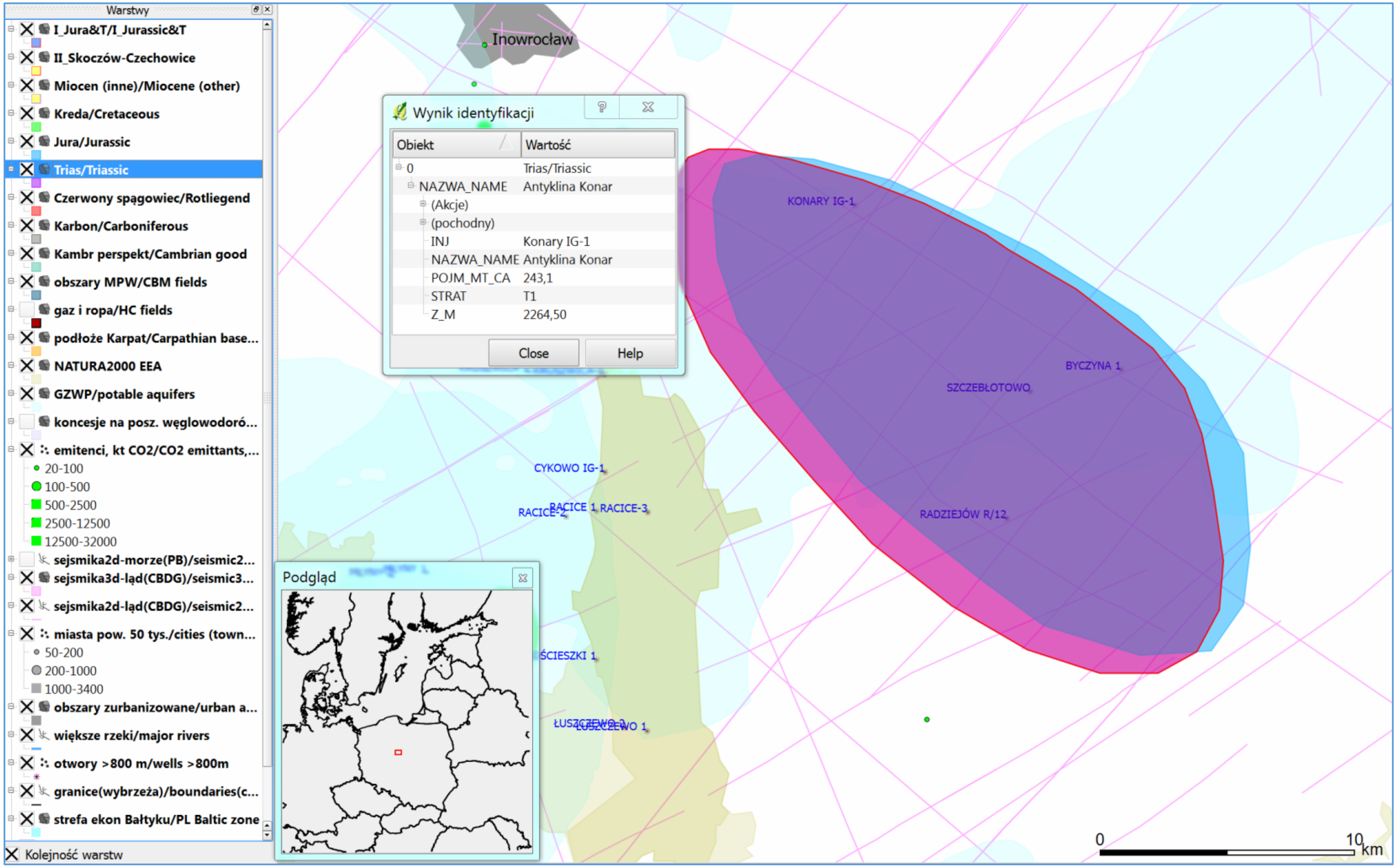
Obiekt	Wartość
0	Kreda/Cretaceous
NAZWA_NAME	Antyklina Turka
(Akcje)	
(pochodny)	
INJ	Turek 2
NAZWA_NAME	Antyklina Turka
POJM_MT_CA	163
STRAT	K1
Z_M	1210,0

Fig. 3_33 Turek anticline in Lower Cretaceous



Obiekt	Wartość
0	Kreda/Cretaceous
NAZWA_NAME	Antyklina Wartkowic
(Akcje)	
(pochodny)	
INJ	Wartkowice 2
NAZWA_NAME	Antyklina Wartkowic
POJM_MT_CA	139.1
STRAT	K1
Z_M	1076,0

Fig. 3_34 Wartkowice anticline in Lower Cretaceous



Obiekt	Wartość
0	Trias/Triassic
NAZWA_NAME	Antyklina Konar
(Akcje)	
(pochodny)	
INJ	Konary IG-1
NAZWA_NAME	Antyklina Konar
POJM_MT_CA	243,1
STRAT	T1
Z_M	2264,50

Fig. 3_35 Konary anticline in Lower Triassic

For the area of the eastern Greater Poland-Kujawy and the adjacent area of Łódź-Mogilno Trough structures in the Jurassic, Cretaceous and Triassic were selected (**Fig. 3_28**).

From the viewpoint of storage safety, the feasibility and reservoir properties the following ranking and suggestions on sequestration scenarios can be determined:

- Brześć Kujawski anticline (**Figure 3_29**) includes thick reservoirs of Borucice formation (top Lower and to a lesser extent, Middle Jurassic) and a number of reservoirs within the Drzewice and Ostrowiec formations (Lower Jurassic). This is an example of the multi-level sequestration system of significant storage capacity. The nearest bigger emittant is the nitrogen plant (and a municipal heating plant) in Włocławek, but the structure potential is more than sufficient for the storage of emissions of the lignite fired power plant of PAK in Konin, located at a distance of about 55 km.

- Konary anticline (**Fig. 3_30**) includes reservoirs of Borucice formation (J1/J2) and a number of reservoirs within the Drzewice and Ostrowiec formations (J1) and in Bunter Sandstone. Within about 25 km NW, in the region of Inowrocław there are several larger and smaller industrial sources of CO_2 emissions (the CHP plants of sodium carbonate works in Inowrocław and Janików, district heating plants, the cement plant in Piechcin) whose emissions, when recalculated to tens of years of operation of the installations, correspond to a fraction of the potential of the structure.

- Strzelno, Trześniew, Turek and Wartkowice anticlines (**Fig. 3_31 - 34**) are structures in the Lower Cretaceous, of medium size, whose suitability for storage is not a quite certain (the seal of the Lower Cretaceous is a carbonate-marly-mudstone complex with a thickness of about one kilometer, rather impermeable according to laboratory analyzes carried out within this project; faults at the base of the complex may be leaking, but in the light of the geochemical analyzes there is rather no threat to the potable aquifers in the formations of the Upper Cretaceous - the storage is optional, after a detailed exploration of the reservoir with new geological and geophysical surveys). One-two structures would suffice for the storage of emissions from the lignite fired power plant Adamów of PAK in Turek (the plant lies within the area of Turek structure). Trześniew anticline lies mostly within the NATURA 2000 protected area.

- Konary anticline in the Lower Triassic formations – the Bunter Sandstone (**Fig. 3_35**) is characterized by a relatively low share of sandstone in the Bunter Sandstone complex and rather poor reservoir properties, which is associated with a relatively large depth of occurrence of the reservoir. It can be optionally used with the structure in the Jurassic (the multi-level sequestration system).

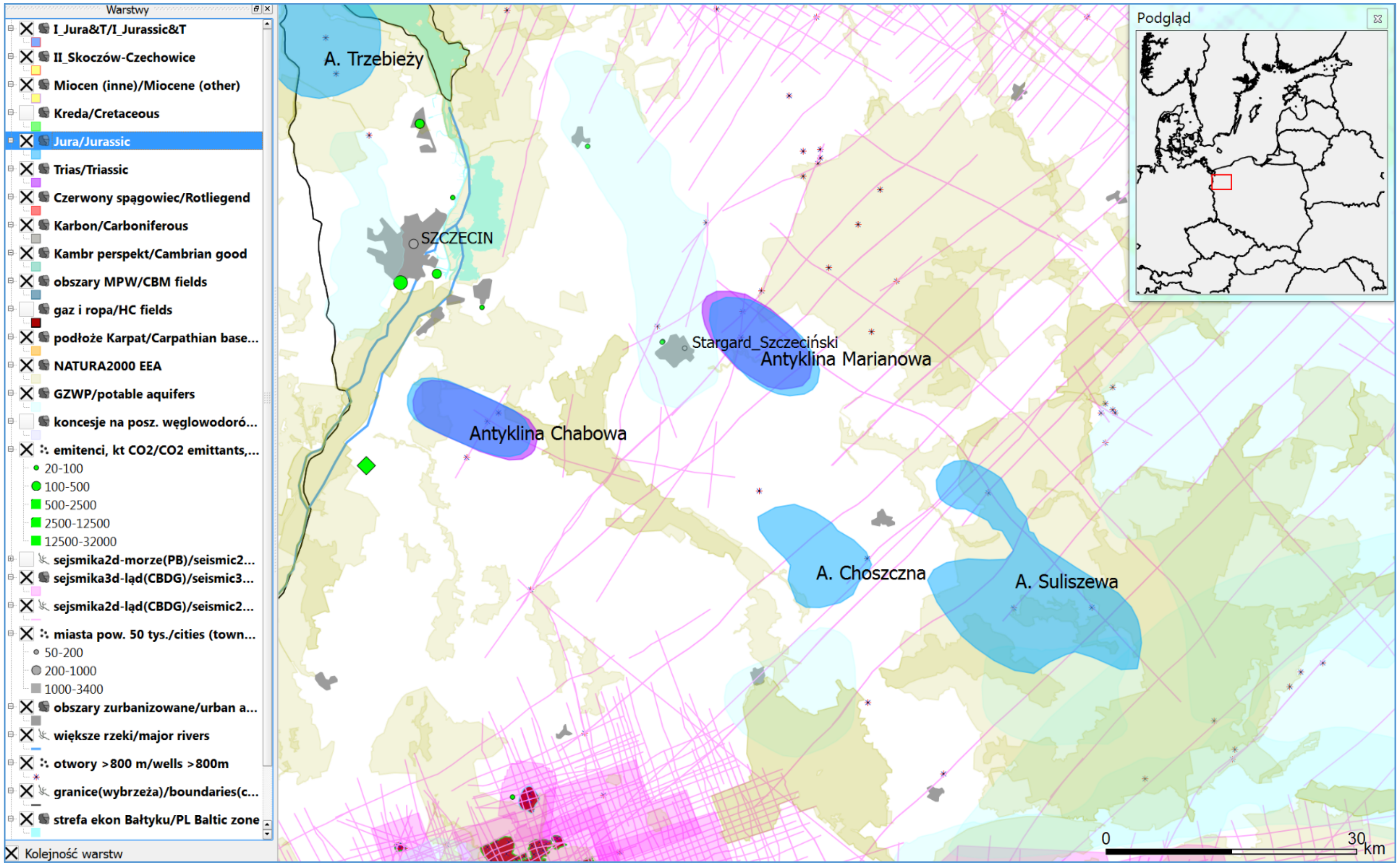
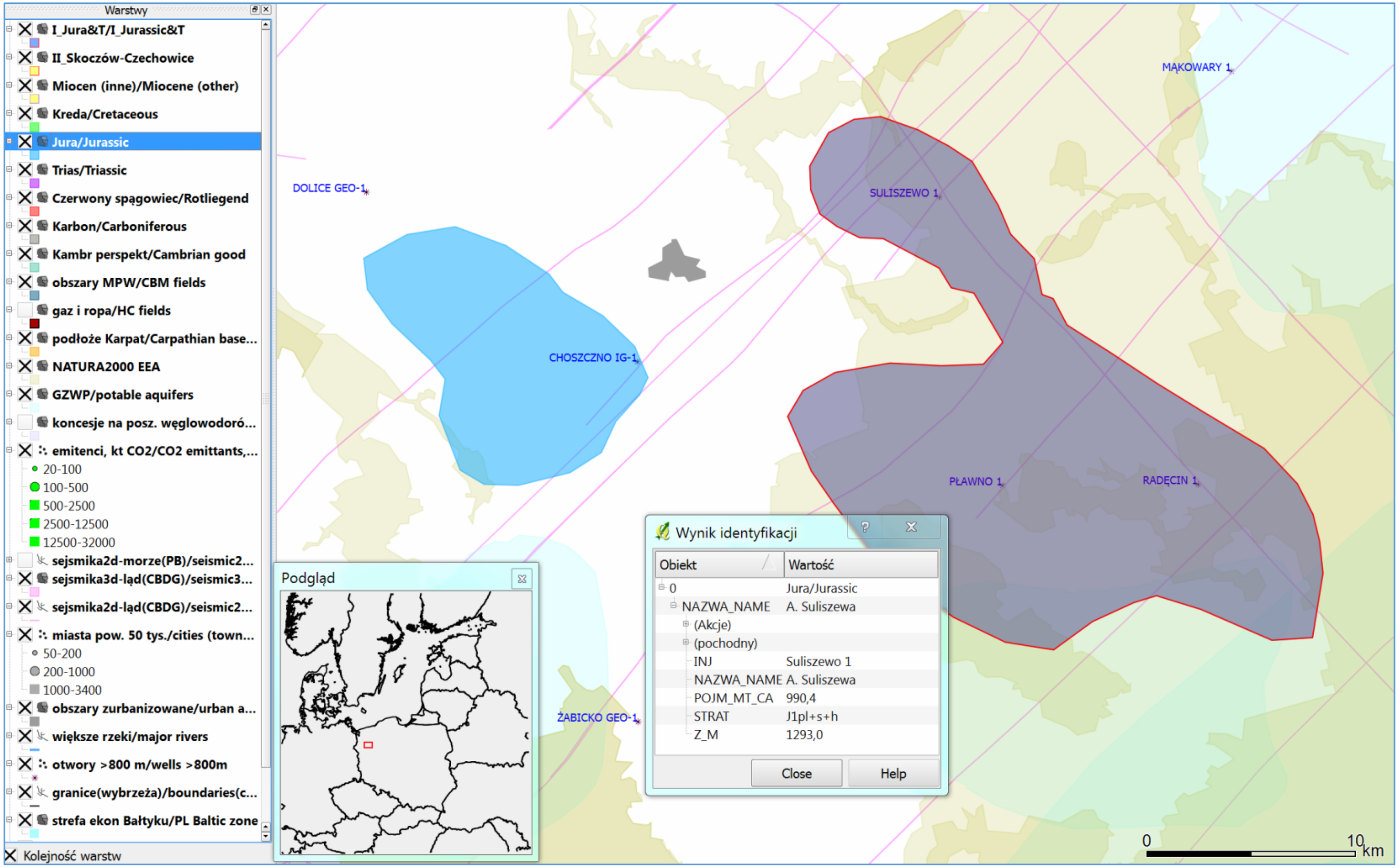
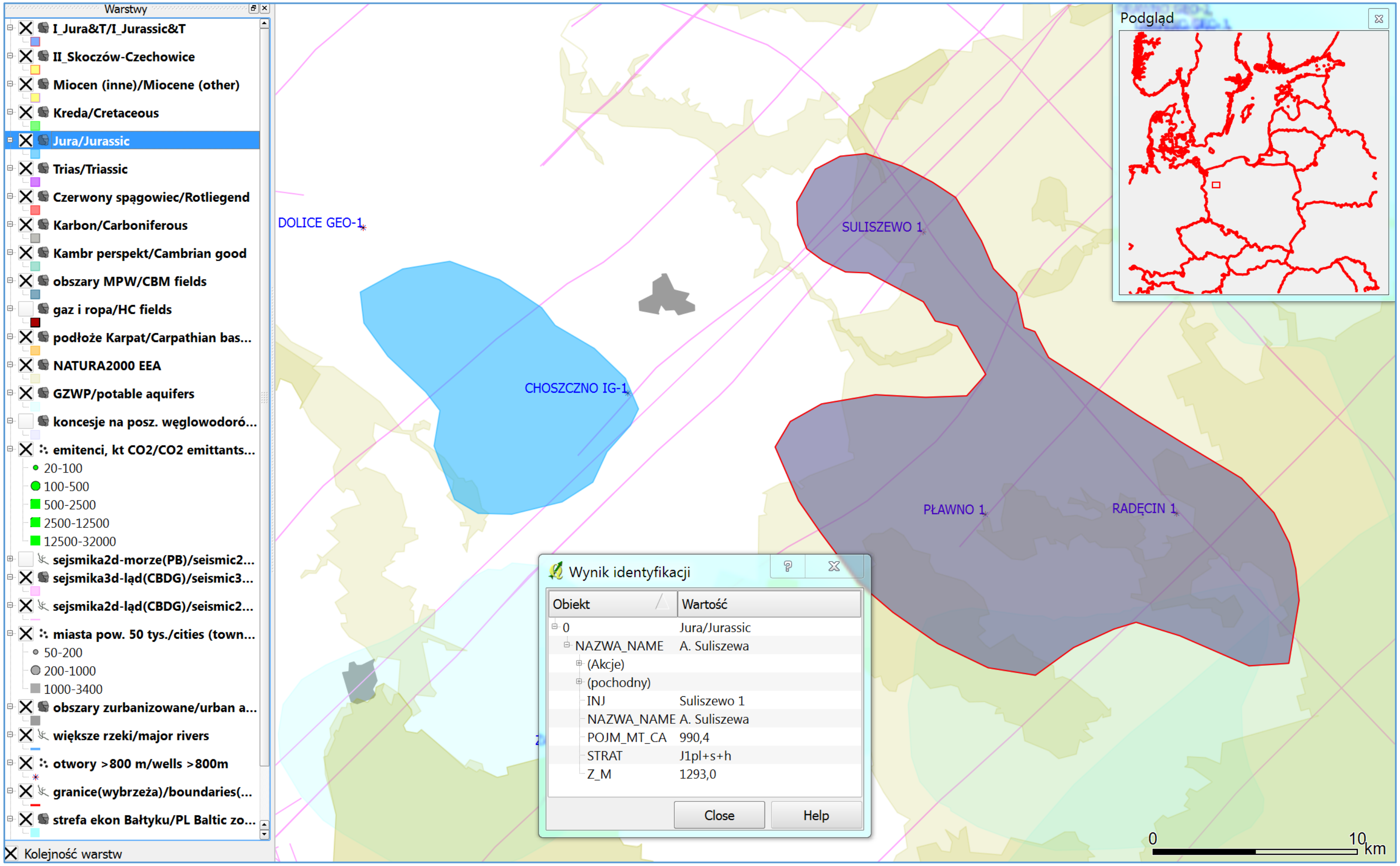


Fig. 3_36 Structures in Jurassic (and Upper Triassic) in Szczecin region



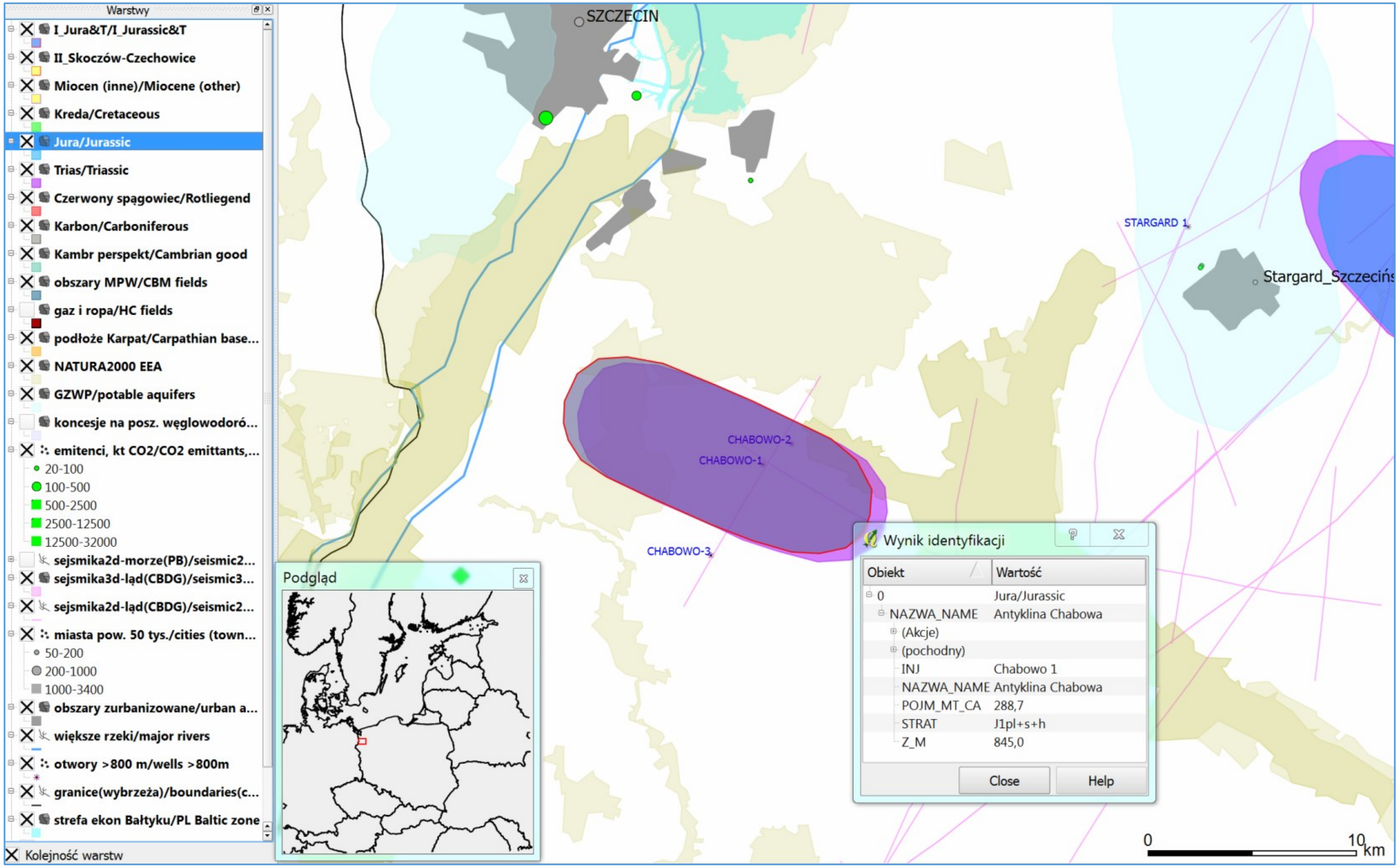
Obiekt	Wartość
0	Jura/Jurassic
NAZWA_NAME	A. Suliszewa
(Akcje)	
(pochodny)	
INJ	Suliszewo 1
NAZWA_NAME	A. Suliszewa
POJM_MT_CA	990,4
STRAT	J1pl+s+h
Z_M	1293,0

Fig. 3_37 Choszczno anticline in Lower Jurassic (*the high/top at depth of 970 m - temperature 37 °C - Górecki [ed.] 2006a*)



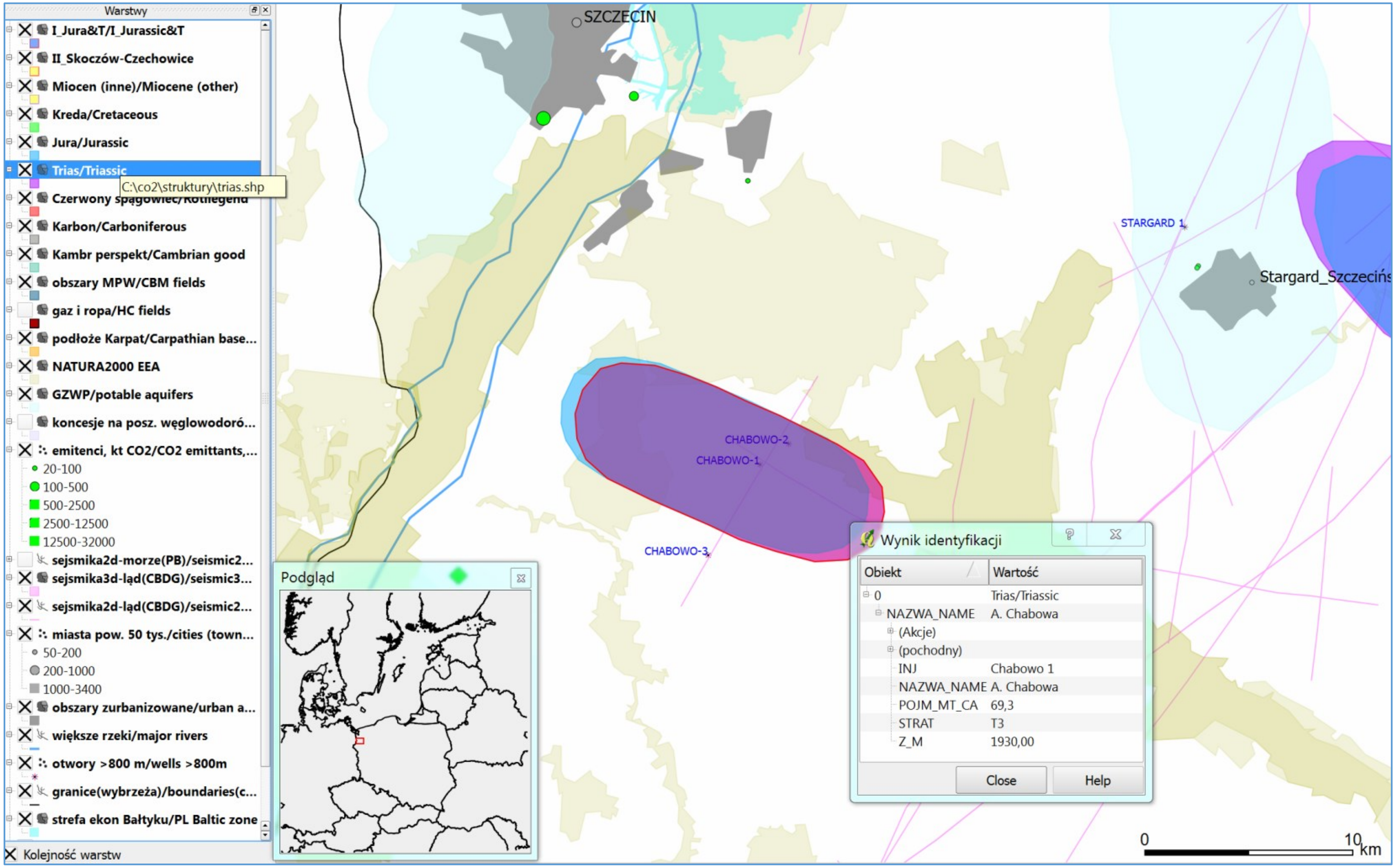
Obiekt	Wartość
0	Jura/Jurassic
NAZWA_NAME	A. Suliszewa
(Akcje)	
(pochodny)	
INJ	Suliszewo 1
NAZWA_NAME	A. Suliszewa
POJM_MT_CA	990,4
STRAT	J1pl+s+h
Z_M	1293,0

Fig. 3_38 Suliszewo anticline in Lower Jurassic (*the high/top at depth of 1220 m - temperature 44.5 °C - Górecki [ed.] 2006a*)



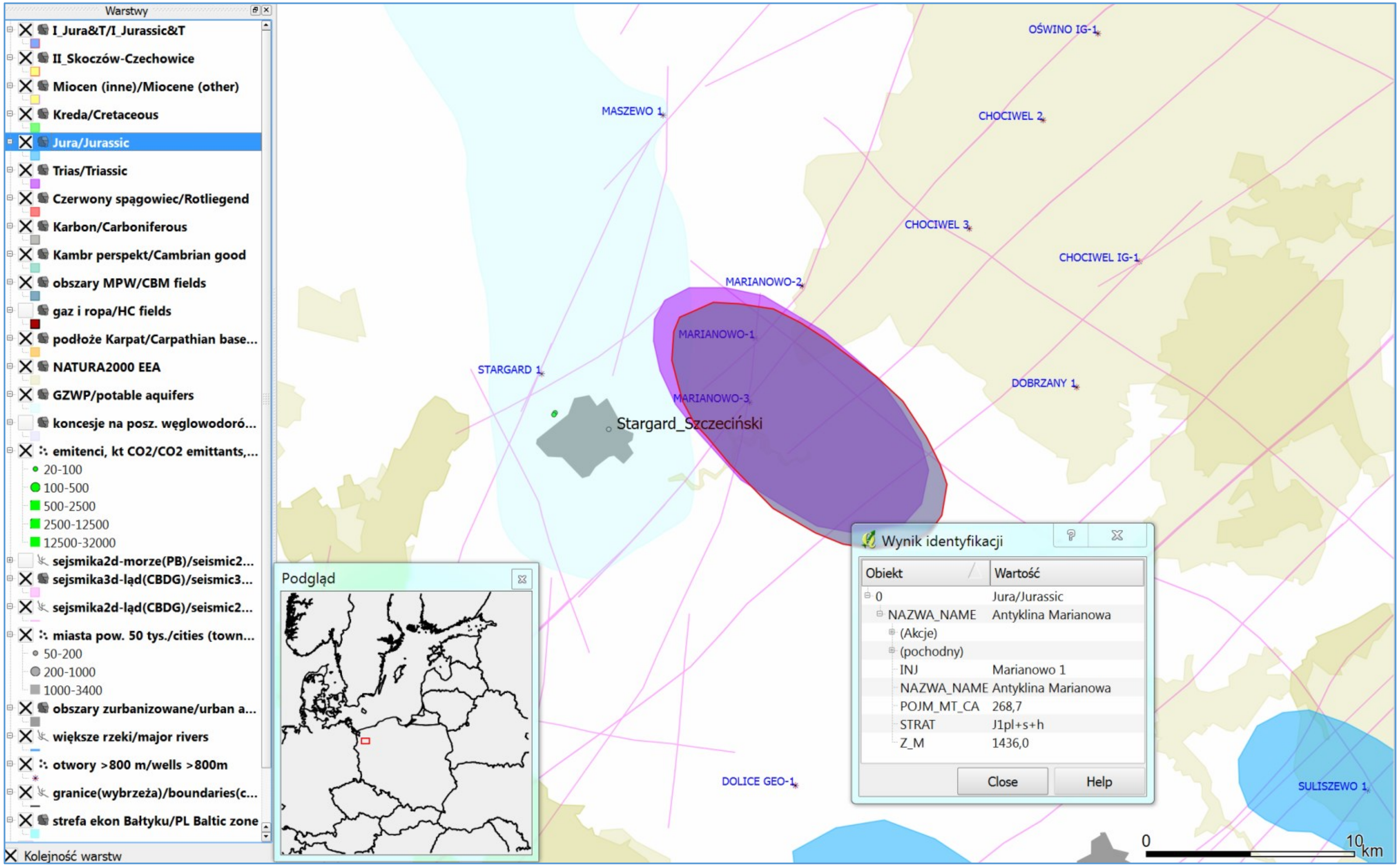
Obiekt	Wartość
0	Jura/Jurassic
NAZWA_NAME	Antyklina Chabowa
(Akcje)	
(pochodny)	
INJ	Chabowo 1
NAZWA_NAME	Antyklina Chabowa
POJM_MT_CA	288,7
STRAT	J1pl+s+h
Z_M	845,0

Fig. 3_39 Chabowo anticline in Lower Jurassic (*Chabowo-1 well - temperature 40 °C - Górecki [ed.] 2006a*)



Obiekt	Wartość
0	Trias/Triassic
NAZWA_NAME	A. Chabowa
(Akcje)	
(pochodny)	
INJ	Chabowo 1
NAZWA_NAME	A. Chabowa
POJM_MT_CA	69,3
STRAT	T3
Z_M	1930,00

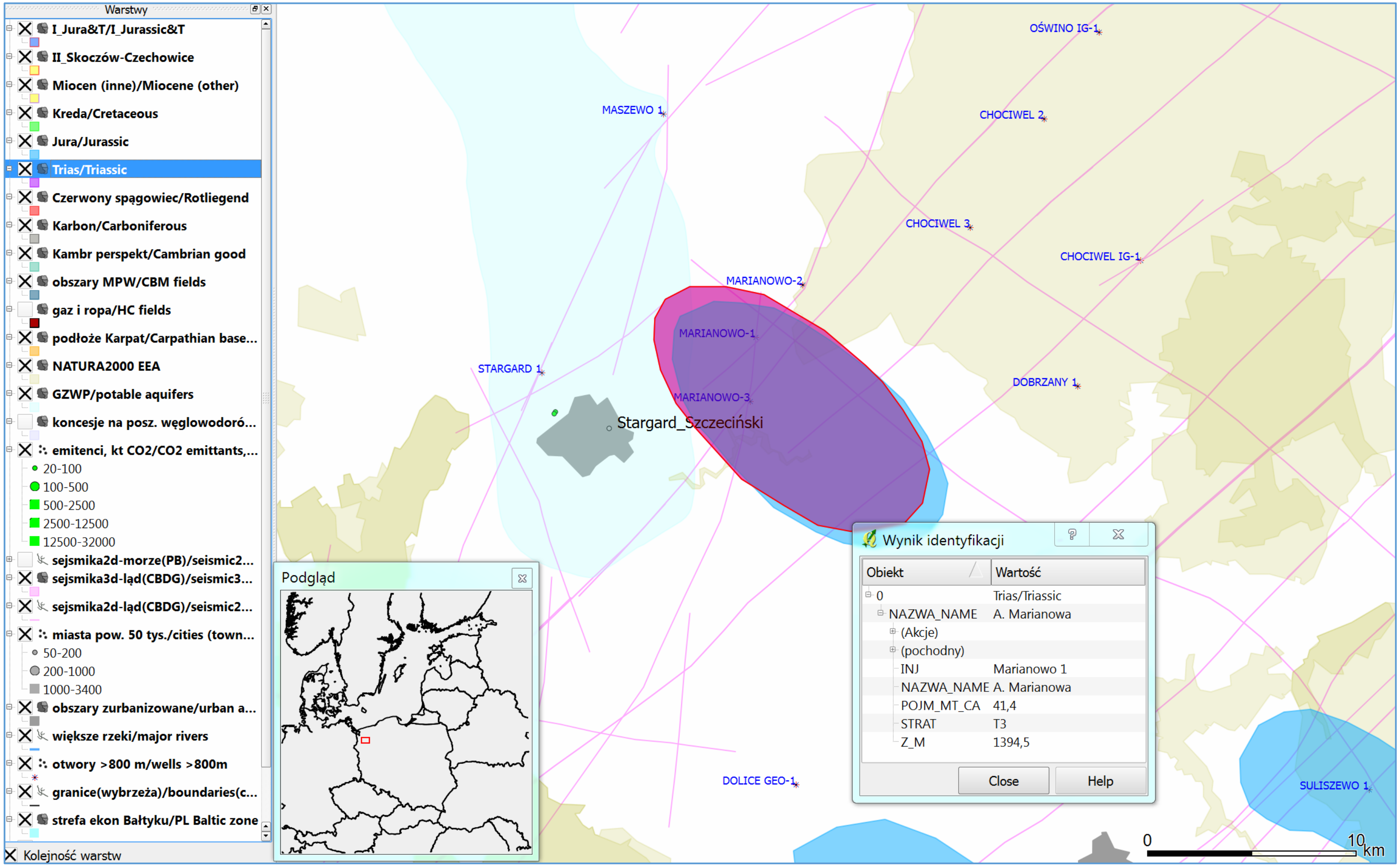
Fig. 3_40 Chabowo anticline in Upper Triassic



Wynik identyfikacji

Obiekt	Wartość
0	Jura/Jurassic
NAZWA_NAME	Antyklina Marianowa
(Akcje)	
(pochodny)	
INJ	Marianowo 1
NAZWA_NAME	Antyklina Marianowa
POJM_MT_CA	268,7
STRAT	J1pl+s+h
Z_M	1436,0

Fig. 3_41 Marianowo anticline in Lower Jurassic



☒ I_Jura&T/I_Jurassic&T
☒ II_Skoczów-Czechowice
☒ Miocen (inne)/Miocene (other)
☒ Kreda/Cretaceous
☒ Jura/Jurassic
☒ Trias/Triassic
☒ Czerwony spągowiec/Rotliegend
☒ Karbon/Carboniferous
☒ Kambr perspekt/Cambrian good
☒ obszary MPW/CBM fields
☐ gaz i ropa/HC fields
☒ podłoże Karpat/Carpathian base...
☒ NATURA2000 EEA
☒ GZWP/potable aquifers
☐ koncesje na posz. węglowodoró...
☒ emitenci, kt CO2/CO2 emittants,...
- ● 20-100
- ● 100-500
- 🟩 500-2500
- 🟩 2500-12500
- 🟩 12500-32000

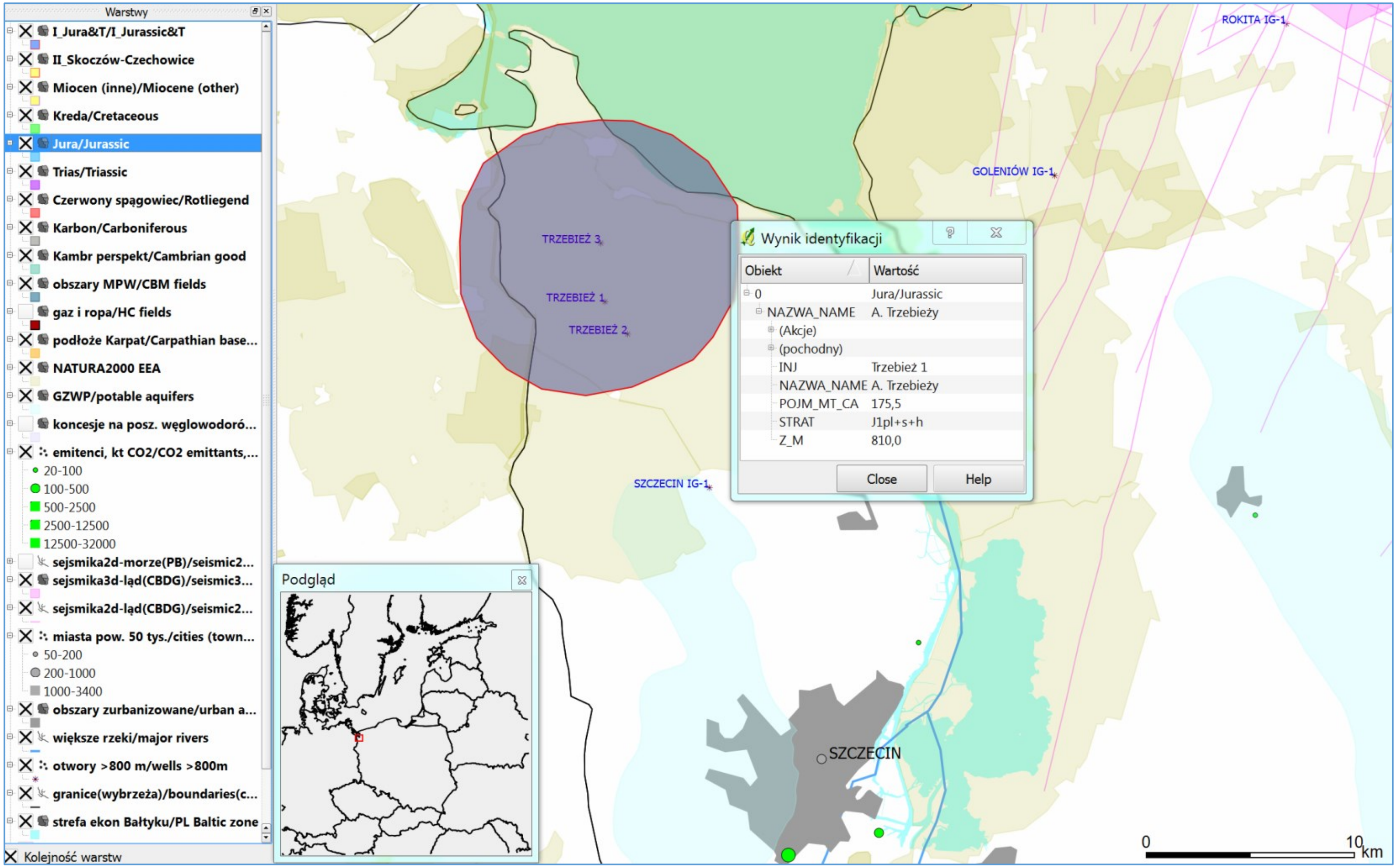
☐ sejsmika2d-morze(PB)/seismic2...
☒ sejsmika3d-ląd(CBDG)/seismic3...
☒ sejsmika2d-ląd(CBDG)/seismic2...
☒ miasta pow. 50 tys./cities (town...
- ● 50-200
- ● 200-1000
- ■ 1000-3400

☒ obszary zurbanizowane/urban a...
☒ większe rzeki/major rivers
☒ otwory >800 m/wells >800m
☒ granice(wybrzeża)/boundaries(c...
☒ strefa ekon Bałtyku/PL Baltic zone

☒ Kolejność warstw

Obiekt	Wartość
0	Trias/Triassic
NAZWA_NAME	A. Marianowa
(Akcje)	
(pochodny)	
INJ	Marianowo 1
NAZWA_NAME	A. Marianowa
POJM_MT_CA	41,4
STRAT	T3
Z_M	1394,5

Fig. 3_42 Marianowo anticline in Upper Triassic



```
Obiekt              Wartość
⊟ 0                 Jura/Jurassic
  ⊟ NAZWA_NAME      A. Trzebieży
    ⊞ (Akcje)
    ⊞ (pochodny)
      INJ           Trzebież 1
      NAZWA_NAME    A. Trzebieży
      POJM_MT_CA    175,5
      STRAT         J1pl+s+h
      Z_M           810,0
```

Fig. 3_43 Trzebież anticline in Lower Jurassic

In the region of Szczecin a number of structures within the Lower Jurassic and Upper Triassic (**Fig. 3_36**) were selected. From the viewpoint of storage safety, the feasibility and reservoir properties the following ranking and suggestions on sequestration scenarios can be determined:

- Choszczno-Suliszewo anticlines (**Fig. 3_37, 38**) in the Lower Jurassic formations with excellent reservoir properties, rather well sealed in the light of currently available information (seismic), with impermeable caprock. The smaller one - Choszczno - is sufficient for the needs of all emittants in the Szczecin region (the large Dolna Odra power plant, the power plants and CHP plants in Szczecin, the steel works, the chemical plant in Police), even including the CHP plant in Gorzów Wielkopolski and other minor emittants south of Szczecin and west of Gorzów Wielkopolski. Suliszewo (Radęcin-Pławno) anticline, also of considerable capacity, is mostly located in the protected area of NATURA2000 sites and hence a small portion may be available for locating the injection wells. They were selected for analyzes in the case study;

- Chabowo anticline (**Fig. 3_39**, **40**), which includes reservoirs of Lower Jurassic and Upper Triassic (a double structure), can also accommodate emissions of the Dolna Odra power plant and Szczecin agglomeration, both of which are located no farther than 20 km. Poorly explored by seismic;

- Marianowo anticline (**Fig. 3_41**, **42**) is also a double structure (Lower Jurassic - the primary reservoir, Upper Triassic - secondary), with similar potential as Chabowo anticline, however, it is considered as a potential strategic (euro-) gas storage for the needs of Polish and German stakeholders;

- Trzebież anticline (**Fig. 3_43**) located north of Szczecin, at the Lagoon, is the structure with the lowest potential in this area (Szczecin region), but also would be more than enough for the needs of Szczecin agglomeration. It is not explored by seismic surveys. Nearly the whole structure is within NATURA 2000 sites.

Consequently we have a problem in the Szczecin region with utilization of the potential of the structures, which exceeds several times the needs of emittants, and the distance to other major emittants in Poland is large, about 200 km or more, so possibly emissions from nearby industrial plants in Germany could be stored there (yet legal regulations on the implementation of the EU directive on the geological storage of carbon dioxide in Poland do not provide provisions for cross-border storage).

In the area under consideration there are potable aquifers in Cenozoic formations, hence the sequestration in formations of the Lower Jurassic and Upper Triassic poses no danger to them. Geochemical analyzes suggest that the contact between the Lower Jurassic brines and the above occurring brines / brackish waters may occur locally (but outside the structures). In the Szczecin region exploration and exploitation of conventional hydrocarbon fields (beyond the structures) is carried out.

In the region of Koszalin the selected structures are within the Lower Triassic (**Fig. 3_44**). The structures in the Lower Triassic are of not so good reservoir properties and storage capacities as those in the Jurassic in the Szczecin region, while of larger capacity than the structures in that region in the Upper Triassic (a secondary reservoir under the Jurassic structures), due to the larger thickness of the reservoirs of the Lower Triassic, at comparable reservoir properties. Hence, the following paragraphs make a continuation of the ranking for the study area of NW Poland.

- Debrzno anticline (**Fig. 3_45**) lies between Koszalin and Bydgoszcz. The nearest emittant is a wood processing plant in Szczecinek (CO_2 emission - 52 thousand tons), then Piła (municipal heating plants) at a distance of about 50 km, and just over 60 km from the structure we got CHP plants in Bydgoszcz whose emissions can be accommodated easily by only part of it;

- Wierzchowo and Koszalin anticlines (**Fig. 3_46** and **47**) seem to be suitable for storage of CO_2 from the small (in terms of emissions) heating plants in Koszalin and Słupsk (a distance of about 60 km), wherein the use of only a small fraction of the potential of each of the structures would be required.

Even more than in the western region (Szczecin region), in the eastern part of the study area VII (Koszalin region) the lack of large emittants that could exploit the potential of the structures is clearly visible. The nearest large emittant is Bydgoszcz, which is however equally close to the huge Mesozoic structures in the Kujawy area.

Small parts of the structures overlap with NATURA 2000 sites, and there is no threat from CO_2 storage in the Lower Triassic to the potable aquifers in the Cenozoic formations. Within the area of Wierzchowo structure a small, practically depleted gas field is located, and in the region of the Koszalin exploration for conventional hydrocarbons is carried out.

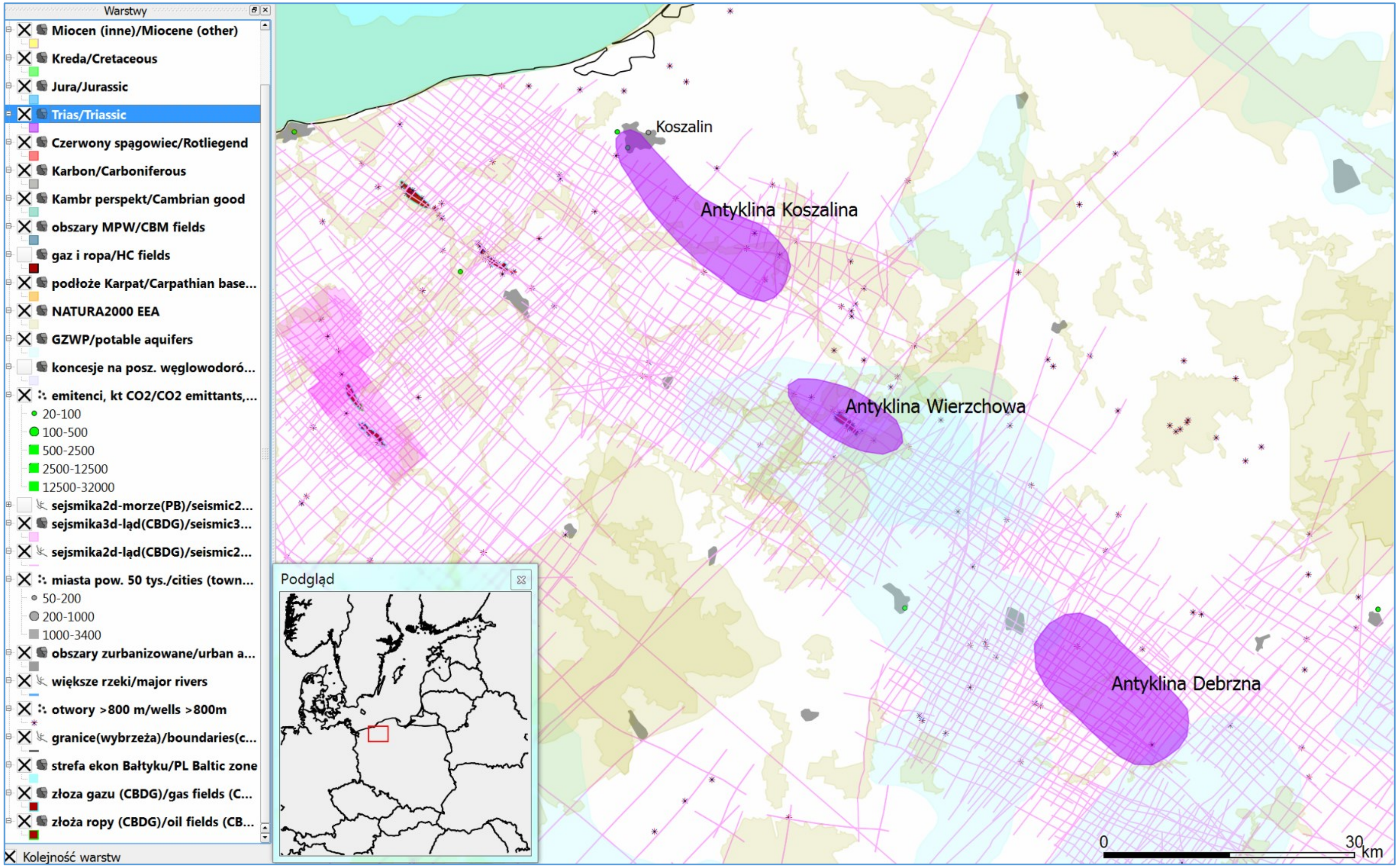
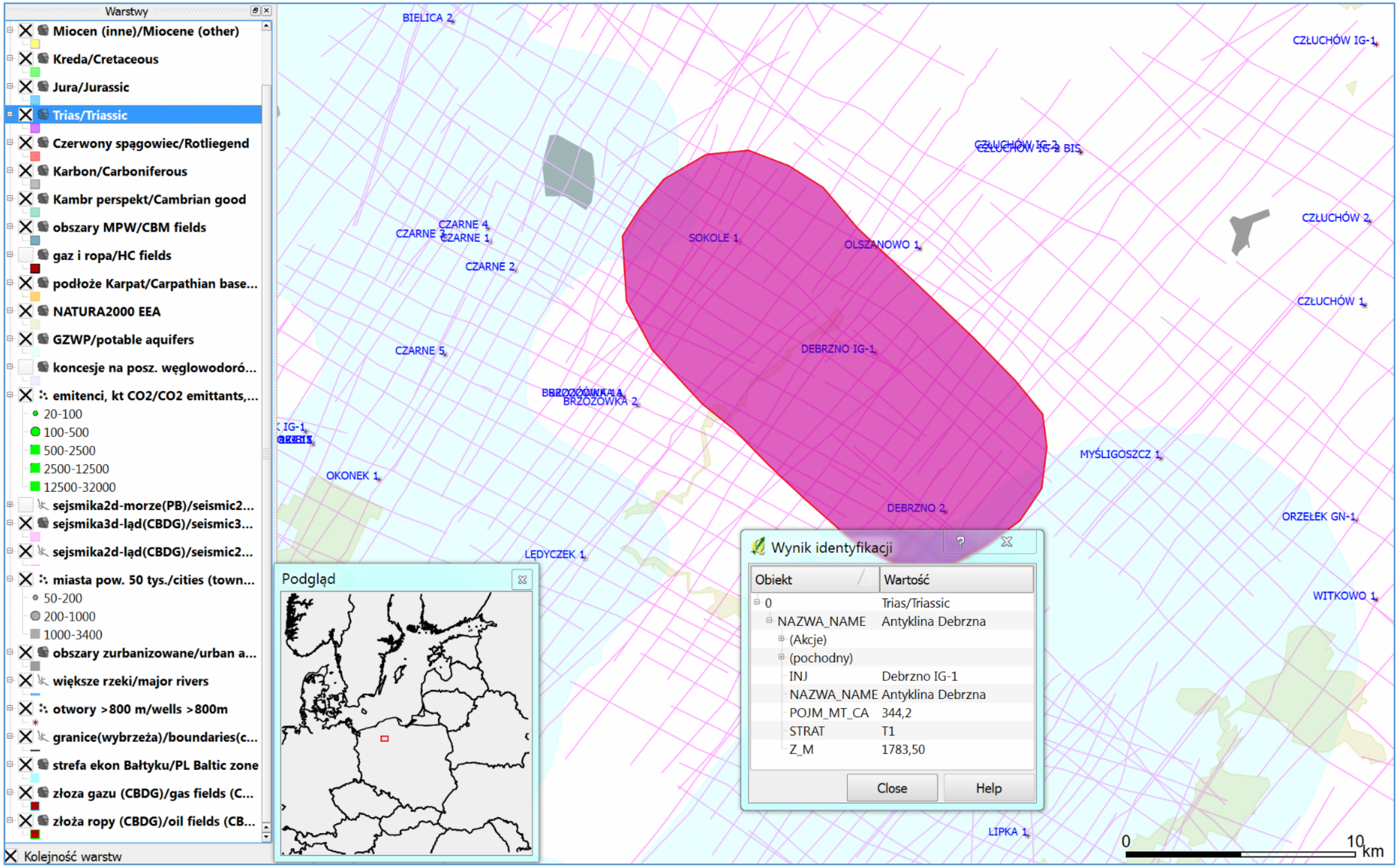


Fig. 3_44 Structures in Lower Triassic, in Koszalin region


Warstwy

- ☒ Miocen (inne)/Miocene (other)
- ☒ Kreda/Cretaceous
- ☒ Jura/Jurassic
- ☒ Trias/Triassic
- ☒ Czerwony spągowiec/Rotliegend
- ☒ Karbon/Carboniferous
- ☒ Kambr perspekt/Cambrian good
- ☒ obszary MPW/CBM fields
- ☐ gaz i ropa/HC fields
- ☒ podłoże Karpat/Carpathian base...
- ☒ NATURA2000 EEA
- ☒ GZWP/potable aquifers
- ☐ koncesje na posz. węglowodoró...
- ☒ emitenci, kt CO2/CO2 emittants,...
  - 20-100
  - 100-500
  - 500-2500
  - 2500-12500
  - 12500-32000
- ☐ sejsmika2d-morze(PB)/seismic2...
- ☒ sejsmika3d-ląd(CBDG)/seismic3...
- ☒ sejsmika2d-ląd(CBDG)/seismic2...
- ☒ miasta pow. 50 tys./cities (town...
  - 50-200
  - 200-1000
  - 1000-3400
- ☒ obszary zurbanizowane/urban a...
- ☒ większe rzeki/major rivers
- ☒ otwory >800 m/wells >800m
- ☒ granice(wybrzeża)/boundaries(c...
- ☒ strefa ekon Bałtyku/PL Baltic zone
- ☒ złoza gazu (CBDG)/gas fields (C...
- ☒ złoża ropy (CBDG)/oil fields (CB...

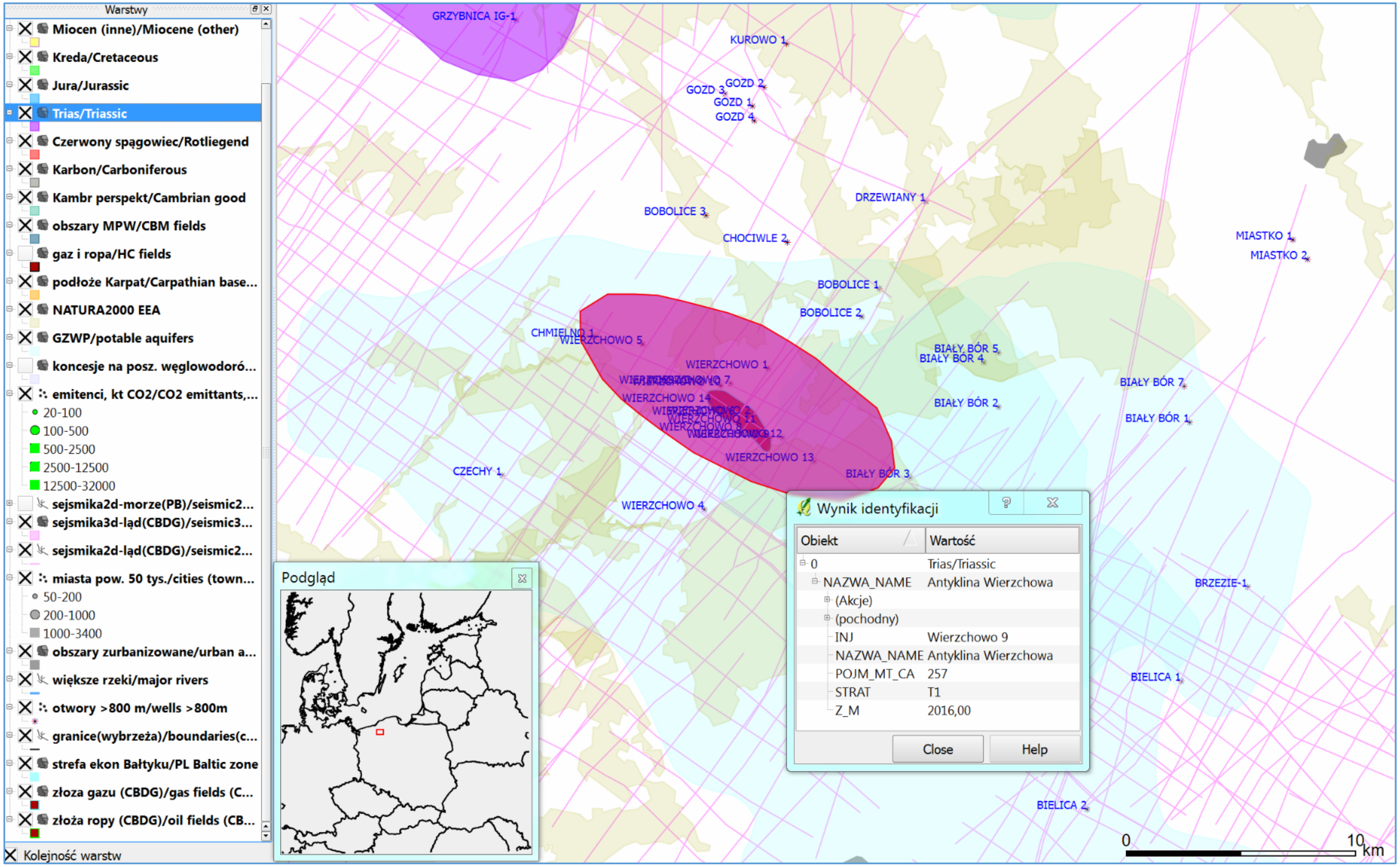
☒ Kolejność warstw

Podgląd

Wynik identyfikacji

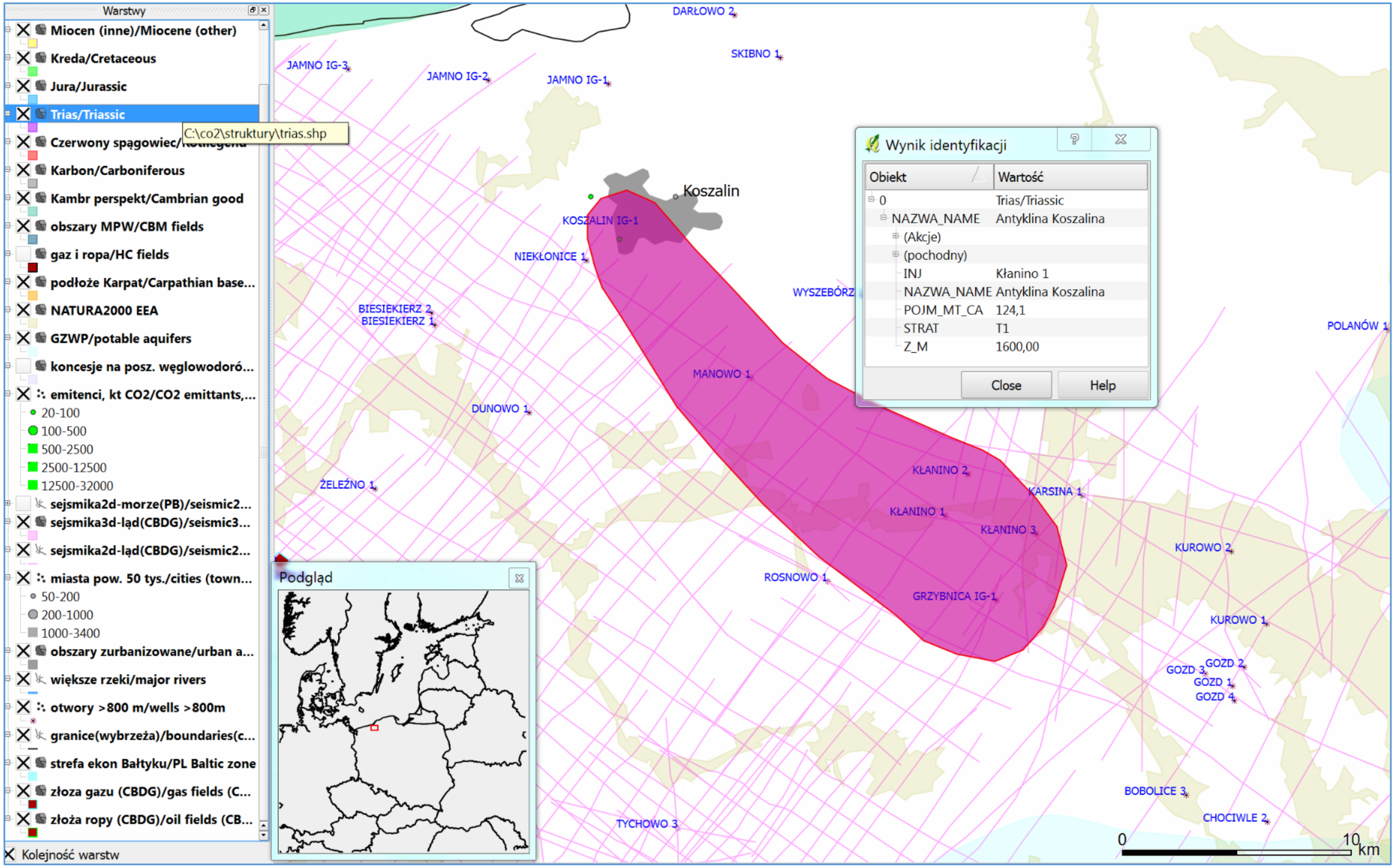
Obiekt	Wartość
0	Trias/Triassic
NAZWA_NAME	Antyklina Debrzna
(Akcje)	
(pochodny)	
INJ	Debrzno IG-1
NAZWA_NAME	Antyklina Debrzna
POJM_MT_CA	344,2
STRAT	T1
Z_M	1783,50

Fig. 3_45 Debrzno anticline in Lower Triassic



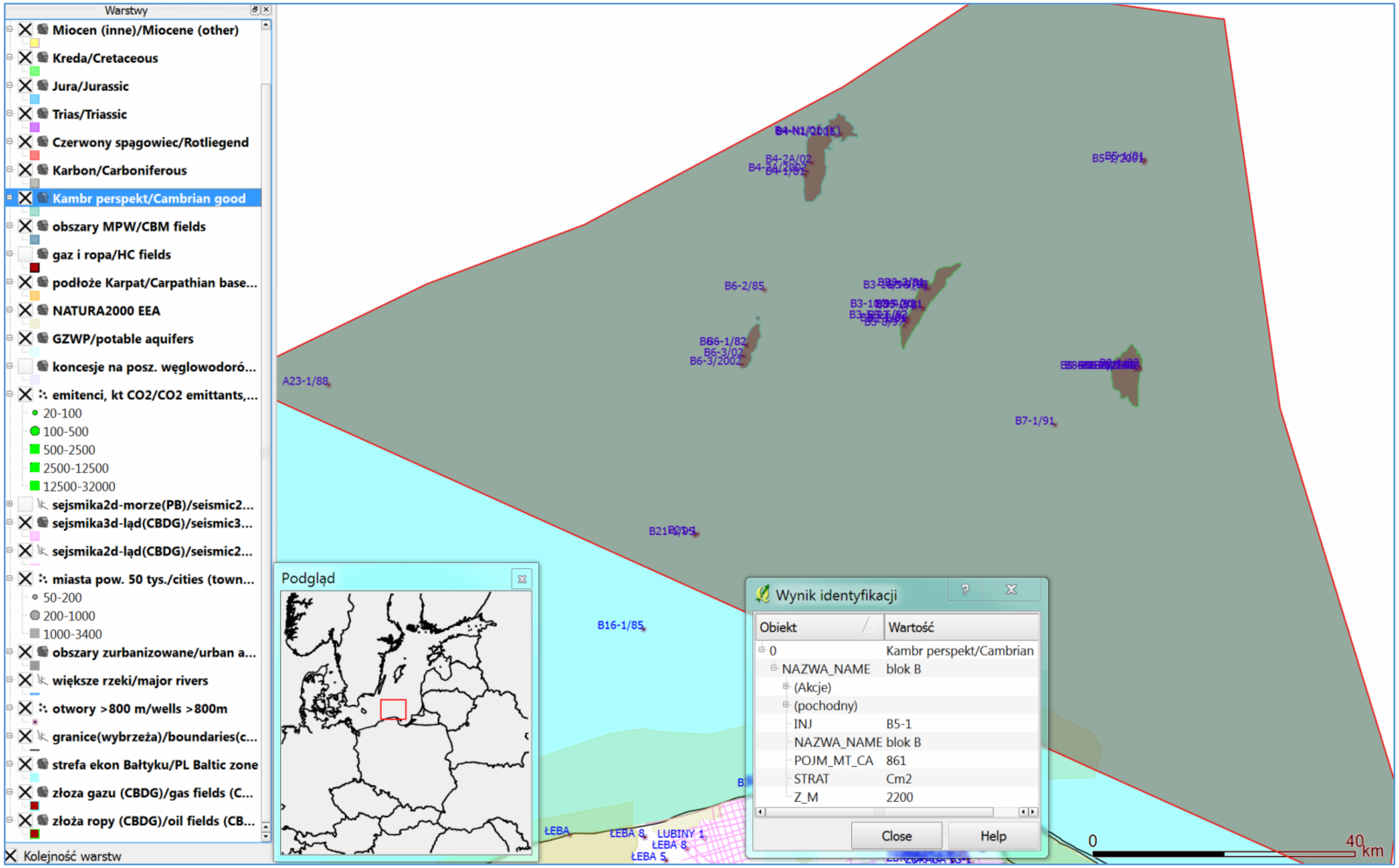
Obiekt	Wartość
0	Trias/Triassic
NAZWA_NAME	Antyklina Wierzchowa
(Akcje)	
(pochodny)	
INJ	Wierzchowo 9
NAZWA_NAME	Antyklina Wierzchowa
POJM_MT_CA	257
STRAT	T1
Z_M	2016,00

Fig. 3_46 Wierzchowo anticline in Lower Triassic



Obiekt	Wartość
0	Trias/Triassic
NAZWA_NAME	Antyklina Koszalina
(Akcje)	
(pochodny)	
INJ	Kłanino 1
NAZWA_NAME	Antyklina Koszalina
POJM_MT_CA	124,1
STRAT	T1
Z_M	1600,00

Fig. 3_47 Koszalin anticline in Lower Triassic



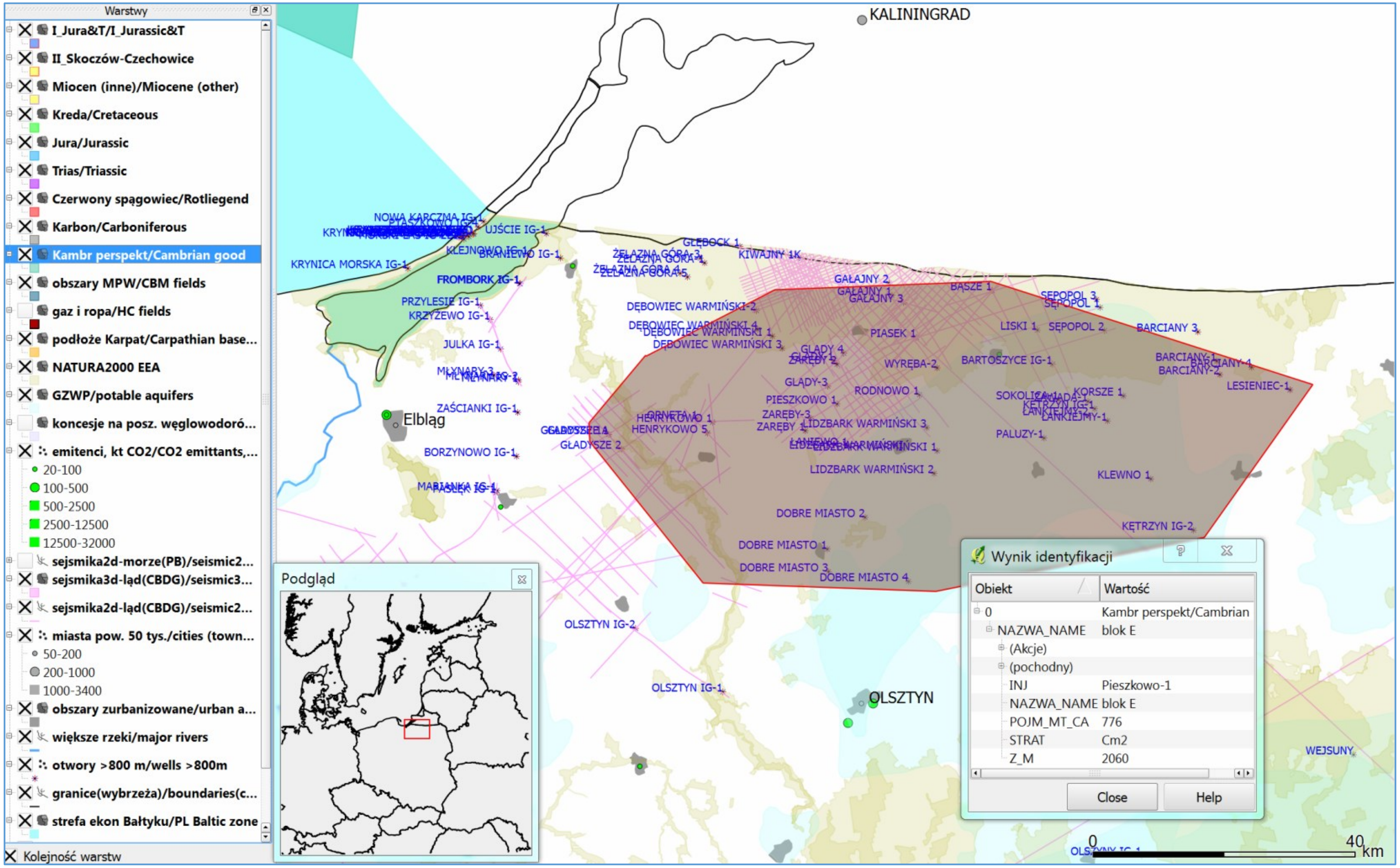
Warstwy

☒ Miocen (inne)/Miocene (other)
☒ Kreda/Cretaceous
☒ Jura/Jurassic
☒ Trias/Triassic
☒ Czerwony spągowiec/Rotliegend
☒ Karbon/Carboniferous
☒ Kambr perspekt/Cambrian good
☒ obszary MPW/CBM fields
☐ gaz i ropa/HC fields
☒ podłoże Karpat/Carpathian base...
☒ NATURA2000 EEA
☒ GZWP/potable aquifers
☐ koncesje na posz. węglowodoró...
☒ emitenci, kt CO2/CO2 emittants,...
  ● 20-100
  ● 100-500
  ■ 500-2500
  ■ 2500-12500
  ■ 12500-32000
☐ sejsmika2d-morze(PB)/seismic2...
☒ sejsmika3d-ląd(CBDG)/seismic3...
☒ sejsmika2d-ląd(CBDG)/seismic2...
☒ miasta pow. 50 tys./cities (town...
  ● 50-200
  ● 200-1000
  ■ 1000-3400
☒ obszary zurbanizowane/urban a...
☒ większe rzeki/major rivers
☒ otwory >800 m/wells >800m
☒ granice(wybrzeża)/boundaries(c...
☒ strefa ekon Bałtyku/PL Baltic zone
☒ złoza gazu (CBDG)/gas fields (C...
☒ złoża ropy (CBDG)/oil fields (CB...
☒ Kolejność warstw

Wynik identyfikacji

Obiekt	Wartość
0	Kambr perspekt/Cambrian
NAZWA_NAME	blok B
(Akcje)	
(pochodny)	
INJ	B5-1
NAZWA_NAME	blok B
POJM_MT_CA	861
STRAT	Cm2
Z_M	2200

Fig. 3_48 Prospective area for CO_2 geological storage in Cambrian, offshore, study area VIII – block B (northern)



Obiekt	Wartość
0	Kambr perspekt/Cambrian
NAZWA_NAME	blok E
(Akcje)	
(pochodny)	
INJ	Pieszkowo-1
NAZWA_NAME	blok E
POJM_MT_CA	776
STRAT	Cm2
Z_M	2060

Fig. 3_49 Prospective area for CO₂ geological storage in Cambrian, onshore, study area VIII – block E

For the study area VIII, i.e. northern Poland including the exclusive economic zone of the Baltic Sea, and north-eastern Poland, Cambrian sandstone formations (Middle Cambrian essentially) are the primary reservoir. We have two areas of Cambrian aquifer prospective for the geological storage of carbon dioxide. These are regional aquifers, so we cannot propose the ranking of structures in this region.

In case of the first one, offshore – the block B, or northern block, the Cambrian reservoir area is marked in **Fig. 3_48** - regional aquifer within the Polish economic zone of the Baltic Sea, of depth range suitable for CO_2 storage and of sufficient reservoir properties (the farther north and NE, the better), including the hydrocarbon fields with varying degrees of depletion (e.g., B3 oilfield is practically depleted). This is a regional aquifer with a complex tectonics, composed of several blocks separated by fault zones which locally can be a barrier to propagation of reservoir fluids, as evidenced by the presence of hydrocarbon traps in the vicinity of some fault zones. The estimated storage capacity for that sub-area of the regional aquifer (**Fig. 3_48**) is indicative in nature and relates more to the lower limit of storage capacity of the whole prospective zone.

Possible scenario for the use of saline aquifers of the offshore Cambrian reservoir would include storage of emissions of the Tri-City emittants (mostly the plants in Gdańsk - municipal CHP plants, refineries of LOTOS, and a not very big CHP plant in Gdynia). This requires a small fraction of the storage capacity of the perspective zone. Also a cooperation with partners from Baltic States (Finland, Sweden) on the use of regional Cambrian aquifer in southern and central part of the Baltic Sea for the needs of all stakeholders is possible (yet legal regulations on the implementation of the EU directive on the geological storage of carbon dioxide in Poland do not provide provisions for cross-border storage).

On the other hand, the onshore area, Block E, generally located east of Elbląg, near the border with Russia's Kaliningrad region (**Fig. 3_49**), is characterized by a rather good reservoir properties. The most prospective seems to be the part of the selected region located where the Pre-Cambrian bedrock is uplifted, in the area of Pieszkowo 1, Zaręba 2, Henrykowo 1 and Gładysze 1 wells – this is the northern part, sufficiently explored by 2D seismic (**Fig. 3_49**). The estimated storage capacity for that sub-area of the regional aquifer (block E) is indicative in nature and relates more to the lower limit of storage capacity of the whole prospective zone. Besides the emittants of Tri-City situated at a distance of about 80 km west, in the vicinity of the block E lie small CHP and heating plants in Elbląg and Olsztyn, for which a small fraction of the capacity of the aquifer would be enough.

Saline aquifers summary

For saline aquifers in the eight study areas of the country the following prospective geological formations have been assessed:

I (Bełchatów) – Jurassic (J1, J2 sandstones), T;

II (USCB) – Miocene;

III (Mazovia) - Jurassic (J1, J2 sandstones), T, Cr1;

IV (the Carpathian overthrust front/the Carpathian foredeep) – basement (K - Cm);

V (Lublin & Podlasie regions) – Carboniferous (C3 sandstones), J, Cm;

VI (Greater Poland - Kujawy) – Permian (P1), T, J, Cr;

VII (NW Poland) – Jurassic (J1 sandstones), T3, T1;

VIII (Łeba-Baltic, including offshore area, and NE Poland) – Cm2.

For Bełchatów study area a number of structures within the Jurassic have been analyzed - some of them also include the saline aquifer horizons in the Triassic (mainly Buntsandstein). These are rather large structures, with a static (effective) capacity from tens to hundreds of million tons of CO_2 each, and in one case even bigger, good reservoir properties and multi-level seal complexes. For further analysis under the case study Budziszewice structure was selected, for which information allowing the construction of reliable models was available. There is rather no conflict with the operation of conventional and unconventional hydrocarbon fields here, and the presence of the potable aquifers in the Cretaceous may limit locally the use of the shallowest reservoirs of Middle Jurassic, where geochemical analyzes indicate the possibility of brine-groundwater contact (e.g., Lutomiersk-Tuszyn area).

In the area of USCB as a principal reservoir, formation of sandstone Dębowiec beds of the Miocene (possibly Zamarski beds and the top part of the Upper Carboniferous) was determined, occurring in the southern part of the area in question. These sandstones are characterized by the average reservoir properties and a rather low storage capacity (static/effective - a few tens of million tons). There are rather no conflicts of interest with exploitation of hydrocarbons, a problem may be the exclusion of some parts of the region (as a location of injection installations) because of the presence of NATURA 2000 and other protected areas.

In the area of Mazovia (Warsaw-Płock emittants) in principle, all Mesozoic formations are promising - from the Lower Triassic to Lower Cretaceous. Most of the structures are located between Warsaw and Płock and they have capacities of hundreds of million tons of CO_2 each, good reservoir properties and multi-level seals (in the top there are thick carbonate-clastic complexes of the Lower Cretaceous, then at least two in the Middle Jurassic and at least one in the Lower Jurassic). They partially overlap with the range of the peripheral zone of the possible occurrence of shale gas fields. Since there is no (potable) groundwater aquifers in the Cretaceous (the deepest is in the Paleogene) it does not appear the storage of CO_2 constitutes any threat to drinking water resources. Except for one case, NATURA 2000 protected areas do not exist within the structures.

In the area of marginal zone of the Carpathians and the Carpathian Foredeep saline aquifers prospective for CO_2 storage are present in the Mesozoic-Paleozoic basement in the western part of the area (between Kraków and Tarnów). Miocene formations within the Carpathian Foredeep are not prospective except the areas/surroundings of the gas fields. There were three sites (storage areas) determined: Zatoka Gdowska (south of Niepołomice) in clastic formations of the Jurassic and two neighboring aquifers Grobla and Niepołomice in Paleozoic carbonates. Realistic storage capacities of these sites are about tens of millions of tons each, and for carbonate reservoirs estimations are subject to a much greater degree of uncertainty than the clastics. Parts of the carbonate saline aquifer sites include NATURA 2000 protected areas, but there are no relevant conflicts of interest with the exploitation of hydrocarbons.

In the region of Lublin there are reservoirs in the Upper Carboniferous formations with average to good reservoir properties locally and a good seal in the uppermost part of the Upper Carboniferous, mainly in the north and NW of Lublin. The capacity of this area is over a hundred million tons. The deepest potable aquifer occurs in the Upper Cretaceous formations (between the aquifer and Carboniferous a number of barriers appears, hence no threats are expected). Area perspective for CO_2 storage meshes partly with a range of peripheral zone of the possible occurrence of shale gas. To the north and north-east, in the region of Podlasie, there is a poorly explored Cambrian aquifer with the potential of perhaps a billion tons.

In the area of Greater Poland the principal aquifer - Permian, is the Rotliegend sandstone formation with average to good reservoir properties, covered by a thick complex of Zechstein with excellent sealing properties. Capacities of Permian structures are up to a hundred-several hundred million tons. Potable aquifers in the area of Permian structures are of Cenozoic age. The whole area includes licenses for exploration and production of hydrocarbons, but the injection of CO_2 into saline aquifers is not necessarily to interfere with the operation of developed gas fields - possibly even improve the efficiency of production. Parts of prospective areas include or are adjacent to NATURA 2000 areas. In the region of Kujawy (Konin area and its surroundings) there are prospective saline aquifer sites in the Lower Cretaceous and Jurassic with a capacity of one hundred-several hundred million tons.

In the area of NW Poland we have a number of structures with capacities of hundreds of million tons (in particular in the regions of Szczecin and Koszalin), which reservoirs are within the Lower Jurassic, Upper and lower Triassic, with good reservoir properties and good seals. In this area we have essentially Cenozoic potable aquifers (there is rather no risk) and basically no conflicts with the production of hydrocarbons.

In the area of northern Poland and Baltic Sea the main aquifer is Cambrian, both offshore (includes the operated oil and gas fields), as well as onshore, with a capacity of several hundred million tons for each of the subdivisions, and a good seal. The onshore area (east of Elblag) includes in part protected areas and exploration licenses on unconventional hydrocarbon resources (a peripheral area, rather less prospective). In the offshore area (eastern part of the Polish economic zone of the Baltic Sea) LOTOS applied for exploration licenses for unconventional hydrocarbon resources (according to PGI-NRI Report, 2012, there are prospects for the occurrence of shale oil here).

CO_2 storage potential of Poland

Below in **Tables 3_1** and **2** the storage capacity potential assessed in the framework of the regional studies (the static, effective capacities) for the saline aquifers in the area of Poland is presented, for particular study areas and geological formations.

Table 3_1 The storage capacity potential for saline aquifers in Poland - study areas

Study area	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*
Number of structures	5	1	10	9	n/a	10	10	n/a
Capacity, Mt	2169	44	2649	253	1008	3584	2958	1637

Table 3_2 The storage capacity potential for saline aquifers in Poland - geological formations

Formation	*Miocene*	*Cretaceous*	*Jurassic*	*Triassic*	*Permian*	*C3*	*C3-D2*	*Cambrian*
Number of structures	7	10	16	7	3	n/a	2	n/a
Capacity, Mt	69	2486	6452	1460	1014	193	176	2645

For individual areas (**Table 3_1**) we often have to deal with the structures and geological formations of different ages, which also differ in the degree of reliability of the estimates of the storage potential as well as storage safety.

For the study area I (Bełchatów) the storage potential in principle refers to Jurassic structures (4 structures - clastic Lower Jurassic clastic and early Middle), for which the said degree of reliability is relatively high (e.g., Budziszewice-Zaosie), but also variable for each structure (in terms of the quantity and quality of available geophysical data). The exception is one Lower Triassic structure (Jeżów T), for which the estimates are based on uncertain and fragmentary information about Buntsandstein reservoir properties.

The study area II (USCB) includes Skoczów-Czechowice site, with a relatively high degree of reliability of the estimates of the storage potential (Dębowiec beds - clastic Lower Miocene).

The study area III (Mazovia) includes Jurassic structures (4 - clastic Middle and/or Lower Jurassic) and Lower Cretaceous structures (6), for which the degree of reliability of the estimates of storage potential associated with the quality and quantity of available geological and geophysical data is relatively high. On the other hand, some doubt may raise the matter of safety of storage in the Lower Cretaceous formations (also clastic formations, but the caprock is composed of carbonate-clastic rocks), in particular in the case of Żyrów structure.

The study area IV (marginal zone of the Carpathians and the Carpathian Foredeep) involves two sites in the Carboniferous-Devonian carbonate formation in the basement of the Carpathian Foredeep and the Carpathian overthrust, for which an estimate of the storage capacity is characterized by a rather low degree of reliability, and one site in the Middle Jurassic clastic formation in the basement of the Carpathian Foredeep and the Carpathian overthrust, with far better reliability. In addition, in the eastern part of the area IV we have several structures with a very small potential (but reliable) that could be used only together with nearby depleted gas deposits.

The study area V (Lublin and Podlasie regions) includes the clastic Upper Carboniferous aquifer of very variable reservoir properties (but there is likely no problem with the quality and quantity of available geological and geophysical data), and the NE part covers the clastic Middle Cambrian aquifer in Podlasie region, which is poorly or not explored by seismic surveys. Thus, for various reasons, the reliability of the assessed storage potential is not too high, but we can speak rather of underestimation than overestimation of the capacities.

The study area VI (Greater Poland-Kujawy) includes three Lower Permian structures (Poznań trough megastructure and two smaller ones, where clastic Rotliegend formations make the reservoir), fairly well explored in terms of available geophysical and geological data, hence the degree of reliability of the estimates of storage potential for them is relatively high. Moreover, in the region of Kujawy the assessed storage potential includes contributions from one Lower Triassic and two Jurassic structures (also clastic), with a significant degree of reliability of storage capacity estimations. However, there are doubts about the safety and feasibility of storage in the three structures in the Lower Cretaceous in Kujawy region (where the caprock is built of carbonate-clastic rocks).

In the study area VII (NW Poland) we have 6 Triassic and 4 Jurassic structures (clastic reservoirs in all cases). These structures differ in quantity and quality of available geological and geophysical data, but overall geological situation (these are "textbook" anticlinal structures - good natural traps associated with salt "pillows" in the basement - for example, Choszczno and Suliszewo structures in Jurassic) implies a relatively high degree of the reliability of storage potential estimates.

The study area VIII includes the clastic Middle Cambrian formation, for which the reliability of the assumed storage capacity value is not too high, but we can speak rather of underestimation than overestimation of capacity.

The regional Cambrian (V, VIII) and Carboniferous (V) aquifers (these are not structures!) have estimated potential of **2 838 million tons**.

In total for 45 structures/sites (I, II, III, IV, VI, VII) we have a capacity of **11 657 million tons** (9171 million tons for 35 structures/sites, if structures in the Lower Cretaceous are excluded).

Thermodynamic conditions for the saline aquifer structures

To illustrate one of the **major** factors affecting the safety of CO_2 geological storage in saline aquifer structures - the state of matter of carbon dioxide injected into the formation, resulting from the thermodynamic conditions occurring there, the relevant parameters are summarized in **Fig. 3_50**. The figure presents the reservoir pressure and temperature values for selected structures and saline aquifer formations. For typical anticlinal structures values of reservoir temperature and pressure occurring at their top parts were assumed. Temperature and pressure values were estimated basing on information from the wells, geothermal atlases (Górecki [ed.], 2006a, b) and other publications, and assumptions of the hydrochemical - hydrodynamic atlas of Poland (Bojarski, 1996). Some sites and formations, not shaped in the form of anticlines (parts of regional sedimentary basins) are an exception, for which the average values of the reservoir top depth were assumed (like Skoczów Czechowice site within Dębowiec beds, where an average value within 800-1000 m depth range, corresponding to temperatures 32-36 ^{o}C was assumed; similarly this was done for the Carboniferous formation of Lublin region and Cambrian formation of Baltic and Podlasie), or an average depth of occurrence of the best reservoir within the carbonate Carboniferous-Devonian complex in the basement of the Carpathian Foredeep and the Carpathian overthrust (Niepołomice and Grobla sites) .

The information is collated on the background of the boundaries of phase transitions of carbon dioxide present in the reservoir conditions (**Fig. 3_50**). It stands out in this case, three phases - gas, liquid and supercritical fluid (IPCC SR CCS, 2007), depending on whether the reservoir pressure or temperature exceeds a critical value. In this case, none of the structures is not characterized by thermodynamic conditions allowing the occurrence of CO_2 in the gas phase, although for some structures, pressure or temperature approaches the area where CO_2 is present in the gas phase (e.g., at the top of B-Z structure, for the upper, Pliensbachian reservoir CO_2 may occur in the liquid phase under supercritical pressure conditions; for a 180 m deeper located Synemurian and Hettangian reservoir carbon dioxide will only occur in the supercritical phase in this case).

Additionally the map of temperature distribution in the area of Poland is shown below for the formation, which is of paramount importance for the geological storage of carbon dioxide (the Lower Jurassic). The GIS/WebGIS application has been supplemented with the layer comprising the temperature distribution at the top of Lower Jurassic (based on Geothermal Atlas of Poland - Górecki (ed.), 2006a - **Fig. 3_51**). This map shows the qualitative temperature fluctuations associated with both the depth of occurrence of the Lower Jurassic formation and the heat flow distribution (Szewczyk & Gientka, 2009).

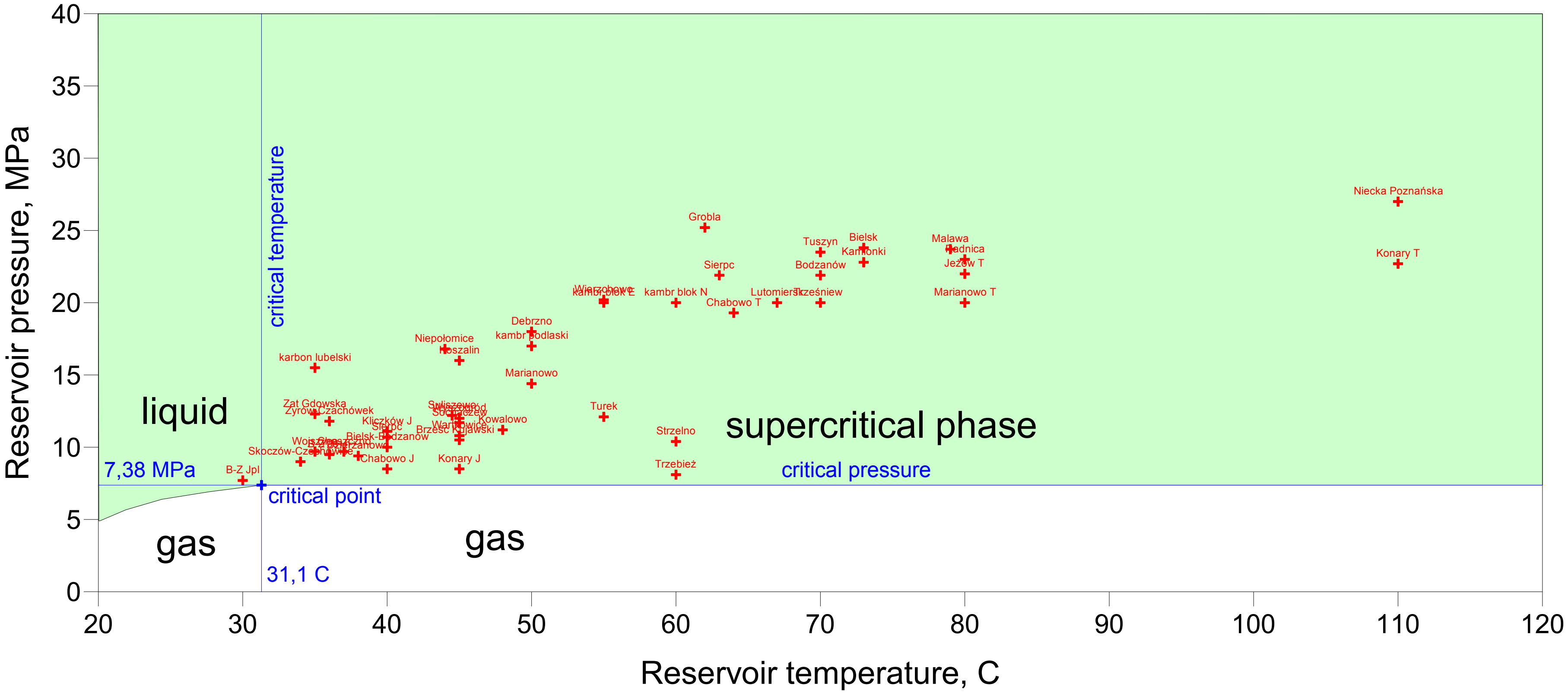


Fig. 3_50 Thermodynamic conditions for the selected saline aquifer structures and formations (the boundaries of phase transitions after IPCC SR CCS, 2007)

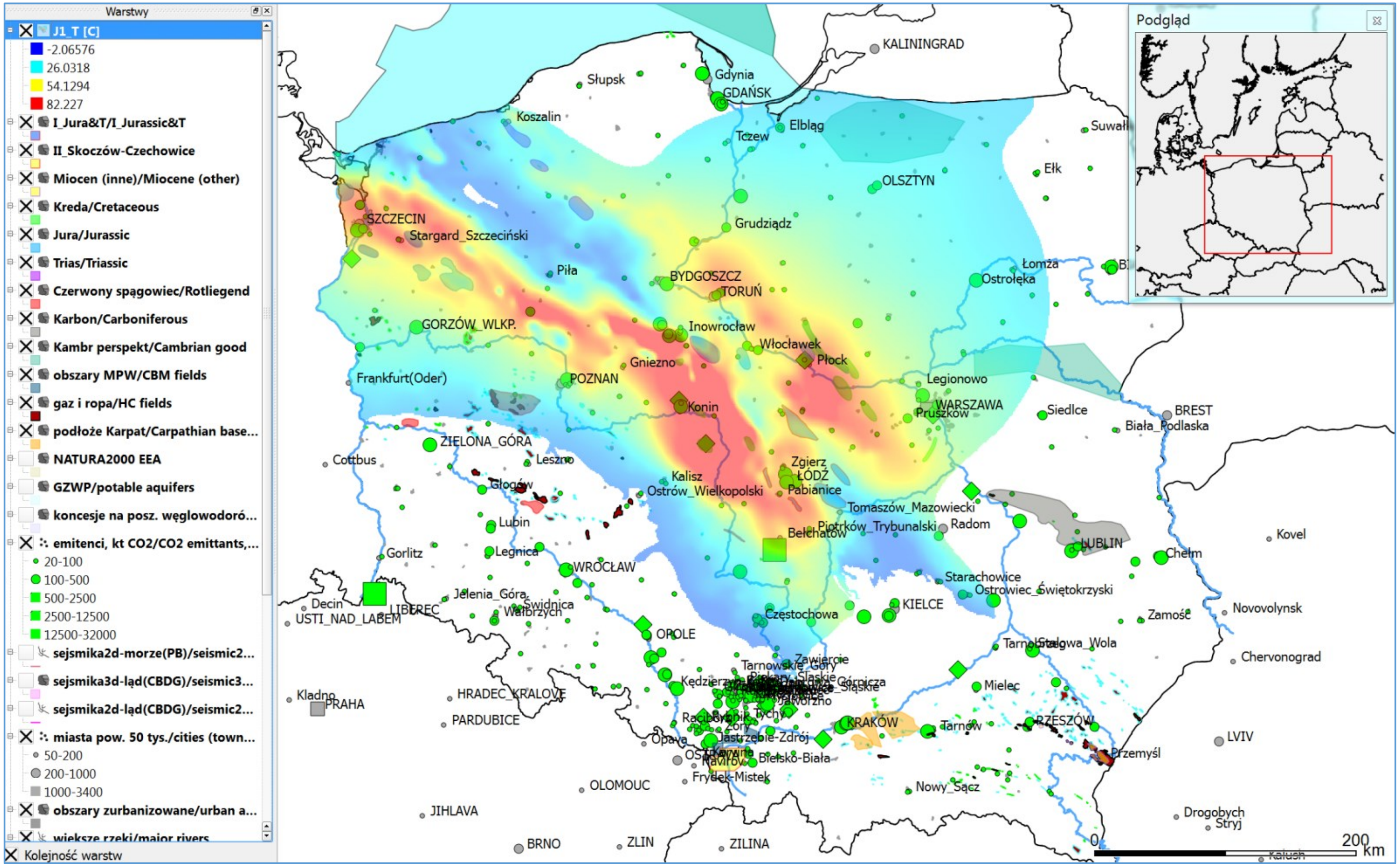


Fig. 3_51 GIS application - map of temperature distribution at the top of Lower Jurassic (based on Górecki [red.], 2006a); see also http://skladowanie.pgi.gov.pl/co2polska/polska.phtml

Tabela 3_3 Parameters, and static (effective) storage capacities for the saline aquifer structures and formations

Study area	Name	Stratigraphy	Area, km2	Reservoir thickness, m	Depth, m	Average permeability, mD	Average porosity, %	Salinity g/l	Temperature, °C	Reservoir pressure, MPa	Storage efficiency, %	Volumetric storage capacity, Mt	Dissolving storage capacity, Mt	Total storage capacity, Mt
I	Budziszewice-Zaosie (B-Z)	J1	217	53	775	300	15	10	30(36)	7,7(9,5)	20	134,6	93,6	228,2
I	Lutomiersk	J1(J1/J2)	36	230	1997	150	15	100	67	20	15	78,2	42,4	120,7
I	Tuszyn	J1	37	120	2265	150	15	37	70	23,5	15	43,8	30,6	74,4
I	Kliczków J	J1	21	300	1112	150	20	127	40	11,1	15	77,1	38,0	115,1
I	Jeżów T	T1	98	300	2392	20	11	360	80	24	20	263,9	6,1	270,0
I	Wojszyce	J	260	200	900	300	20	10	35	9,7	20	811,2	544,7	1355,9
II	Skoczów-Czechowice	Miocene	350	40	1000	40	12	35	34	9		44[4]		
III	Bielsk-Bodzanów	Cr1	100	128	1011	1000	30	2,3	40	10	15	241,9	208,8	450,8
III	Dzierżanowo	Cr1	75	122	939	1000	20	10	38	9,4	15	115,3	95,8	211,1
III	Sierpc	Cr1	75	116	1068	1000	30	39	40	10,7	20	219,2	118,8	338,0
III	Sochaczew	Cr1	85	108	1165	1000	30	5,5	45	11,7	20	231,3	147,4	378,8
III	Wyszogród	Cr1	150	108	1199	1000	30	5,5	45	12	15	306,2	260,2	566,4
III	Żyrów	Cr1	40	40	1183	1000	30	27,5	36	11,8	5	10,1	23,1	33,2
III	Sierpc	J	75	150	2190	200	15	10	63	21,9	20	141,8	88,4	230,1
III	Bielsk	J	22	220	2377	200	15	39	73	23,8	20	61,0	33,0	94,0
III	Bodzanów	J	30	200	2192	200	15	5,5	70	21,9	20	75,6	48,2	123,8
III	Kamionki	J	75	144	2280	200	15	5,5	73	22,8	20	136,1	86,7	222,8
IV	Niepołomice	D	269	64	876	10	8	30	44	16,8	2	11,6	65,5	77,0
IV	Grobla	D	442,4	50	1525	10	8	30	62	25,2	2	14,9	84,1	99,0
IV	Zat. Gdowska	J	115	50	1228	100	14	30	35	12,3	4	13,5	38,3	51,8
IV	Malawa	Miocene	3,1	375	1410	82	17		79	23,7	10	8,8	4,8	13,6

---

[4] Estimated by GIG; EU GeoCapacity methodology gives, assuming the storage efficiency factor of 2%, approximately 14.1 Mt of volumetric capacity and 77.9 Mt of dissolving capacity (total 92.1 Mt).

V	Lublin region	C3	2000	30	1550	50	5	30	35	15,5	4	50,4	142,6	193,0
V	Podlasie Cambrian	Cm	650	200	1718	200	15	30	50	17	1	81,9	926,8	1008,7
VI	Poznań trough (G-U-B-P)	P1	470	200	2676	60	10	30	110	27	5	197,4	446,8	644,2
VI	Radnica	P1	65	100	2290	40	17	30	80	23	20	92,8	52,5	145,3
VI	Kowalowo	P1	90	175	1110	20	16	30	48	11,2	10	105,8	119,8	225,6
VI	Strzelno	Cr1	24	110,5	1040	700	20	30	60	10,4	20	44,6	25,2	69,8
VI	Trześniew	Cr1	50	110,5	1996	300	20	70	70	20	20	92,8	43,4	136,2
VI	Turek	Cr1	84	81	1210	1000	20	90	55	12,1	20	114,3	48,7	163,0
VI	Wartkowice	Cr1	49,5	104	1076	700	20	15	45	10,8	20	86,5	52,6	139,1
VI	Konary	J	250	160	847	300	15	5,5	45	8,5	20	504,0	321,2	825,2
VI	Brześć Kujawski	J	122	348,5	1047	300	17	5,5	45	10,5	20	607,1	387,0	994,1
VI	Konary	T1	250	87,5	2265	100	10	150	110	22,7	20	183,8	59,4	243,1
VI	Chabowo J	J1	87	160	845	1000	17	77	40	8,5	20	198,8	89,9	288,7
VII	Choszczno	J1	102	168	1235	1000	20	112	37	9,7	20	287,9	110,8	398,6
VII	Suliszewo	J1	300	127	1293	1500	22	100	44,5	12,2	20	704,1	286,3	990,4
VII	Marianowo	J1	160	72	1436	1000	20	110	50	14,4	20	193,5	75,1	268,7
VII	Trzebież	J1	137,5	54	810	700	20	100	60	8,1	20	124,7	50,7	175,5
VII	Chabowo T	T3	87	40	1930	200	17	106	64	19,3	20	49,7	19,7	69,3
VII	Marianowo T	T3	101,5	22	1395	100	15	67,5	80	20	20	28,1	13,3	41,4
VII	Debrzno	T1	150	160	1784	100	15	110	50	18	15	226,8	117,4	344,2
VII	Wierzchowo	T1	160	120	2016	100	14	110	55	20,2	15	169,3	87,7	257,0
VII	Koszalin	T1	70	100	1600	100	15	100	45	16	20	88,2	35,9	124,1
VIII	block N(B)	Cm	2200	70	2200	50	10	30	60	20	2	129,4	732,0	861,3
VIII	block E	Cm	1000	100	2060	200	15	30	55	20	1	63,0	713,0	776,0

3.2 Hydrocarbon fields

(Adam Wójcicki, Jan Lubaś, Sławomir Szuflita)

Necessary data were collected/updated basing on information from hydrocarbon field reports available at the Central Geological Archive, Archive of POGC and available publications (borehole data, structural maps, cross-sections, maps of reservoir parameters, etc.) and the database of the "Interactive Atlas ..." (Wójcicki et al., 2008).

In case of the hydrocarbon fields, we have two instances: enhanced recovery of hydrocarbons – depleted oil fields, to a lesser extent, gas fields - or only storage of carbon dioxide in a maximum quantity (large depleted gas fields, preferably consisting of a single or two gas-bearing horizons). The selection criteria for hydrocarbon fields are given in Section **2.1**. On the basis of these criteria it was proposed 38 fields (including some multi-part) as potential CO_2 storage sites, located in western Poland, the north-west, south-east and one in the Baltic Sea (B3 - depleted to a significant degree); **Figs 3_52**, **A**, **B**.

For the selected 10 oil (and gas) fields the following ranking can be proposed:

- BMB (*the static storage capacity – 33.2 Mt*) (NW Poland),
- B3 (*7 Mt*) (Baltic),
- Kamień Pomorski (*3.9*) (NW Poland),
- Nosówka (*1.4*) (the Carpathian overthrust front / the Carpathian foredeep),
- Radoszyn (*1.1*) (NW Poland),
- Górzyca (*2.5*) (NW Poland),
- Węglówka (*1.9*) (the Carpathians),
- Lubaczów (*6.1*) (the Carpathian overthrust front / the Carpathian foredeep; initially developed – mainly natural gas),
- Jaszczew (*10.4*) (the Carpathians),
- Osobnica (*0.7*) (the Carpathians).

Similarly, in the case of gas fields the following ranking can be suggested:

- Załęcze-Wiewierz, Żuchlów (*82.9 and 91.9 Mt*) (southern Greater Poland / Lower Silesia),
- Bogdaj-Uciechów (*53.5*) (southern Greater Poland),
- Wilków, Jodłówka (*13.6 and 15.5*) (southern Greater Poland / Lower Silesia, the Carpathian overthrust front / the Carpathian foredeep),
- Tarchały (*11.7*) (southern Greater Poland),
- Tarnów Jura, Łąkta (*10.1; 10.4*) (the Carpathian overthrust front / the Carpathian foredeep),
- Paproć, Brzostowo, Bukowiec, Czeszów (*9.5; 9.1; 2.4; 5.8*) (Greater Poland),
- Gorzysław, Góra, Jarocin, Ujazd (*2.4; 3.1; 1.9; 6.2*) (Greater Poland)
- Grochowice, Grodzisk Wlkp. (*7.6; 6.1*) (Greater Poland).
- Przemyśl, Husów[5]-Albigowa-Krasne (*244.6; 35.2*) (the Carpathian overthrust front / the Carpathian foredeep),
- Jarosław, Mirocin (*28.6; 19.3*) (the Carpathian overthrust front / the Carpathian foredeep),
- Tarnów miocen (*5.9*) (the Carpathian overthrust front / the Carpathian foredeep),
- Kielanówka, Pilzno S, Rączyna, Zalesie (*8.5; 9; 0.5; 3.2; 8.7*) (the Carpathian overthrust front / the Carpathian foredeep),
- Stężyca (*2.5*) (the Lublin region).

From the viewpoint of CCS projects the biggest fields are interesting, such as Żuchlów gas field (**Fig. 3_53** - near Głogów, in the vicinity of CHP plants of LGOM copper basin and about 70 km from Wrocław, adjacent to Załęcze-Wiewierz gas field, of only slightly less capacity) and BMB oil field (**Fig. 3_54** - near Gorzow, where, however, there are no relatively big emittants, and hence a possible scenario is the use of the field for a storage site of the Dolna Odra power plant, located approximately 50 km, and before that, for CO_2-EOR).

---

[5] With the exception of a part of the Husów structure, used for gas storage.

Analyzes on the feasibility and cost-effectiveness of the use of CO_2 for enhanced oil and gas recovery for 10 selected fields were the subject of the project carried out by INiG and PGI-NRI for the Ministry of the Environment (Lubaś [ed.], 2012).

Selection of the hydrocarbon fields, for which then detailed analysis in case studies were conducted, was the subject of consultations between representatives of the project consortium (of Oil and Gas Institute) with experts and decision-makers of POGC (the owner of the operating licenses for all fields). As a result, the structures – Nosówka oil field and Wilków gas field (and Łąkta field) were selected, basing on the ranking criteria, as well as taking into account the policy and strategy of POGC on the possible future use of the structures (for example, as gas storages).

Warstwy

☐ I_Jura&T/I_Jurassic&T
☐ II_Skoczów-Czechowice
☐ Miocen (inne)/Miocene (other)
☐ Kreda/Cretaceous
☐ Jura/Jurassic
☐ Trias/Triassic
☐ Czerwony spągowiec/Rotliegend
☐ Karbon/Carboniferous
☐ Kambr perspekt/Cambrian good
☐ obszary MPW/CBM fields
☒ gaz i ropa/HC fields
☐ podłoże Karpat/Carpathian base...
☒ NATURA2000 EEA
☒ GZWP/potable aquifers
☐ koncesje na posz. węglowodoró...
☒ emitenci, kt CO2/CO2 emittants,...
- 20-100
- 100-500
- 500-2500
- 2500-12500
- 12500-32000

☐ sejsmika2d-morze(PB)/seismic2...
☐ sejsmika3d-ląd(CBDG)/seismic3...
☐ sejsmika2d-ląd(CBDG)/seismic2...
☒ miasta pow. 50 tys./cities (town...
- 50-200
- 200-1000
- 1000-3400

☒ obszary zurbanizowane/urban a...
☒ większe rzeki/major rivers
☐ otwory >800 m/wells >800m
☐ złoża ropy (CBDG)/oil fields (CB...
☐ złoża gazu (CBDG)/gas fields (C...

☒ Kolejność warstw

Fig. 3_52 Selected hydrocarbon fields

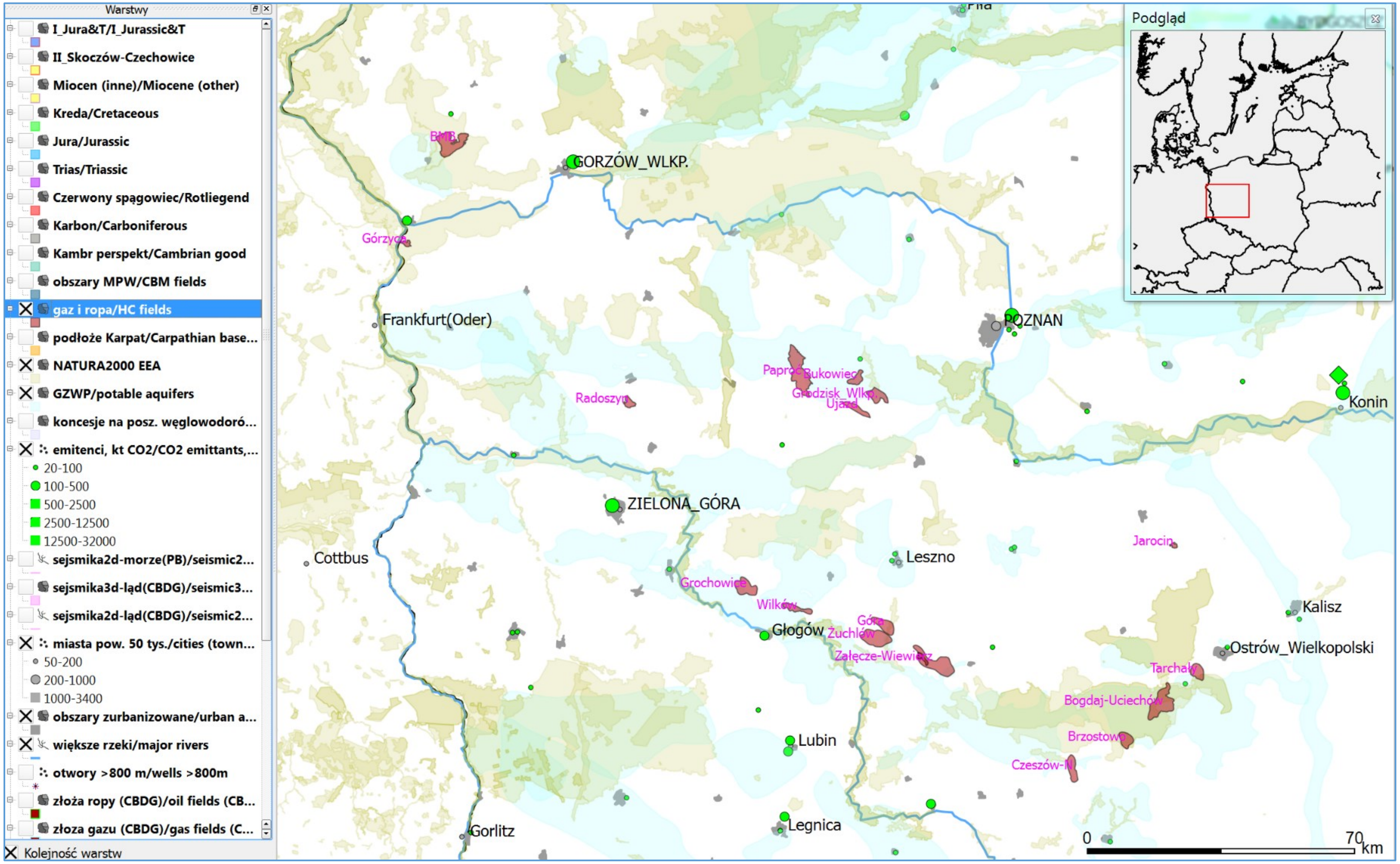


Fig. 3_52A Hydrocarbon fields – western Poland

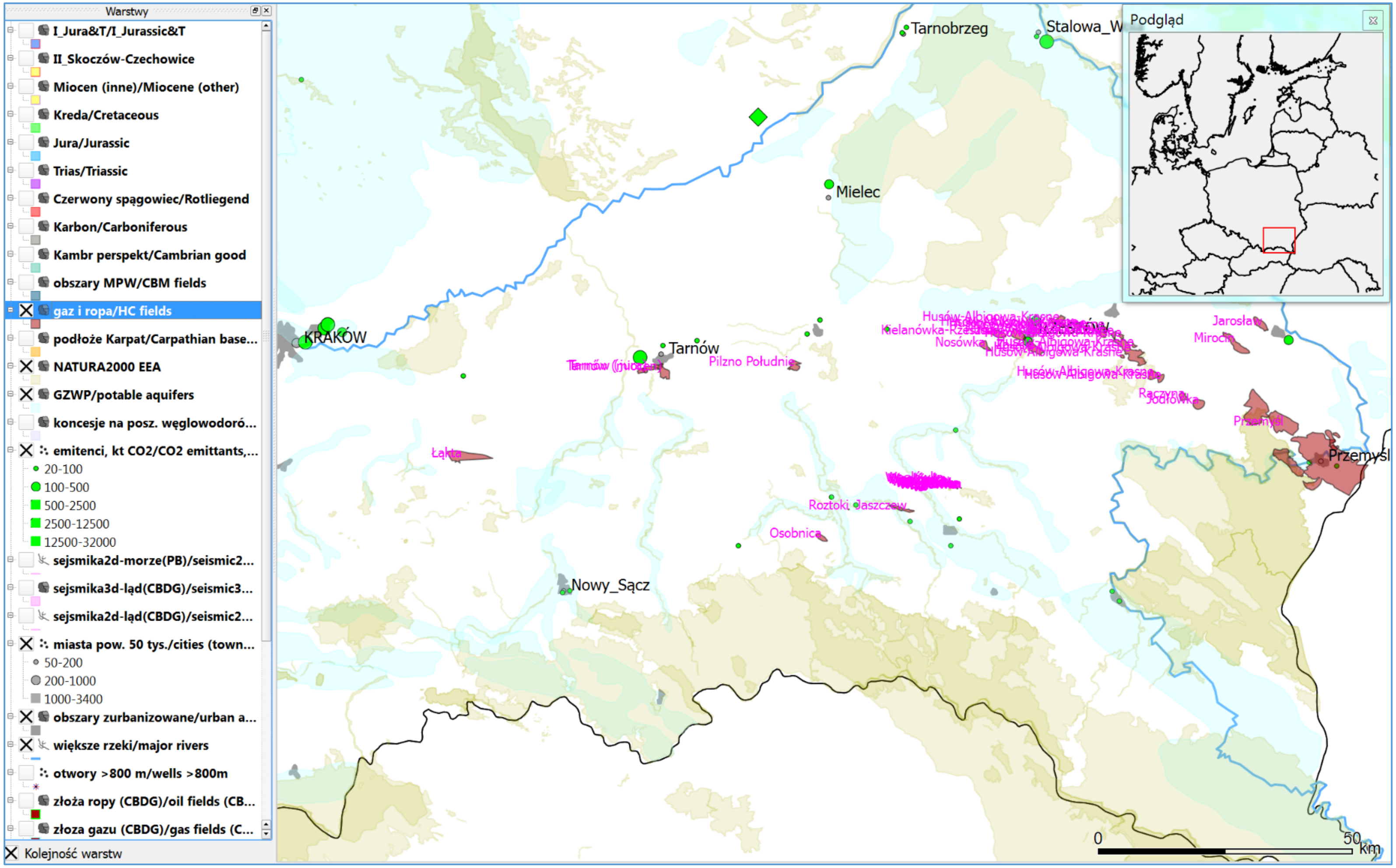
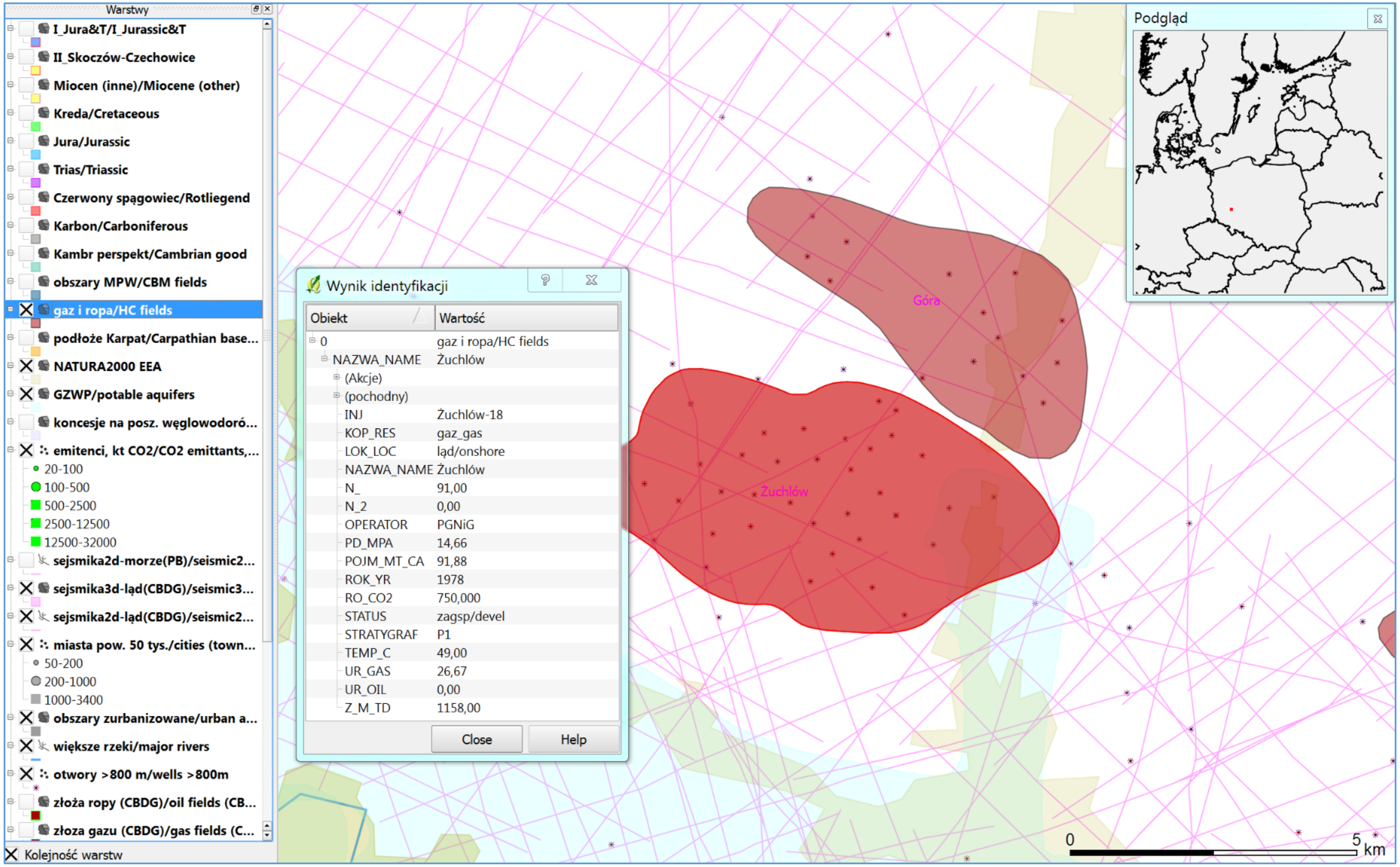
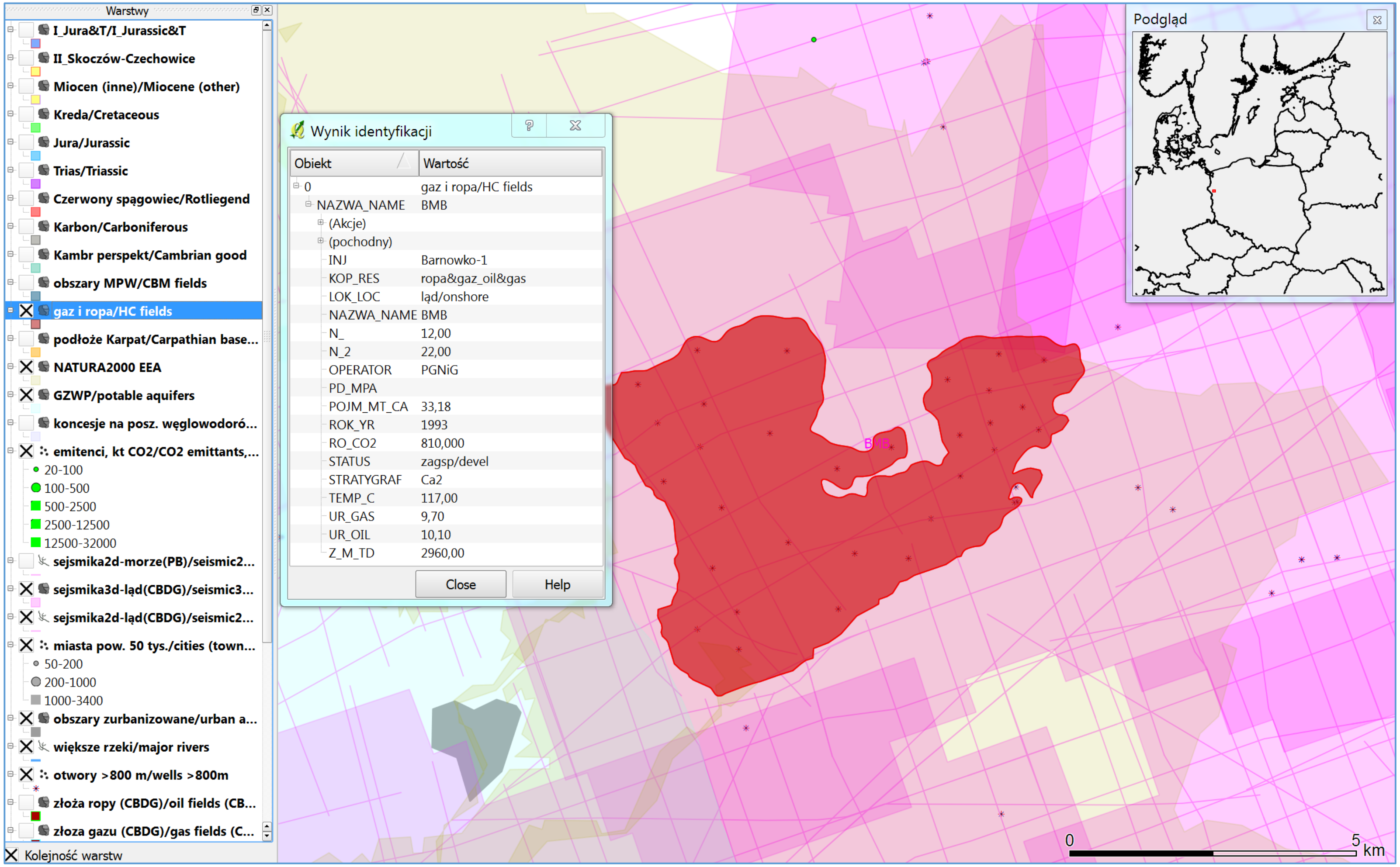


Fig. 3_52B Hydrocarbon fields – south-eastern Poland



Obiekt	Wartość
0	gaz i ropa/HC fields
NAZWA_NAME	Żuchlów
(Akcje)	
(pochodny)	
INJ	Żuchlów-18
KOP_RES	gaz_gas
LOK_LOC	ląd/onshore
NAZWA_NAME	Żuchlów
N_	91,00
N_2	0,00
OPERATOR	PGNiG
PD_MPA	14,66
POJM_MT_CA	91,88
ROK_YR	1978
RO_CO2	750,000
STATUS	zagsp/devel
STRATYGRAF	P1
TEMP_C	49,00
UR_GAS	26,67
UR_OIL	0,00
Z_M_TD	1158,00

Fig. 3_53 Żuchlów gas field (near Głogów)



Obiekt	Wartość
0	gaz i ropa/HC fields
NAZWA_NAME	BMB
(Akcje)	
(pochodny)	
INJ	Barnowko-1
KOP_RES	ropa&gaz_oil&gas
LOK_LOC	ląd/onshore
NAZWA_NAME	BMB
N_	12,00
N_2	22,00
OPERATOR	PGNiG
PD_MPA	
POJM_MT_CA	33,18
ROK_YR	1993
RO_CO2	810,000
STATUS	zagsp/devel
STRATYGRAF	Ca2
TEMP_C	117,00
UR_GAS	9,70
UR_OIL	10,10
Z_M_TD	2960,00

Fig. 3_54 Barnówko-Mostno-Buszewo oil field (BMB field - near Gorzów Wlkp.)

Hydrocarbon fields summary

In the case of hydrocarbon fields a few dozens of structures, of the appropriate size of the original recoverable reserves (UR) and the appropriate degree of depletion, may be useful for sequestration.

The exploited and selected hydrocarbon fields in Poland are grouped into two major petroleum provinces. The first is the region of the marginal zone of the Carpathian overthrust (flysch) and the Carpathian Foredeep - SE part of the country where the production of oil and natural gas was carried out for many decades (the oil production even since the second half of the nineteenth century). Hydrocarbons, mainly natural gas, occur there in formations of Neogene (Miocene), Paleogene and Cretaceous. The second province is in western Poland where gas fields are found in the formations of Permian - Zechstein and Rotliegend. In NW part of the country we have a few oil and gas fields (not gas fields alone), the largest of which - BMB near Gorzów (storage capacity of 30-40 million tons) is not depleted to a significant extent when it comes to original recoverable reserves of oil, and a smaller field of Kamień Pomorski in the area of Wolin – depleted to a large extent. Beyond these provinces we have an offshore oil field in the Baltic Sea - B3, the only operated for a long time, and a small oil and gas field Stężyca in the Lublin region. The storage capacities of these fields usually range from a few to several dozen of million tons of CO_2. Four gas fields: Przemyśl in SE and Żuchlów, Załęcze-Wiewierz and Bogdaj-Uciechów in the west, have a storage capacity of over 50 million tons. For several oil fields (NW Poland, SE Poland and Baltic Sea) CO_2 injection, mostly on a small scale, to enhance the oil recovery would be possible, which is likely to be economically viable even at the current price of ETS allowances. The enhanced hydrocarbon recovery by CO_2 injection is also possible for depleted (depleting) gas fields, though rather for the largest, but the potential revenue from such activities would be far less per ton of injected CO_2 than in the case of oil fields.

The storage potential of the hydrocarbon structures is in the range **784 - 1021 million tons**. These are mostly depleted gas deposits; the share of the several selected oil fields, with varying degrees of depletion, is less than 10% of the above values.

3.3 Coal beds

(Janusz Jureczka, Adam Wójcicki, Jarosław Chećko, Robert Warzecha, Tadeusz Bromek)

The results of the work carried out within the regional studies suggest that the potential CO_2 storage areas are in the central and southern part of the Upper Silesian Coal Basin (USCB) (**Fig. 3_55**).

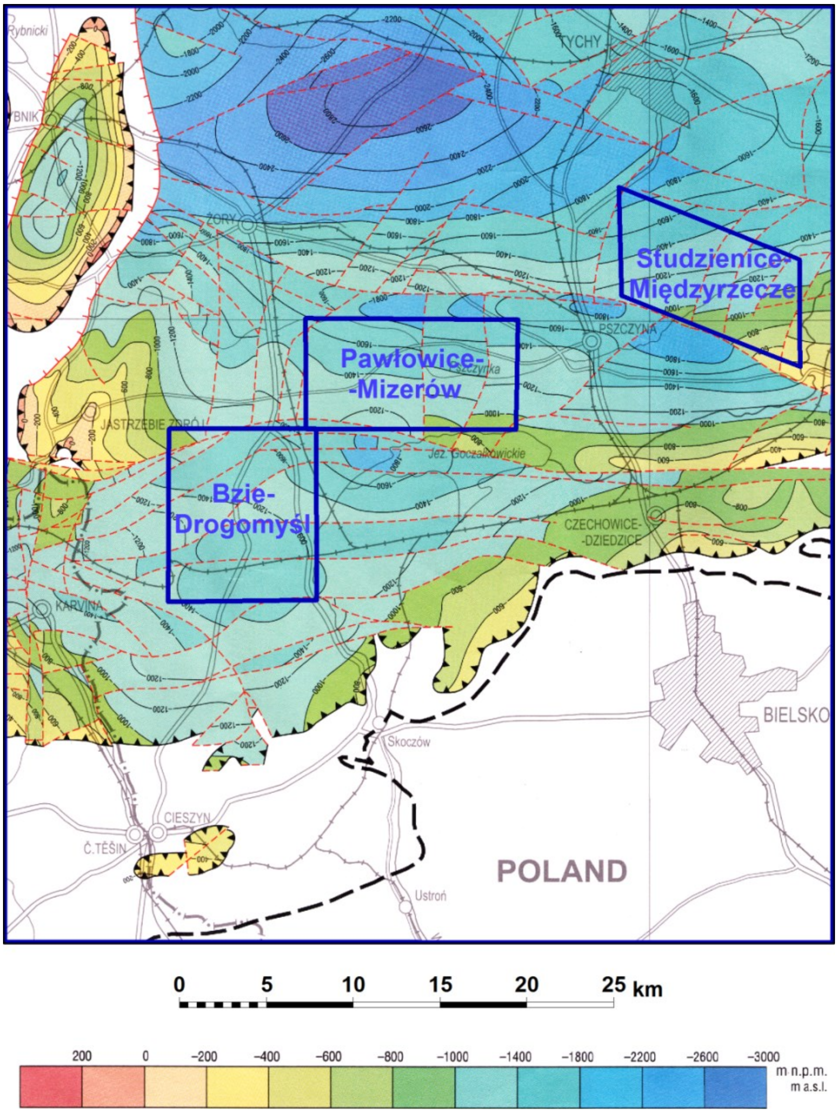


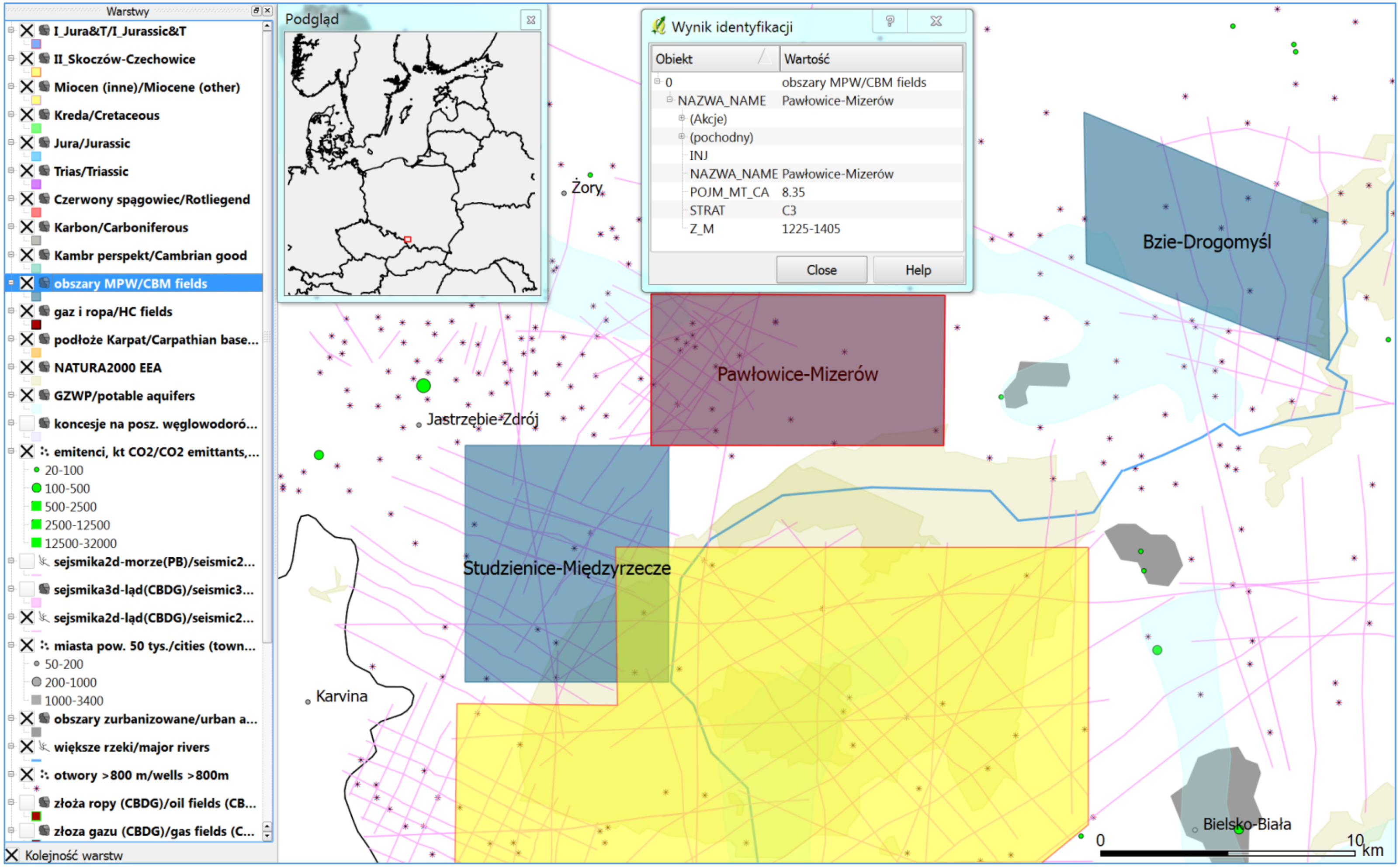
Fig. 3_54 Location of the central-southern region (of the USCB) on the background of the structural map of Upper Silesian Sandstone Series floor (Jureczka i in., 2005)

These are the following three sites, generally located north of the Skoczów-Czechowice site in saline aquifers (**Fig. 3_55** and **56**), of similar usefulness and parameters:

- Pawłowice-Mizerów site in central part of the USCB, east of “Pniówek” coal mine;
- Studzienice-Międzyrzecze site in central part of the USCB;
- Bzie-Drogomyśl site in south-western part of the USCB, south of “Pniówek” coal mine.

The area including these three sites seems to be the most promising for the use of CO_2-ECBMR technology. Since the variability of lateral distribution of methane content in coal beds at specific depth intervals is relatively small and the methane content values comparable for all three sites, the Pawłowice-Mizerów site has been selected for further analysis in the case study, due to the fact the methane content in coal beds is the best explored by wells there.

The industrial application of CO_2-ECBMR technology may include injection of up to 200 thousand tons of CO_2 into a horizontal well (for a few years - the lifetime of the ECBM project) in order to obtain the production of several dozen million m^3 of methane (Davis et al., 2004). For this purpose, it is unprofitable to build a transport pipeline but rather carry the purchased CO_2 by trucks or train. In Upper Silesia, for example, CO_2 is produced in the nitrogen plant in Kędzierzyn.



Wynik identyfikacji

Obiekt	Wartość
0	obszary MPW/CBM fields
NAZWA_NAME	Pawłowice-Mizerów
(Akcje)	
(pochodny)	
INJ	
NAZWA_NAME	Pawłowice-Mizerów
POJM_MT_CA	8.35
STRAT	C3
Z_M	1225-1405

Fig. 3_55 Site in coal beds – Pawłowice-Mizerów

Coal beds summary

Regarding the injection of CO_2 into un-mineable coal beds to enhance the recovery of coal bed methane, the analysis has been restricted to the Upper Silesian Coal Basin (USCB), and more precisely - its central-southern part. The analysis was used to identify three small areas in the central-southern part of the Upper Silesian Coal Basin where the use of CO_2-ECBMR technology is clearly possible in a realistic timeframe. Other coal basins (Lower Silesian Coal Basin, Lublin Coal Basin) seem to be inappropriate for CO_2 storage due to safety issues or the status of exploration of CBM resources.

Due to the geological structure of the USCB, distance from active coal mines and the lack of urban areas - in terms of possible conflicts of interest and the safety of storage – for further studies the central and south area was chosen; where three sites were determined and subjected to a detailed analysis in terms of geology, the net coalbed thickness, the basic chemical-technological parameters of coal and methane content. Of these three sites Pawłowice-Mizerów is the best explored by deep wells.

The storage potential for coal beds can be estimated at **20 - 100 million tons** range. The first value refers to the possible exploration permits within the USCB - three sites in the central-southern part of the Upper Silesian Coal Basin, with a storage capacity of **5-8 million tons** of CO_2 each, where these values relate to the storage in only two relatively thick coal seams (each of thickness of several meters) located in the entire prospective area. The latter figure is a hypothetically assumed area of the USCB where CO_2 storage would be possible, although in poorer reservoir conditions, within a depth range of 1-2 km.

4. CASE STUDIES

As a result of the regional studies a number of sites in the saline aquifers (taking into consideration possible needs of the CCS demonstration projects in Bełchatów and Kędzierzyn, planned when this project started), hydrocarbon fields and a site in coal beds were selected for detailed analyses (case studies).

The case studies for those sites included an initial characterization of potential storage sites in accordance with the guidelines given in Annex 1 of the EU directive on the geological storage of carbon dioxide.

4.1 Saline aquifers

(Adam Wójcicki, Janusz Jureczka, Sylwia Kijewska, Michał Wojtowicz, Marta Kuberska, Maciej Tomaszczyk, Jarosław Chećko, Aleksandra Koteras, Stanisław Nagy, Bartosz Papiernik, Radosław Tarkowski)

Budziszewice-Zaosie (Bełchatów)

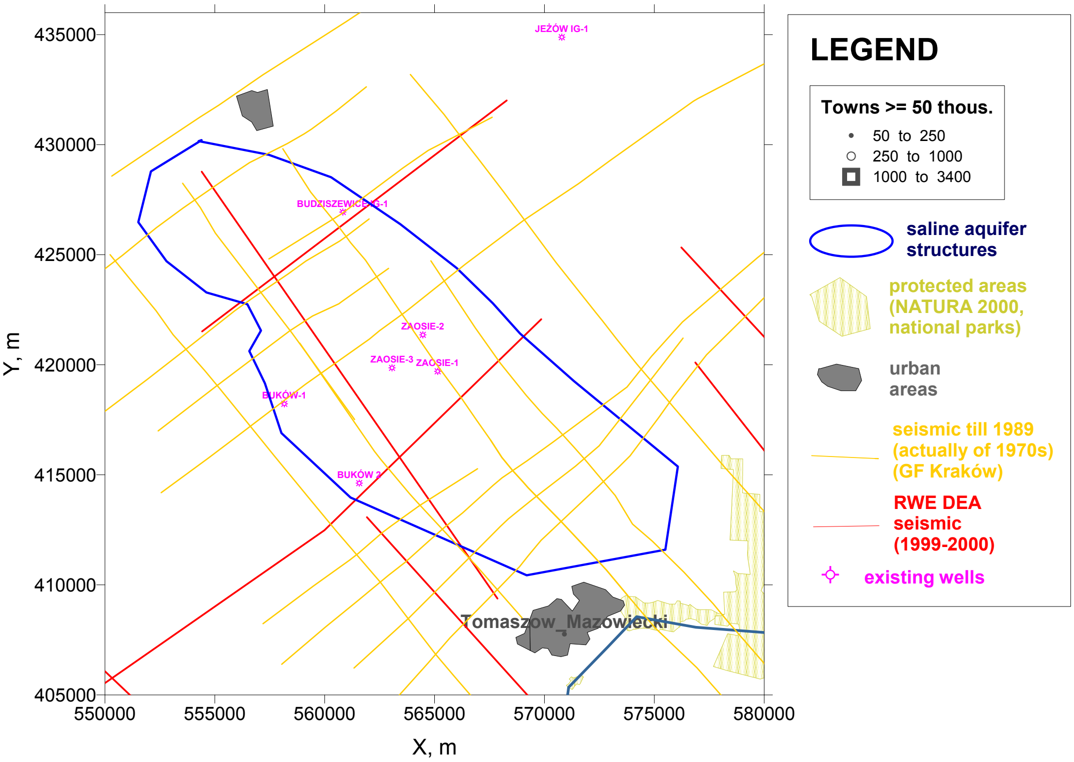


Fig. 4_1 Wells and seismic lines in the area of the structure

Budziszewice-Zaosie structure (**Fig. 4_1**, **2**, **4**), lies between Tomaszów Mazowiecki and Łódź (see also Chapter 3.1, study area I), is drilled by five wells, and in its area more than a dozen of seismic profiles have been acquired in 1970-2000, but only some of which could be used in the construction of the static/geological/structural-parametric model of the structure (**Fig. 4_2**).

The principal reservoirs are the Lower Jurassic sandstones (also a scenario for the Lower Triassic sandstones was analyzed by INiG), with a thickness of approximately 50-100 m. They occur within the Upper Pliensbachian (Drzewice formation, at a depth of 770 m at the top of the structure), with effective porosity of about 14-25 % according to laboratory measurements, and the permeability of about 300 mD, and Synemurian and Hettangian (Ostrowiec formation, locally Zagaje formation), with a porosity after laboratory analyzes of approximately 14-20 % and permeability as in the Upper Pliensbachian. According to well logging data effective porosity of the Lower Jurassic sandstones is approximately 15%. Primary seal is the Lower Toarcian (Ciechocinek formation) with a thickness of approximately 100 m, then above lies the impermeable Upper Aalenian of a slightly smaller thickness, and the seal between the Upper Pliensbachian and Synemurian reservoirs is weak (especially at the top of the structure). A cautionary indicator is a low mineralization of the brines in the Lower Jurassic reservoirs (several g/l), which, however, may be associated with the discharge areas (J1 outcrops) in the Holy Cross Mountains (about 100 km SE; in case of Wojszyce structure mineralization is also quite low) or fossil waters (?).

Basing on the static/geological model of the Jurassic (**Fig. 4_3**) simulations of CO_2 injection scenarios involving the location of the wells at the top of the structure (AGH - GEM program - 1 horizontal well, or 2-4 vertical wells; an example in **Fig. 4_4**), or on its slope (GIG - TOUGH2 - 4 vertical wells) have been performed. Injection in such quantities as planned in the CCS demo project of PGE Bełchatów (about 2 million tons per year) was assumed, with the exception of one variant of the pilot injection (20 kt/year). In both scenarios, simulations of the behavior of injected CO_2 for tens, hundreds and thousands of years were made. It was found that injection on a slope of the structure impacts to a lesser extent on the existing pressure field and the original reservoir conditions are reestablished faster, than in the case of injection into the top of the structure.

Basing on the results of injection simulations and the geological model a preliminary risk analysis was performed. The problem to be solved here, next to the structure closure to the NW (in Koluszki-Łódź direction), is the seal quality at the top of the structure. For this purpose, a detailed site characterization and baseline monitoring for the structure would be necessary, for which the assumptions were prepared in this project (**Fig. 4_4**), as well as the plans for environmental monitoring around the injection wells (MEERI PAS), and exemplary studies on the implementation of the pilot injection (PGI-NRI and AGH).

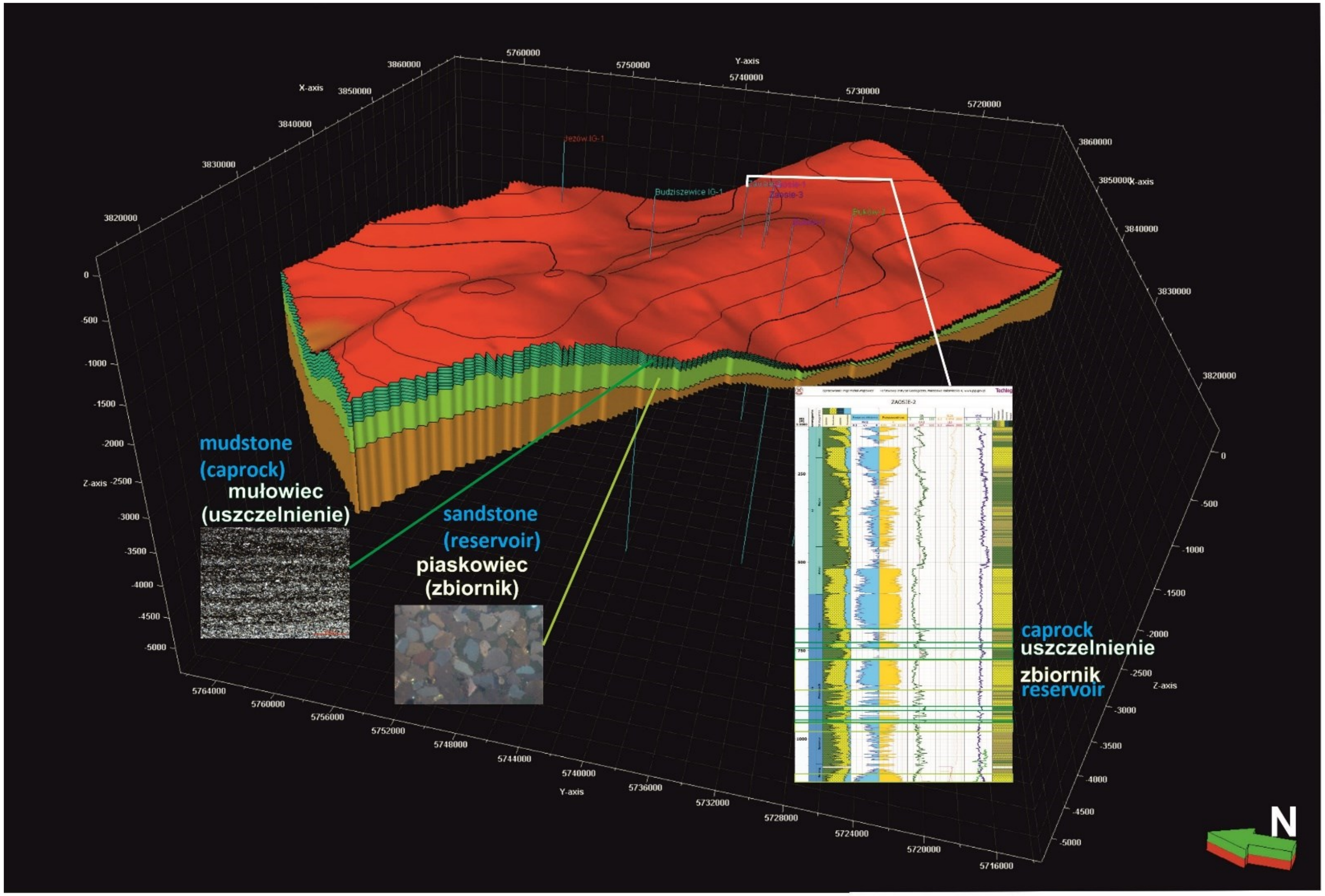


Fig. 4_2 Model of Budziszewice-Zaosie structure (B-Z; Petrel), with an example of well-logging interpretation and rock samples

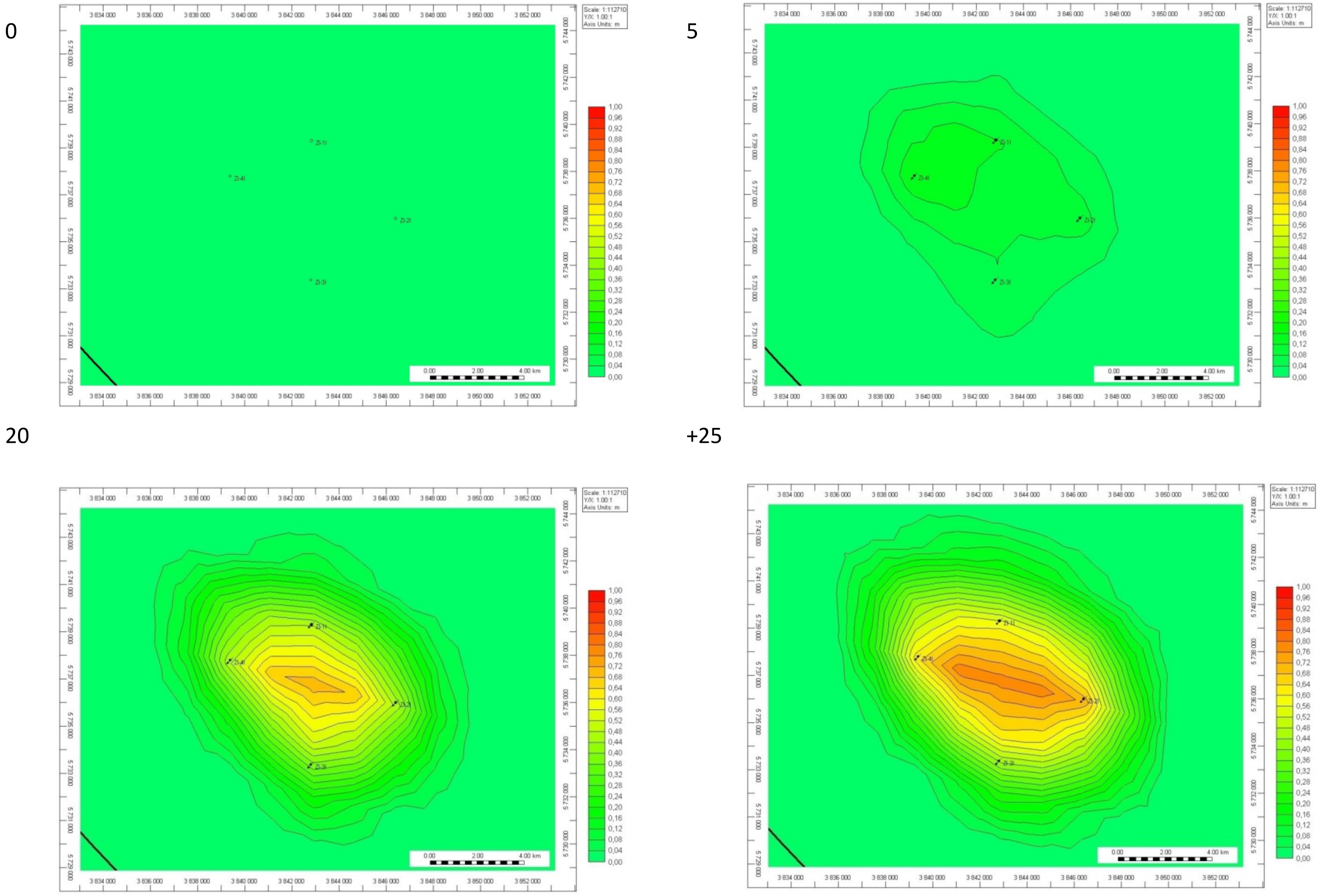


Fig. 4_3 Example of simulations of CO_2 injection into Jurassic reservoirs (Jpl3, Js+h) of B-Z structure; 0, 5 and 20 y. of injection and 25 y. after injection

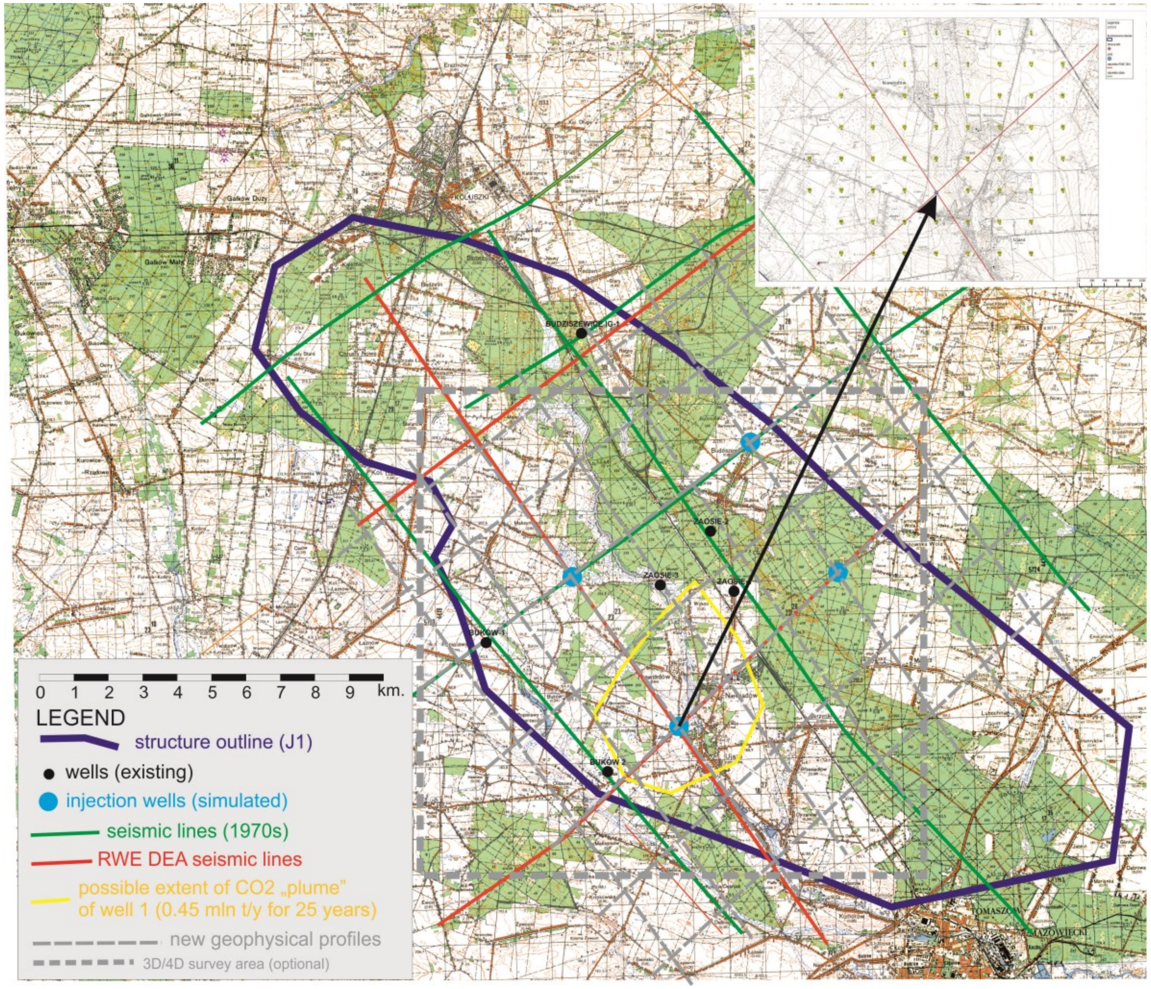


Fig. 4_4 Location of the simulated injection wells and proposed field surveys (site characterization, baseline monitoring)

Skoczów-Czechowice (USCB)

The coverage of the study area with wells penetrating Miocene and its basement is relatively dense (**Fig. 4_5**), but only for a few wells cores were preserved (including one PGI well). Virtually in all deep boreholes well logging data are available, but only for the few the interpretation of lithology and petrophysical parameters was conducted, because the area was explored rather in order to assess hard coal resources in the Upper Carboniferous than, for example, to determine the properties of the Miocene caprock.

Results of petrophysical and petrological analyses of core samples were available in the most of the wells and they were, next to archive structural (seismic) and geological maps the basis for the development of the static model by GIG using Petrel program (**Fig. 4_6**). In the case of the sandstone and conglomerate formations of Dębowiec beds the average effective porosity is only slightly higher than 10% (the minimum for geological storage) and average permeability of about 40 mD; similar properties are characteristic for Zamarski beds (of a small thickness) occurring locally underneath. In case of the basement of Miocene (the Upper Carboniferous), slightly better reservoir properties can be observed locally within the Cracow Sandstone Series, than for Dębowiec beds, and within the Upper Silesian Sandstone Series - worse (PGI-NRI, Upper Silesian Branch).

Simulations of injection of carbon dioxide into the reservoir within the Lower Miocene sediments (Dębowieckie and locally Zamarski beds) have been conducted (GIG - TOUGH2 program) using one or four wells (**Fig. 4_7**), assuming respectively 0.45 and 0.25 million tons of CO_2 per well, in the period of 25 years. Such (assumptions for) scenarios of CO_2 injection resulted from the reservoir properties of the aquifer, as well as guaranteed the reservoir pressure increase at the top of the aquifer will not exceed more than a dozen percent, which excludes any threat to the integrity of the storage complex. In total, the injection of 25 million tons of CO_2 was achieved, which is an equivalent of emissions of a medium size energy installation.

Although the object appears to be safe as a potential CO_2 storage site, its use would require additional detailed geological and geophysical field works (new wells, seismic) and evaluation of storage risks to Morcinek, Bzie and possibly Pniówek collieries. Also it would be important to explore the wellbore integrity status for all abandoned wells within the range of stored CO_2, as well as the impact of storage on a nearby geothermal aquifer in the area of Jaworze. Therefore, the plan for site characterization and baseline monitoring (including a seismological network - GIG) has been developed, as well as the assumptions for the implementation of test CO_2 injection in the region of Iskrzyczyn (PGI-NRI and AGH, this is for one of the injection simulation wells in **Fig. 4_7**).

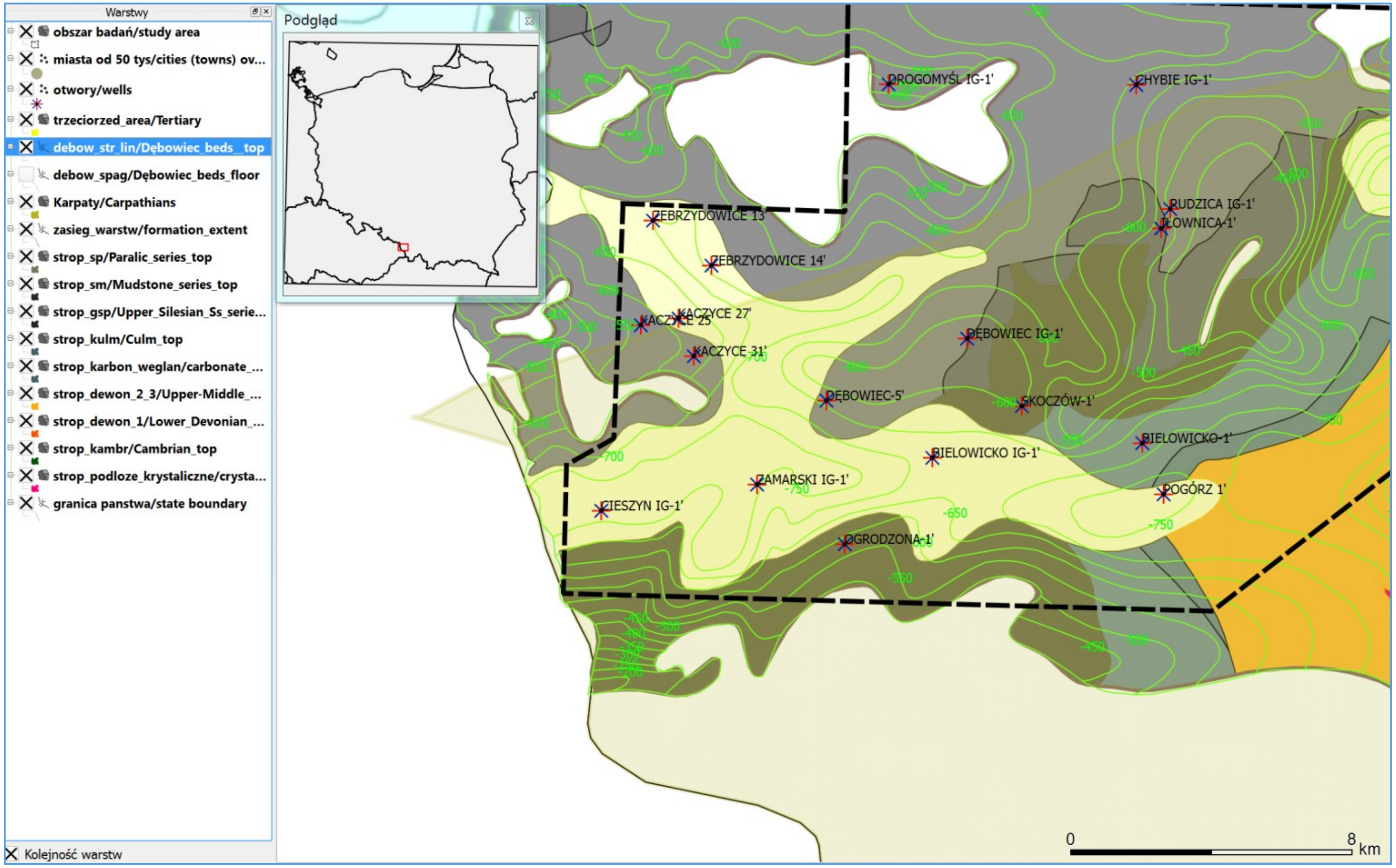


Fig. 4_5 Summary of geological data for the study area; map of the top of Dębowiec beds in the form of isolines (a.s.l.; the terrain surface within the study area is at a height of 250-300 m above sea level), and respective colors denote ranges of the various geological formations in their basement

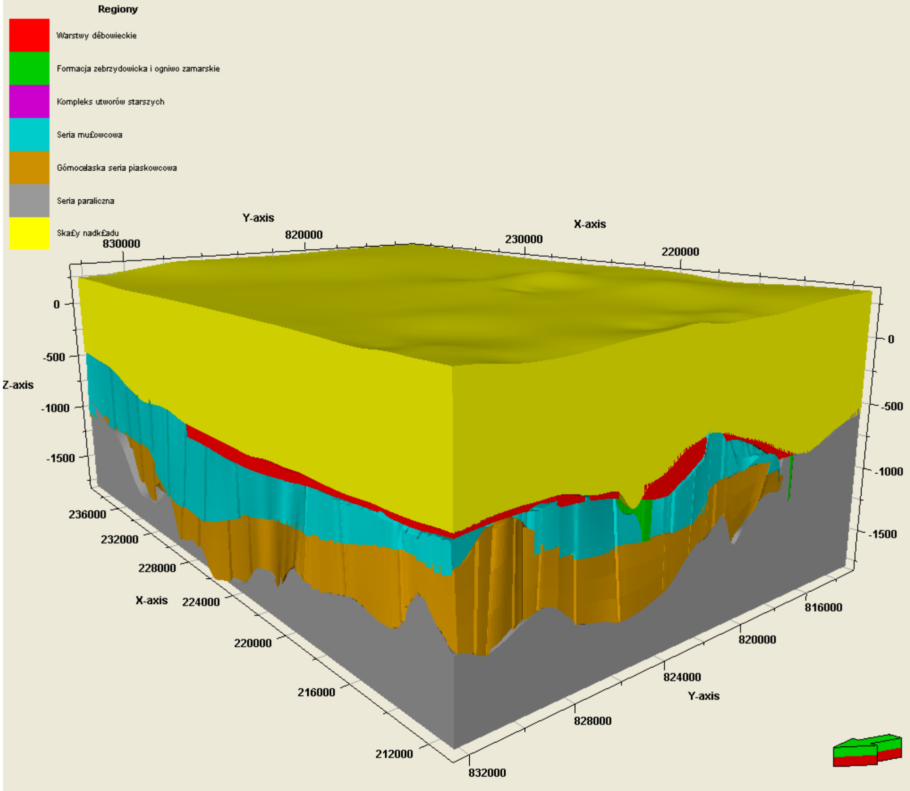


Fig. 4_6 Geological (static) model of Skoczów-Czechowice site

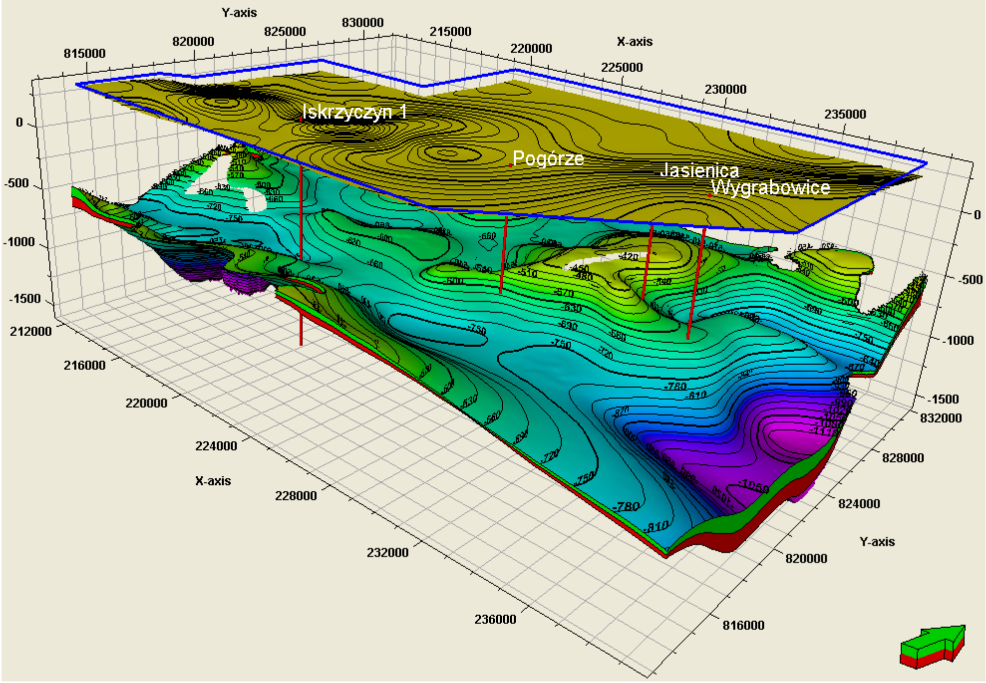


Fig. 4_7 Top of Dębowiec beds, terrain surface and (simulated) injection wells

Choszczno-Suliszewo (NW Poland)

Choszczno - Suliszewo (Pławno - Radęcin) structure (C-S structure) is located in NW Poland, about 60 km SE of Szczecin agglomeration (**Fig. 4_8**). The (wider) study area is explored by 28 wells, and in the area of the structure and its immediate surroundings information from 12 boreholes has been available: a few data on reservoir and hydrogeological properties and core samples, and for five wells the wireline logs (**Fig. 4_9**) of quality that allows the interpretation of shaliness and reservoir properties. In the study area there is a dozen of seismic profiles of rather poor quality (most of them are about thirty years old), which interpretation, made by the PGI-NRI, was used to refine and reambulate the structural maps developed by AGH. Prospective reservoirs in the region of the structure include the Lower Jurassic sandstones (Upper Pliensbachian, especially Synemurian & Hettangian - see **Fig. 4_9**) and the seal is the Lower Toarcian, not counting the complexes of Middle Jurassic, moreover, between the two reservoirs the seal of a small thickness appears.

This information has been used by AGH to construct a static (geological) model, which was the basis for a number of variants of the injection simulation. The results show very good properties of the reservoir - shaliness is about 20%, porosity of 20%, and permeability of at least 1000 mD.

The simulations (by AGH - GEM simulator) of the injection into each high of the structure (**Fig. 4_10**; 1 million tonnes of CO2 per year, for 25 years; and for the Suliszewo high another option of 2 million tons/year, until the structure is filled - so its total capacity amounted to 634 million tons) have been conducted. In parallel GIG performed the injection simulations using Ecllipse 300 program, assuming the injection rate 1 and 2 million tons/year for the Choszczno and Suliszewo highs respectively. In the model inferior parameters of the seal were observed locally in the top of the Choszczno high and a possible leakage of CO2 from the Upper Pliensbachian reservoir to Lower Toarcian seal after a significant increase of the reservoir pressure there.

In addition to the doubtful seal quality in the top of the Choszczno high (PGI-NRI interpretation of the seismic sections did not detect any discontinuities in the caprock, while the analysis of reflection coefficients by MEERI PAS - Dziewińska & Tarkowski, 2012 - suggested such a possibility) the problem may be here the integrity of old, abandoned wells (the use of cements not resistant to carbonate corrosion). The uncertainty of mapping of the geometry of the structure (seismic of poor quality) and distribution of reservoir and filtration parameters for the entire Choszczno-Suliszewo (Radęcin-Pławno) site are also important.

Hence, before making an investment decision the detailed site characterization and the baseline monitoring, in terms analogous to the B-Z structure, would be necessary.

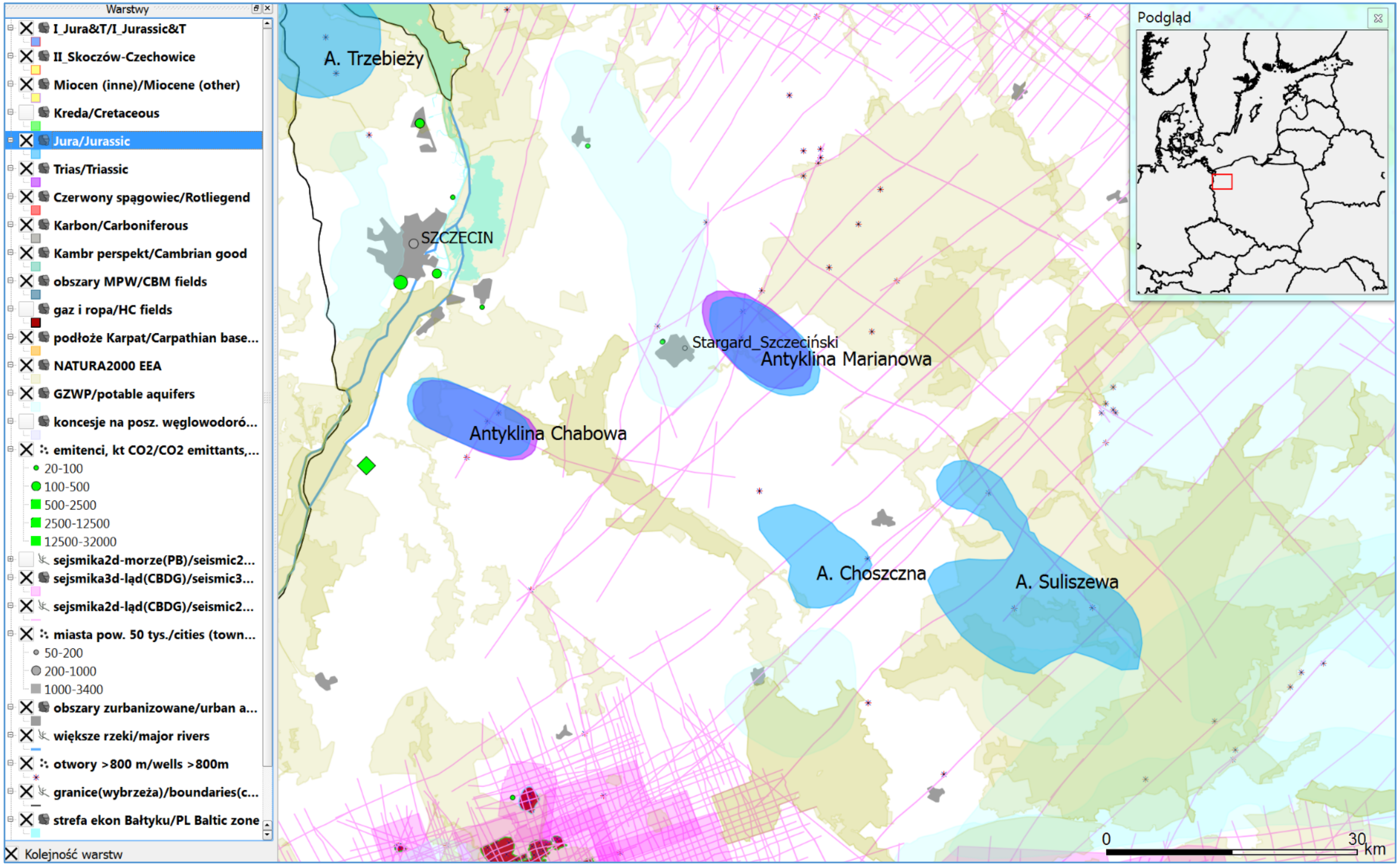


Fig. 4_8 Location of Choszczno-Suliszewo(-Radęcin-Pławno) structure and relevant wells and seismic lines in the study area

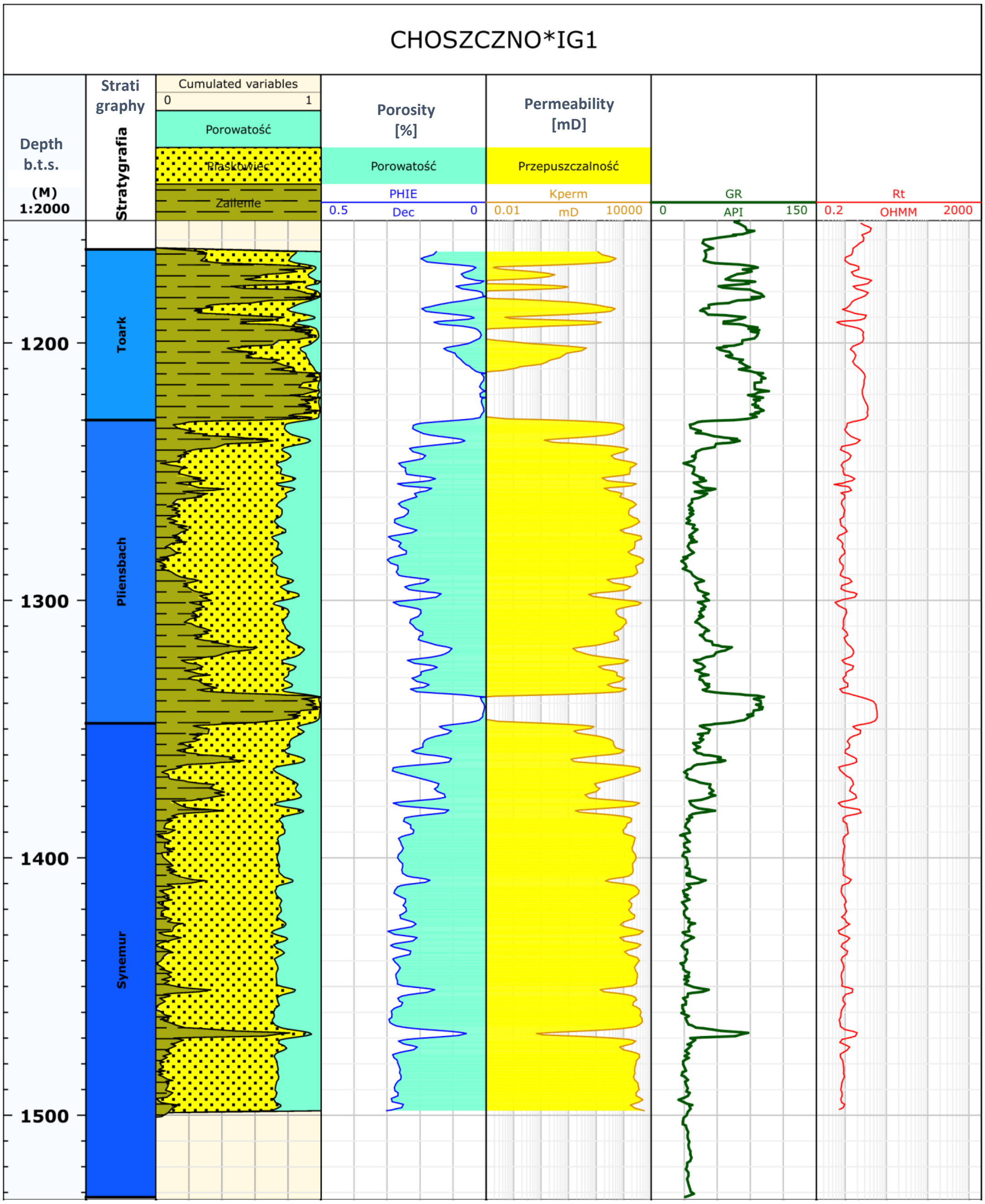


Fig. 4_9 Results of petrophysical interpretation of well-logging data – as an example, Choszczno IG-1 well, including lithology, shaliness, effective porosity and permeability interpretation

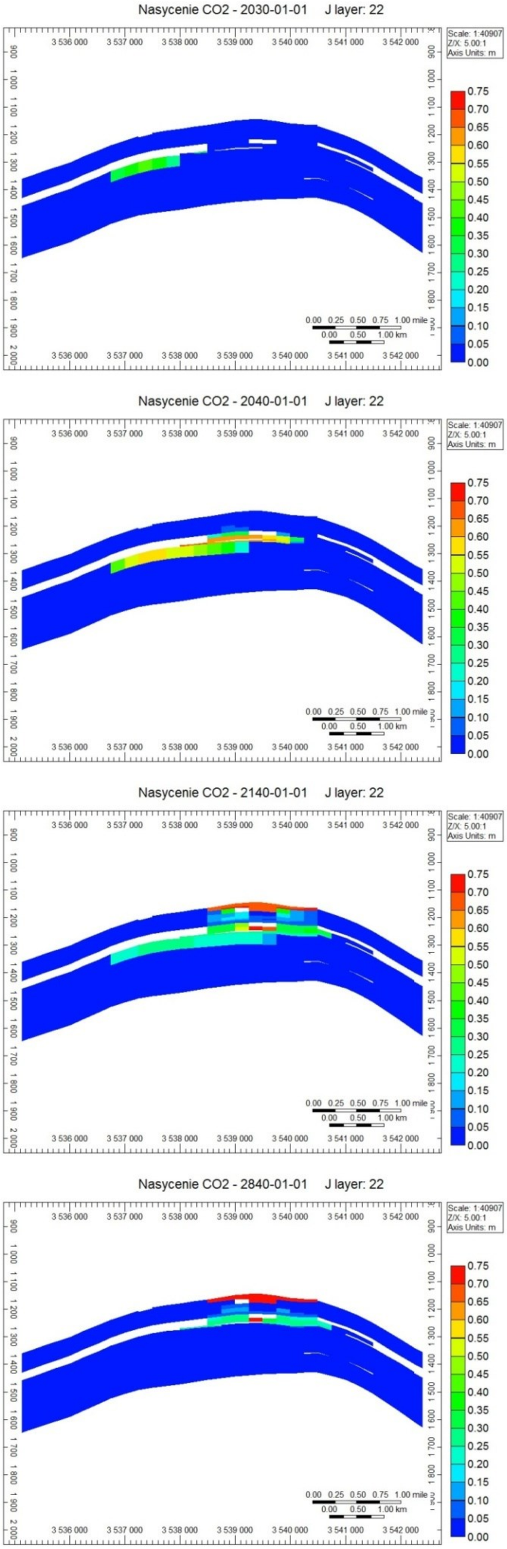


Fig. 4_10 CO_2 migration to the top of Pliensbachian at the top of Suliszewo high

Poznań trough (Greater Poland)

For the purposes of CO_2 storage the south-western part of Poznań trough was selected (by INiG; about 20 miles SW of Poznań), which is limited to the west and south by Wolsztyn ridge (**Fig. 4_11**). The brine saturated Rotliegend sandstones in NE dip to a depth of 5 km, which makes also a kind of closure, because the injected gases tend to move upwards. The whole aquifer is covered with a sealing complex of Zechstein evaporites. So, the isolated fragment is a perfect megastructure for the purposes of CO_2 sequestration. The considered part of Poznań trough has a considerable reservoir thickness, and the presence of reservoir of good properties (as Rotliegend formations - according to information from the wells, archive laboratory analyzes, effective porosity of the reservoir series reaches over a dozen % and permeability often exceeds 100 mD) creates extremely favorable and unique geological conditions for future CO_2 sequestration.

In the process of construction of the static/geological model (by INiG) regional and detailed (areas of gas accumulations) structural maps of the top of Rotliegend (by POGC) were used as well as information from wells, including wireline log data and laboratory data on reservoir parameters of Rotliegend. The resulting model of the aquifer (Petrel program - **Fig. 4_12**) consists of 10 layers, with different distribution of reservoir parameters.

CO_2 injection simulations have been performed according to two scenarios, involving injection into either 3 or 7 wells for 50 years (as a result, respectively 10.6 and 24.7 million tons of CO_2 have been stored - **Fig. 4_13**). In both cases the behavior of reservoir fluids during the relaxation period i.e., for 300 years after the injection stopped has been simulated.

Risk analysis has been carried out basing on Quintessa FEP database, which shows that it is essential to confirm the structure (storage complex) integrity by determining the parameters of the Zechstein caprock above the reservoir throughout the entire area, which in the future may be impacted by CO_2 injection. Besides, the correct closure of the old wells occurring within the range of carbon dioxide injection is important.

As this is probably the case for saline structures, models of the storage complex for Poznań trough are characterized by an insufficient detalization, so that they cannot be the basis for a reliable presentation of the program of monitoring of the effects of CO_2 injection into the geological formations. Therefore, in order to develop the ultimate monitoring program it is proposed to make a feasibility study (including modeling of wave field and seismic inversion, to verify the seismic record) to design 4-D seismic, recognized as the most proper monitoring technology (Jędrzejowska-Tyczkowska et al., 2004).

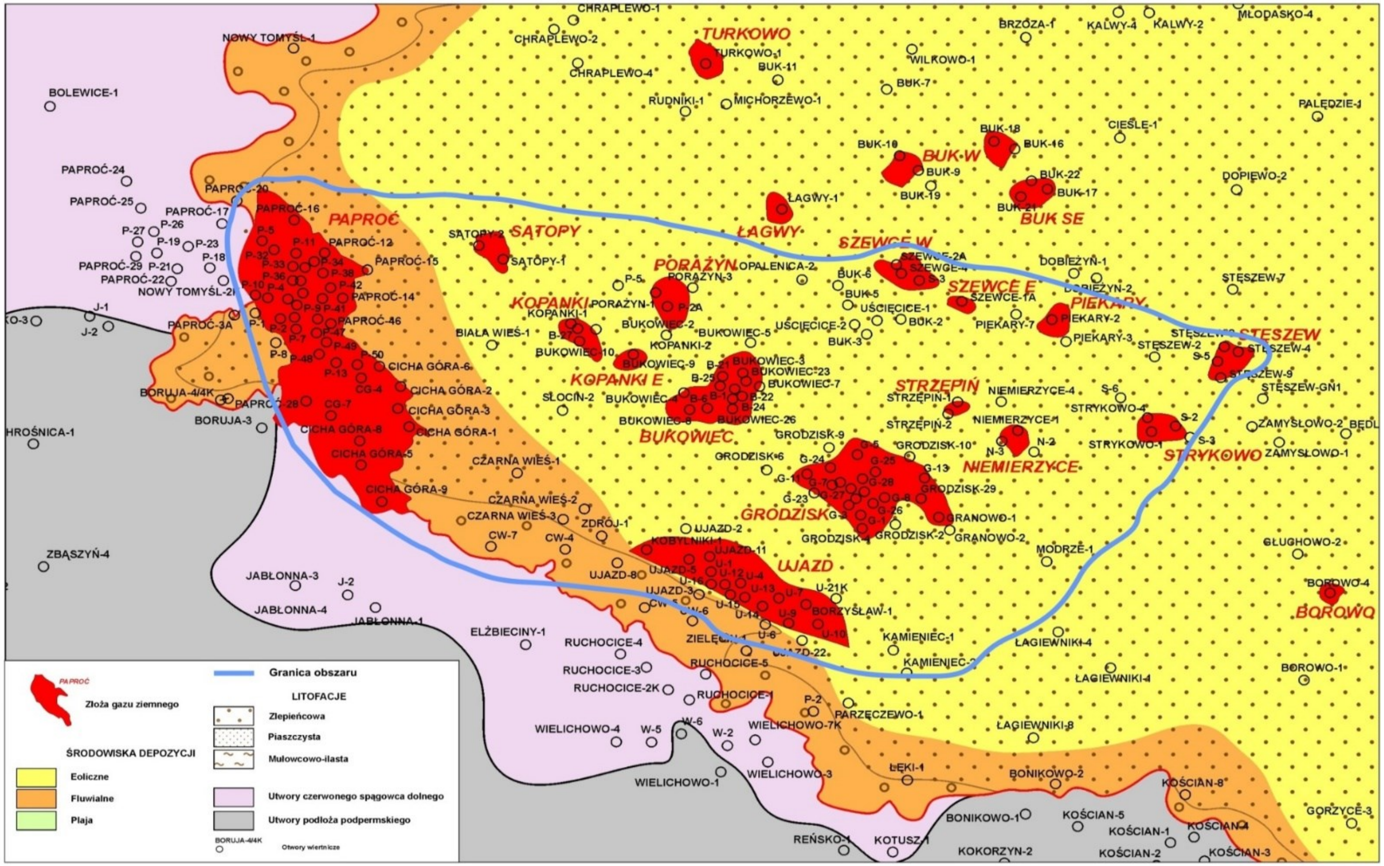


Fig. 4_11 Part of Poznań trough with borders of the study area

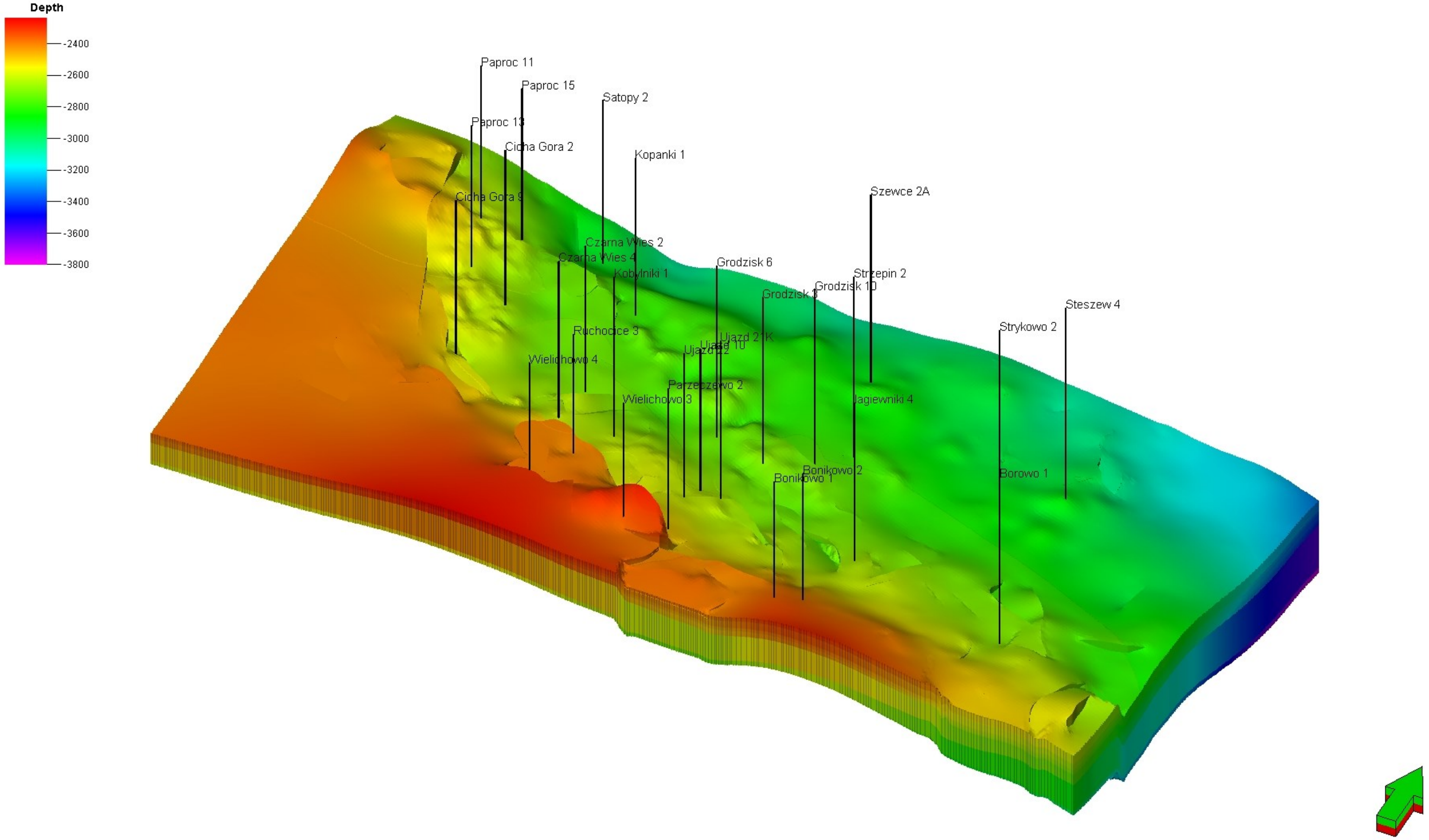


Fig. 4_12 3-D view of the model of Poznań trough site

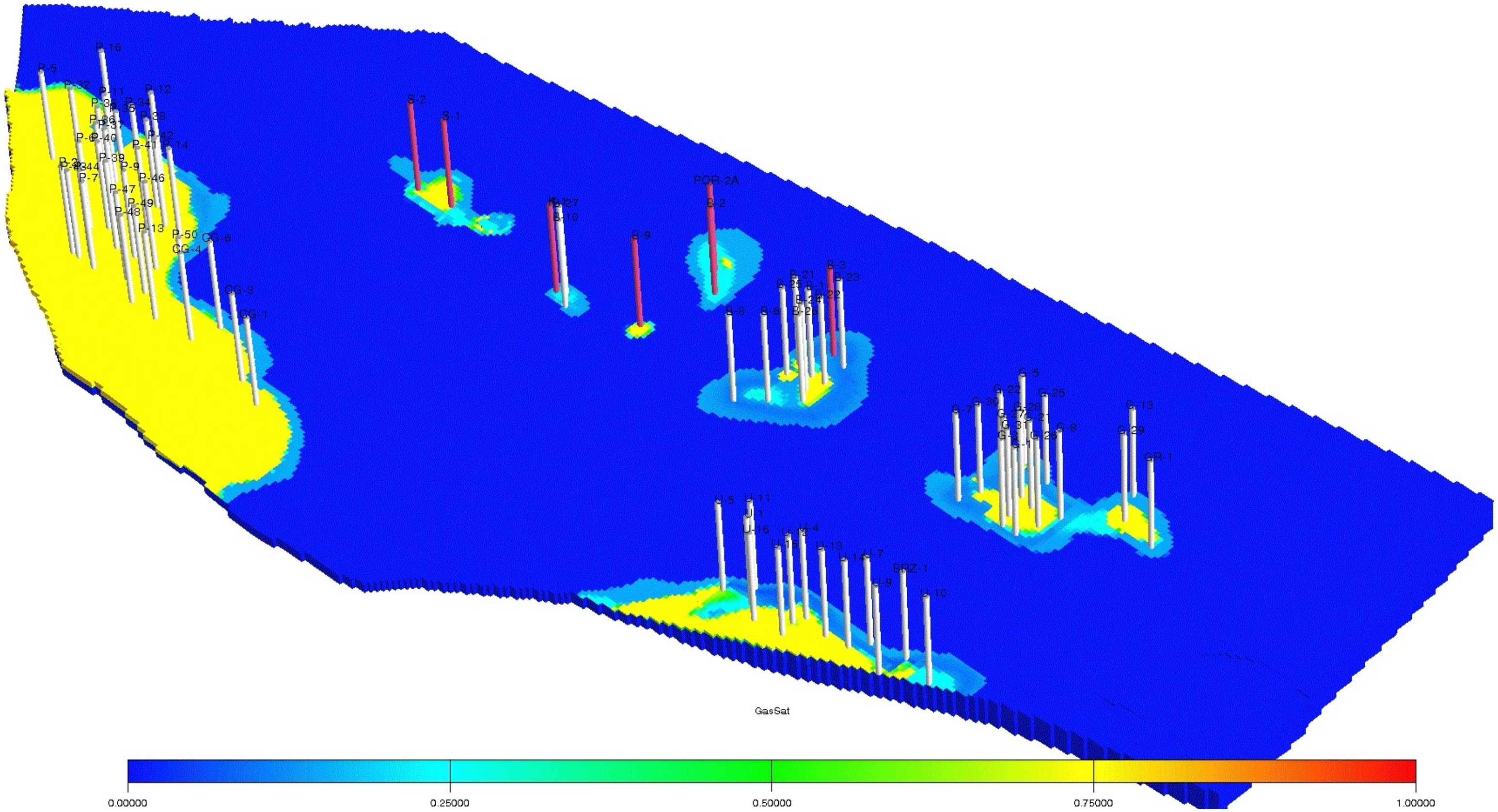


Fig. 4_13 Poznań trough site – distribution of wells within local structural highs (injection wells of 2 variant – denoted in red)

Saline aquifers summary

Budziszewice-Zaosie structure

The study of Budziszewice-Zaosie structure (located about 60 km from the Bełchatów power plant) was the first comprehensive attempt to characterize a potential storage site of carbon dioxide in accordance with the requirements of the EU directive on the geological storage of carbon dioxide (2009/31/EC) in Poland. This structure had been the best explored by wells (6 wells) and seismic (3 sections of 1999-2000, 6 usable profiles of 1970s) of all considered sites in the Bełchatów region before the new field works were performed under the CCS demo project of PGE Bełchatów. It does not meet perfectly all the textbook criteria as a potential storage site for the demonstration project, but only for this structure a reliable analysis scheduled in the case study could have been performed, basing on the available (then) archive data.

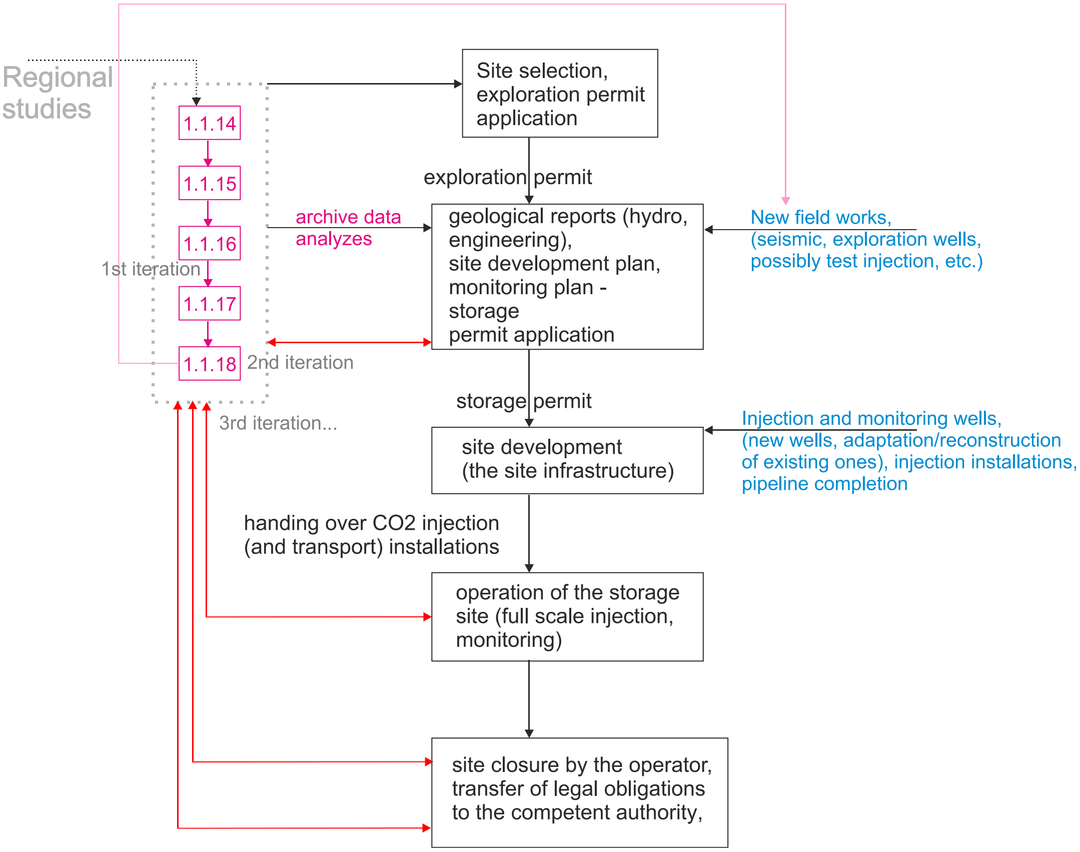


Fig. 4_14 Relation of the work performed under the case study, as in case of B-Z structure, to the life cycle of the CCS demonstration project, if the structure would be selected as the storage site

Budziszewice structure includes two reservoirs with good properties, useful for the geological storage of carbon dioxide in the Lower Jurassic formations, (Synemurian reservoir is safe, but it is locally connected in the top part of the structure to the shallower Upper Pliensbachian reservoir; the main seal is the Lower Toarcian formation) and to a lesser extent the Lower Triassic reservoir.

For various injection scenarios the dynamic, or practical capacity was obtained in the range of **50 - 120 million tons**, depending on the number and configuration of the injection wells and utilized reservoirs, and the static, effective capacity twice as large. Injection into the Synemurian formation (and locally Hettangian) would be safe and feasible, preferably in the wells located on the slope of the structure, on condition the proposed program of the baseline monitoring (on the initial status of the structure, before injection) is implemented, which would give the resulting model of the structure with a degree of detail sufficient for the needs of demonstration project. In addition to the assumptions of the geological workplan on monitoring the potential storage site also geological workplans on wells for pilot injection of carbon dioxide have been elaborated.

In this case (this is likely a rule for saline aquifers), available geological and geophysical data (1st iteration - **Fig. 4_14**) would be insufficient to produce a documentation for the storage permit. For this purpose, results of new field works carried out in the framework of the exploration permit, would be necessary (2nd iteration - **Fig. 4_14**, which also would include the baseline monitoring - after the assumptions developed under the case study), and only would answer the question of whether the structure is actually suitable to store the assumed amount of CO_2, whereas the scope of work performed under the case study allowed the determination of the area of our ignorance.

Skoczów-Czechowice site

After the assessment of coarse and medium grained clastic rock complexes appearing in the geological profile of the Upper Silesian Coal Basin it follows that the complex of Dębowiec beds is characterized by the most favorable parameters for CO_2 storage.

Considering the geological (reservoir thickness and depth of its occurrence) and hydrogeological parameters, as well as the current status of geological and hydrogeological exploration and the location of coal mines, it can be concluded that the area stretching from Cieszyn and Skoczów till Czechowice-Dziedzice is of the biggest potential (further studies and possible location of storage facilities would be possible in the southern and eastern parts of the area, on the slopes of the site that is not, however, an anticline, but rather a trough), and the also analyzed Andrychów-Kęty area near Bielsko-Biała is less perspective.

This (first) area of occurrence of the aquifer of Dębowiec beds has been subjected to a detailed analysis on the possibilities of safe CO_2 storage. The calculated static, effective CO_2 storage capacity for Dębowiec beds within the area has been estimated at 40-60 Mt, while dynamic, practical, unfortunately only **20-25 million tons** of CO_2. Hence the storage site can only suffice for the needs of a medium sized CO_2 emittant from the region of Upper Silesia, and is not suitable for the storage of emissions from power plants.

Choszczno-Suliszewo(-Radęcin-Pławno) structure (C-S structure)

Choszczno and Suliszewo (Radęcin-Pławno) anticlines are located in the south-western part of the Szczecin trough in the border zone of the adjacent (to south) Gorzów block. This is actually Choszczno-Suliszewo-Radęcin-Pławno structure with four highs. The reservoirs are Lower Jurassic sandstones with excellent reservoir properties, and the analyzed storage complex includes formations from the Lower Toarcian (primary seal) through Pliensbachian, Synemurian and Hettangian (reservoirs).

A number of variants of CO_2 injection were assumed, referring to individual structure highs, for both established number of wells and the period of operation of the CCS project (25 years - a total of **100 million tons** of dynamic capacity, assuming as a standard a constant injection rate of 1 million tons of CO_2/year/well) as well as for injection until the structure is filled completely - to yield a maximum dynamic capacity of **634 million tons** - close to the static capacity, denoting full storage potential of the site.

The performed modeling implies a very good and stable conditions for CO_2 storage in the structure. The storage potential is enormous, and the risk of incorrect assessment of the capacity appears to be insignificant. The factors which constitute a possible risk of CO_2 storage in this region include primarily low quality and quantity of data that define the reservoir and filtration parameters of the reservoir and seal horizons. Poor is also the status of exploration of tectonic there, which makes it impossible to exclude the possibility of migration of CO_2 from the storage complex to the overburden. In the present area there are 19 wells, which can be a path of migration of the injected CO_2 and hence it is important to known their wellbore integrity status and ways to abandonment.

The problem is (in)accessibility of Pławno-Radęcin highs where there are NATURA 2000 protected areas, and partly also Suliszewo high where protected areas are adjacent to the location of the injection well. Only Choszczno high is located away from protected areas.

If the decision to store CO2 in these anticlinal structures is taken, it will be necessary to carry out a 3-D seismic survey, which will allow a detailed mapping of their geometry and reliable exploration of porosity using seismic inversion. The use of 4-D seismic would make it possible to monitor safety of the filled in structure.

The structure is adequate to meet the needs of CO_2 emittants from Szczecin agglomeration and possibly Dolna Odra power plant.

Poznań trough

The site is located in the northern part of the Fore-Sudetic monocline within the regional unit - Poznań trough, limited to S and SW by the Wolsztyn ridge. The reservoir includes sandy formations of the Upper Rotliegend. Measurements of brine saturation with natural gas in the reservoir showed a significant amount of dissolved gas. Natural gas migrating through the aqueous phase after filling the local small traps has been blocked from the top by the caprock of Zechstein evaporites and began to spread to the sides of the megastructure. So the entire Rotliegend horizon is filled with formation water saturated with natural gas, only slight morphological elevations or its geological strata wedges - lithological traps - are (or were) filled with gas.

Simulations of the injection into the megastructure of Poznań trough, adopting two variants of injection: 3 or 7 wells for 50 years, with the injectivity of about 73 thousand tons of CO_2 per year per well, which gave the total amount of injected CO_2 within the limits of **11 - 25 million tons** (for a medium size emittant of Poznań) have been implemented. The structure has a (static) sequestration capacity exceeding an order of magnitude the assumed amount of injected CO_2. At the current stage of the structure assessment, properties of aquifers do not guarantee a sufficient CO_2 injectivity below the limit on the maximum bottom-hole pressure and require an intensive well stimulation. Hence a relatively low injection rate has been adopted for a single well, which does not represent any threat to the integrity of the caprock. Furthermore, wellbore integrity of the old wells, that many penetrate Rotliegend in the area of question, is important, in terms of the impact of the CO_2-free phase and the carbon dioxide dissolved in brine.

The process of CO_2 injection into the structure is accompanied by:

- CO_2 phase convection to the upper strata of the structure, simultaneously with the effect of dissolution of CO_2 in the brine limiting the extent of its migration in both the vertical direction (to the structure top) and lateral directions, which could constitute potential escape paths of CO_2 out of the structure,

- displacement of methane from the brine with CO_2 and migration of methane to the top of the structure, supplying natural gas traps located there - this process takes place at a slow pace, however, in period of hundreds of years.

So we have to deal here with a form of the enhanced recovery of gas, although in a very long term.

4.2 Hydrocarbon fields

Jan Lubaś, Wiesław Szott, Halina Jędrzejowska-Tyczkowska, Stanisław Nagy, Bartosz Papiernik, Adam Wójcicki

Nosówka oil field

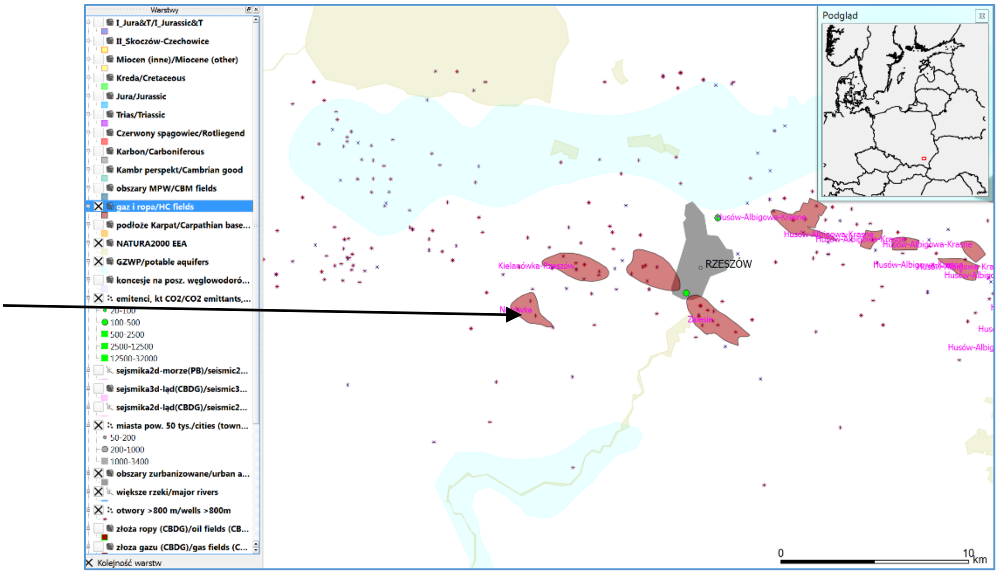


Fig. 4_15 Nosówka oil field - location

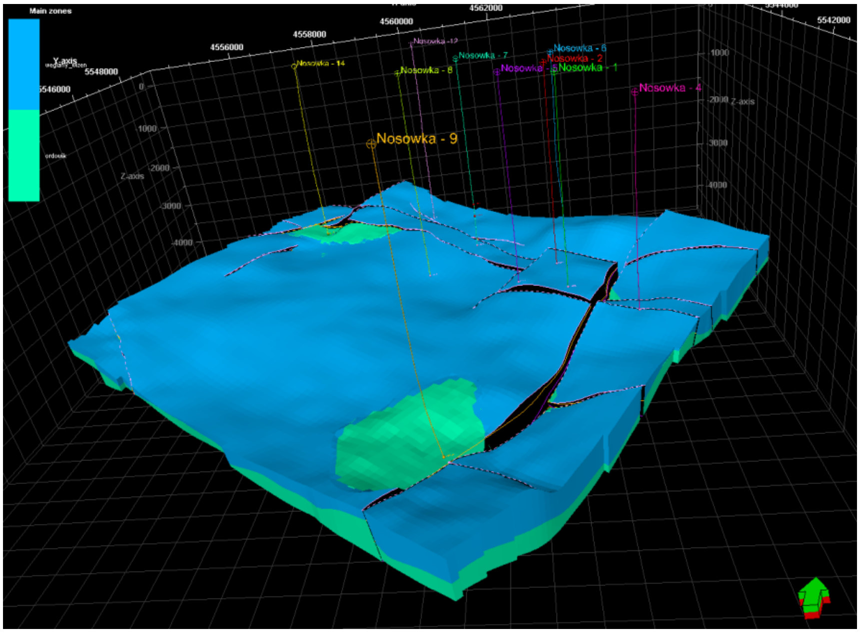


Fig. 4_16 Model of Visean reservoirs (blue) and Ordovician formations (turquoise)

Nosówka oil field is located west of Rzeszów (**Fig. 4_15**), in the marginal zone of the Carpathian overthrust (in the SW part of the Gulf of Rzeszów) and occurs in Paleozoic rocks of the basement (above it, in Miocene, there is also a gas field).

A 3-D static model of the carbonate (limestone and dolomitic limestone) Lower Carboniferous (Visean) oil bearing formations has been worked out (by INiG, like the rest of these analyzes), comprising the structural model of the site (Petrel program - **Fig. 4_16**), defined by the surfaces of the top of carbonates and the underlying Ordovician formations and fault surfaces, as well as parametric models of shaliness, porosity, permeability and formation water saturation. For this purpose the results of an archive 3-D seismic survey and information from 10 wells located in the study area were used. According to information from the wells the effective porosity of the structure is 3.4% (but this is a pore-fractured reservoir) and the average permeability of 30 mD.

The geological (static) model of the structure was supplemented with the information necessary to carry out multi-variant and long-term simulations of oil production with simultaneous sequestration of carbon dioxide, i.e., transport properties in the rock-formation fluid system, the thermodynamic properties of formation fluids and their interaction. To perform the modeling Petrel and Eclipse 300 programs of GeoQuest Schlumberger were used. The influence of the production mode on the feasible recovery rate for the oil field and the storage potential was analyzed for two selected values of the maximum allowable gas-oil ratio.

The most promising results were obtained for the variant of oil production with the use of Nosówka-1 and Nosówka-5 wells (in all variants the subject of analysis was the central block, the other parts of the field are not developed yet), preceded by pre-sequestration of CO_2 using the injection well Nosówka-2, wherein oil production starts when the average reservoir pressure reaches the initial pressure value (**Fig. 4_17**). In this scenario, the obtained oil recovery ratio is about 64%, which means a profit of about 130 thousand Nm^3 of oil (after injection of about 0.55 million tons of CO_2) in comparison with the corresponding base variant.

The risk analysis (Quintessa FEP) showed that the greatest risk of storing CO_2 in the structure is associated with a blowout event in the injection well. On the other hand, wells can constitute a risk in the longer time scale after the injection of CO_2, although laboratory analyzes have shown that the cement slurries used for cementing the casing in the wells within the field are resistant to the carbonate corrosion. Any possible migration above the caprock is not a threat.

To monitor the process of CO2 injection, 4D/3C seismic surveys, preceded by elaboration of a corresponding feasibility study (of the monitoring plan) have been proposed.

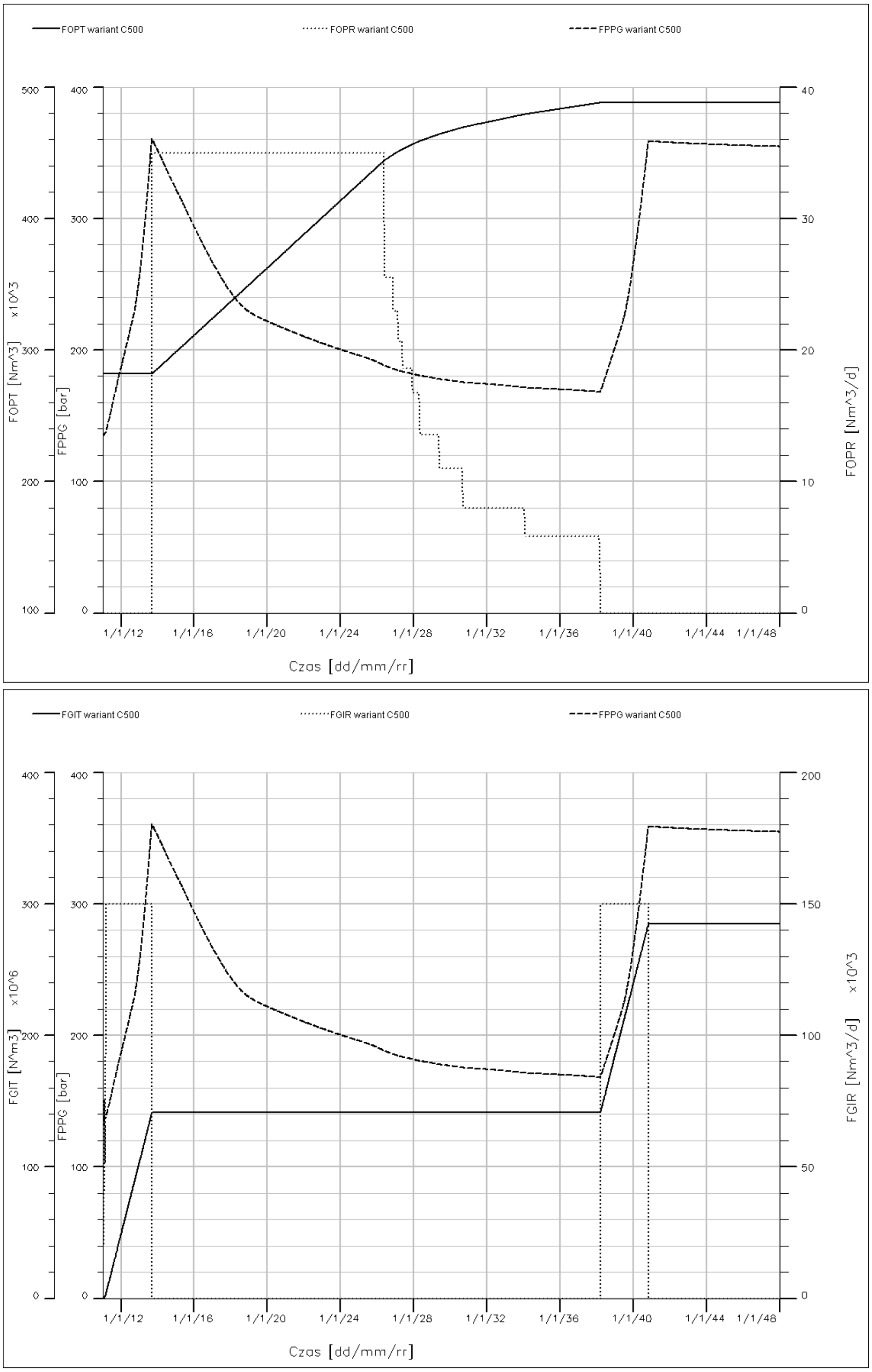


Fig 4_17 Variant of optimal CO_2 injection into Nosówka oil field; top - total oil production (FOPT), oil productivity rate (FOPR), mean reservoir pressure (FFPG); down - total CO_2 injection (FGIT), CO_2 injectivity rate (FGIR), mean reservoir pressure (FFPG)

Wilków gas field

Wilków(-Szlichtyngowa) gas field is located in the area of Fore-Sudetic Monocline, near Głogów (**Fig. 4_18**) and is present in Rotliegend sandstones (P1).

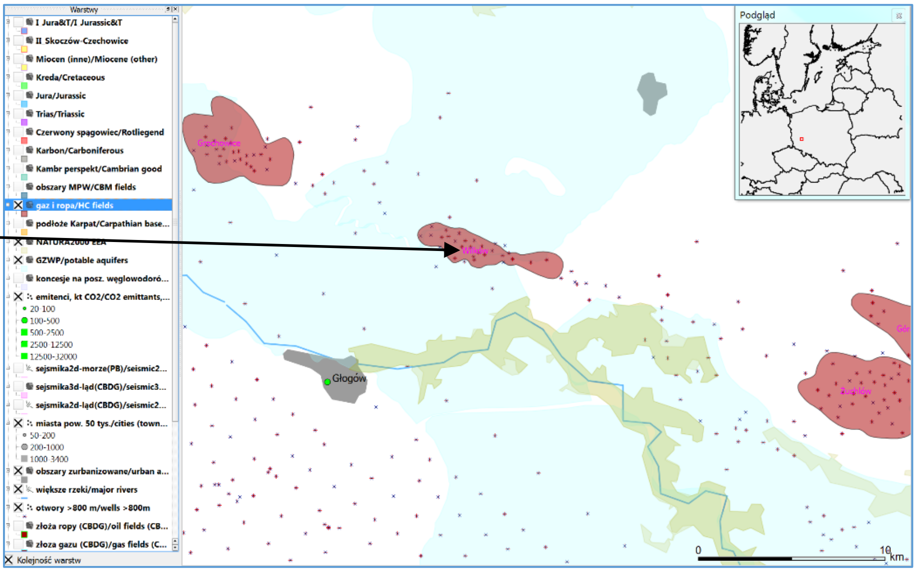


Fig. 4_18 Wilków gas field

For the area of the field information from 34 wells and archive seismic data (structural maps of the top of P1) were available. The average effective porosity of the reservoir series is 13%, after well-logging data (about 15% according to laboratory tests), the shaliness is 20-30%, permeability of magnitude of tens of mD (average 67 mD after laboratory tests). This information has been used to construct the static model (AGH) (**Fig. 4_19**), which was the basis for the elaboration of the simulation model.

The simulation model (AGH) was calibrated on the basis of the available information on the field production history (POGC data, MIDAS database - **Fig 4_20A**). For CO_2 injection 5 wells were selected, and a target injection rate was adopted at the level of 1.8 Mt CO_2 per year, and the injectivity of individual wells was controlled "automatically", basing on their potential (the gas production recorded earlier).

If the maximum allowed reservoir pressure at the end of the injection makes the initial pressure, the total amount of injected CO_2 is approximately 10.0 Mt (after 5.6 years of injection), but if we admit the final pressure increase by 10% above to the initial pressure, the storage capacity of the structure increases till 11.3 Mt (**Fig. 4_21**). On the other hand, total gas production is slightly smaller than in the variant without injection for the same timeframe (because some production wells were disabled).

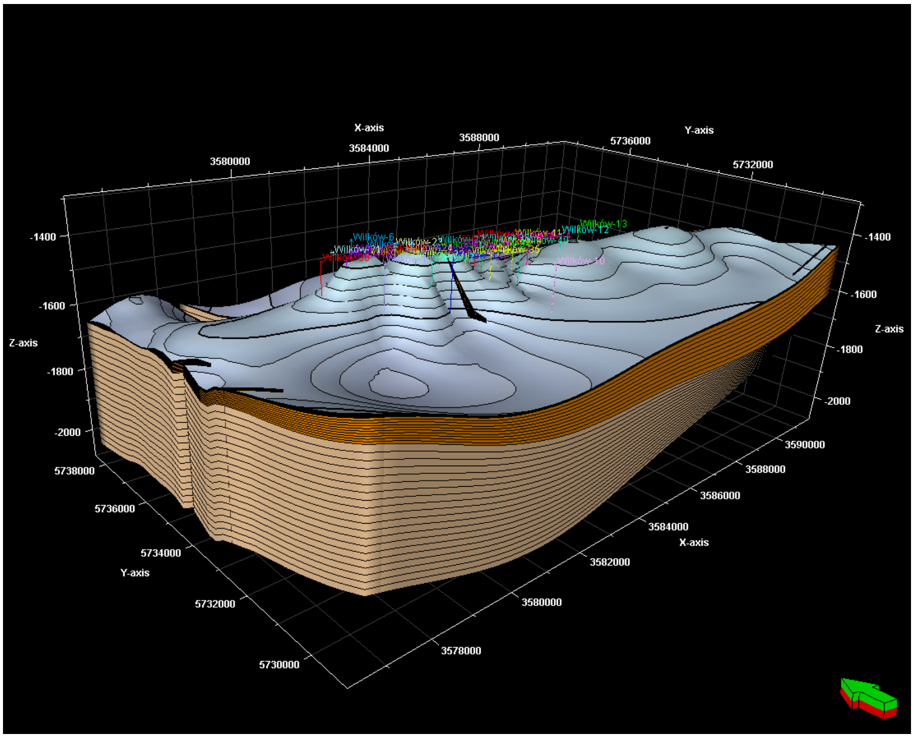


Fig. 4_19 Model of Wilków gas field in Rotliegend formation

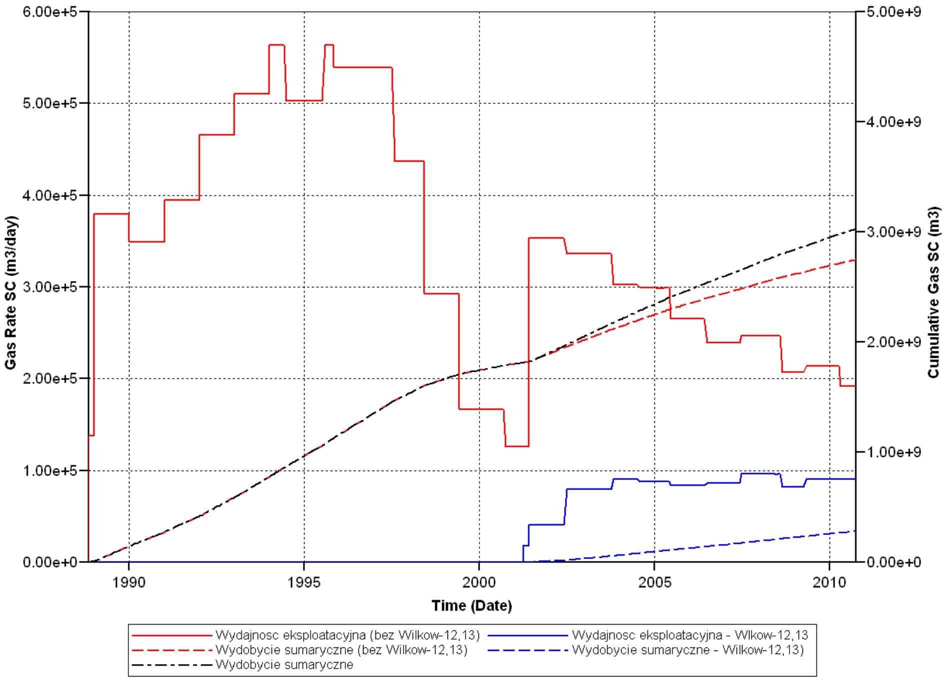


Fig. 4_20 Production history of Wilków gas field

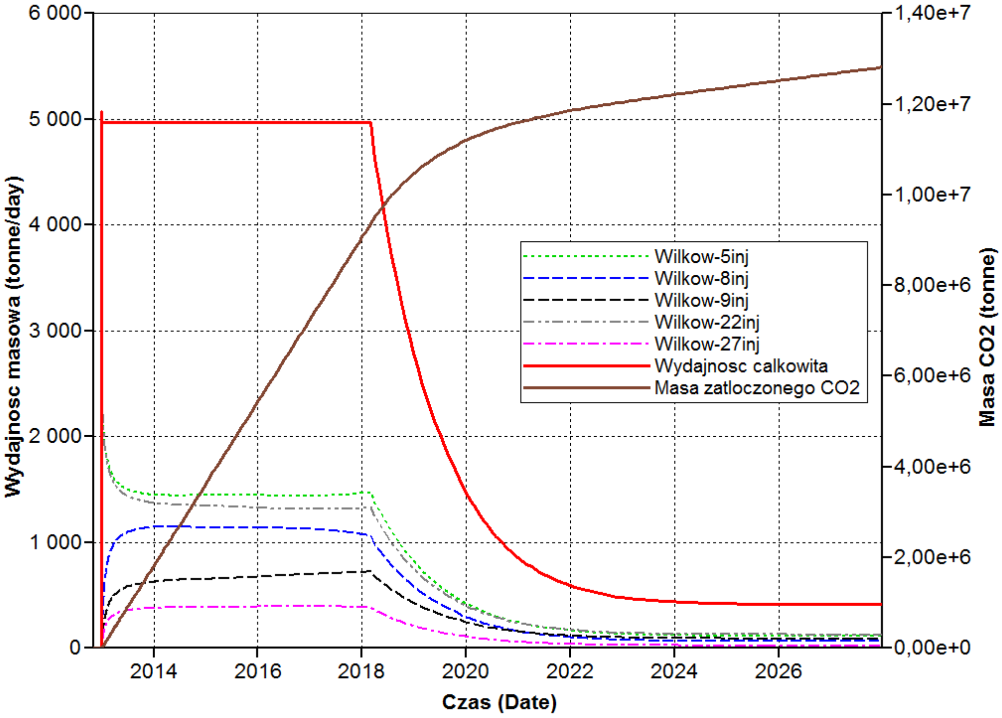


Fig. 4_21 The injectivity of individual wells of Wilków gas fields (ton/day; dashed lines), the total injectivity (ton/day; solid red) and the total mass of injected CO_2 (tons; solid brown).

Risks associated with CO_2 storage in the case of Wilków structure refer primarily to uncertainty of the reservoir model, related to the insufficient amount of data on reservoir parameters (e.g., permeability), poor quality of seismic data and incomplete data on the production history.

Assumptions on construction of the test injection well within the field (PGI-NRI and AGH), as well as on environmental monitoring (MEERI PAS), gravimetric, DC-resistivity and electromagnetic monitoring (PBG) for the selected location of the (5) wells injection were worked out.

Łąkta gas and condensate field (with underlying saline aquifer)

Łąkta field lies in the marginal zone of the Carpathian overhtrust, in the Mesozoic formations of the basement, at a distance of about 40 km SE of Cracow (**Fig. 4_22**).

The simulation model of the discussed structure (**Fig. 4_23**), made, like the further analyzes, by INiG, includes a reservoir horizon in the formations of dolomitic limestone and sandstone of Malm and Cenomanian. The model takes into account the layers underlying the reservoir in order to properly reflect the influx of formation waters underlying the gas field as well as waters in the surrounding zone. Forecasts of CO_2 sequestration for four scenarios of different layout of the injection wells and of different criteria limiting the sequestration process were worked out. In all cases, the behavior of the formation fluids was simulated during the period of relaxation, i.e., till 1000 years after the injection stopped. The impact of CO_2 injection into the structure on the value of gas production was analyzed, however, the aim of the modeling was to maximize the sequestration potential of the object in question. In the study Petrel and Eclipse 300 modeling and simulation programs of GeoQuest Schlumberger have been used.

Results of the injection simulations suggest that the structure has a limited storage capacity (4-8 million tons of CO_2, depending on the variant) because of the large activity of formation waters manifested a by high reservoir pressure despite a relatively high degree of depletion of its natural gas resources. Maximizing the storage capacity requires a strategy of simultaneous injection of CO_2 and production of natural gas remaining in the field (so we got the additional production of about 0.4 billion Nm^3 of gas). However, the use of the existing system of wells for the implementation of this strategy requires the reconstruction of production wells located at the top of the structure and the adaptation of the peripheral, water saturated wells for CO_2 injection.

Regarding the risks associated with the injection of CO_2 into the structure, only the integrity of existing wells is essential, because the cement slurries not resistant to CO_2 were used to cement these wells. Hence, appropriate reconstruction works on improving the durability of the applied cement plugs should be taken.

For the purpose of designing the monitoring during injection and the baseline, the analysis of the velocity field and seismic inversion in order to obtain a more detailed and reliable model of the structure (the problem is, though to a lesser extent than in case of the saline aquifer structures, a diverse and often poor quality of seismic data and information from the wells) have been performed.

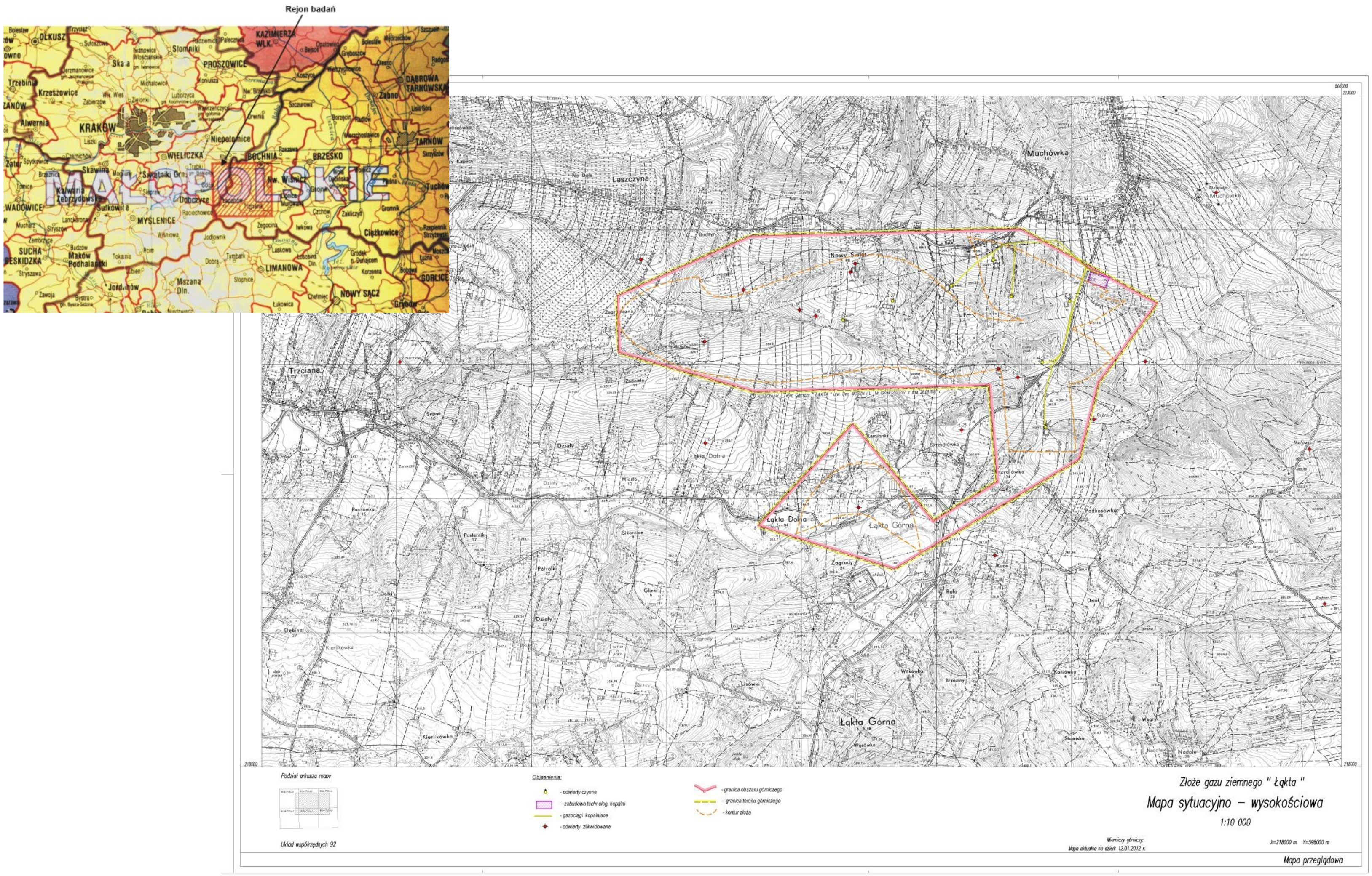


Fig. 4_22 Location of the site – Łąkta gas and condensate field (with underlying saline aquifer)

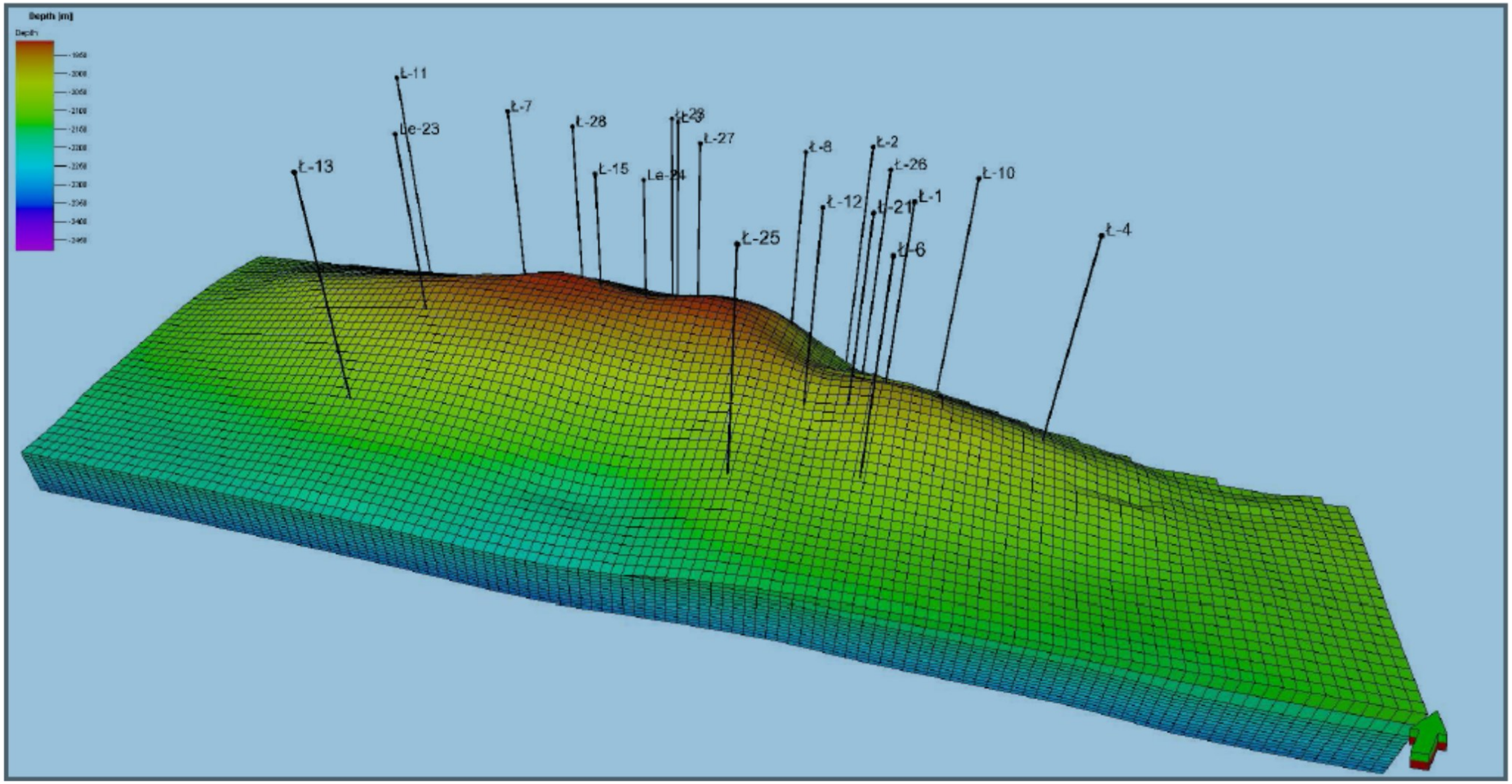


Fig. 4_23 View of the spatial structure of the reservoir simulation model of Łąkta gas field

Hydrocarbon fields summary

Nosówka oil field

Nosówka oil field is located in the marginal zone of flysch Carpathians in the south - western part of the so-called Gulf of Rzeszów. Accumulation of oil appears in carbonate rocks, represented by limestones and dolomitic limestones of Visean (Lower Carboniferous).

A dynamic reservoir simulation model of Nosówka field in Visean formations was constructed to verify the CO_2 storage potential while maintaining the continued production of the oil field, and several variants of injection were performed. The most promising results were obtained for the variant assuming oil production in two wells, preceded by an initial CO_2 sequestration by injection into (the third) one well, wherein production begins when the average reservoir pressure reaches the initial pressure value (and after oil production **stops,** CO_2 is injected again until the average reservoir pressure reaches the initial pressure value). In this scenario, the obtained oil recovery ratio is about 64%, which means a profit of about 130 thousand Nm^3 of oil (after injection of about 0.55 million tons of CO_2) in comparison with the corresponding base variant. In this case, injection of about 0.55 million tons of CO_2 has been assumed (initial sequestration of CO_2 before the oil production and again CO_2 injection after its completion - both phases last for about 2.5 years each). Needed CO_2 (about 100 thousand tons/year) could be provided either by a small emittant of Rzeszow, or Tarnów (the nitrogen plant). Such a CCS project, with enhanced oil recovery, has the potential to be implemented in the near future and could even be cost-effective (see the Weyburn project in Canada/USA).

Wilków gas field

Wilków gas field appears in the top part of Rotliegend sandstones. It is located in the Fore-Sudetic Monocline, within the regional unit - Zielona Góra depression, limited to the north by Wolsztyn elevation, and to the south by the Fore-Sudetic block.

The simulation results show that the injection, with the assumed CO_2 flow rate, fills very quickly the structure and the increase of CO_2 share in the produced gas (and hence, decrease of the content of hydrocarbons) will quickly turn off the subsequent wells. The total amount of injected CO_2 (the storage capacity of the structure) depends on the assumptions on the maximum allowed reservoir pressure at the end of injection and the predetermined amount of the injection wells (5 wells in our case). If the maximum allowed reservoir pressure at the end of the injection makes the initial pressure, the total amount of injected CO_2 is approximately **10.0 Mt** (after 5 years and 7 months of injection). If we allow the final pressure increase by 10% above to the initial pressure, the storage capacity of the structure increases till **11.3 Mt**. This is the dynamic, practical storage capacity, while the static, effective storage capacity is slightly higher.

No essential enhancement of gas recovery was achieved, hence Wilków field is only suitable for a CO_2 storage site of one of not very big emittants in the Legnica-Głogów Copper Basin (the closest is the CHP plant in Głogów).

Łąkta gas and condensate field (with underlying saline aquifer)

Łąkta gas and condensate field lies in the marginal zone of the flysch Carpathians. Accumulation of oil appears in carbonate rocks, represented by cavernous-fractured Upper Jurassic limestones, and in Cenomanian sandstones.

Results of the CO_2 injection simulations suggest that the structure has a limited storage capacity because of the large activity of formation waters manifested a by high reservoir pressure despite a relatively high degree of depletion of its natural gas resources. Maximizing the storage capacity requires a strategy of simultaneous injection of CO_2 and production of natural gas remaining in the field. The use of the existing system of wells for the implementation of this strategy requires the reconstruction of production wells located at the top of the structure and the adaptation of the peripheral, water saturated wells for CO_2 injection. Depending on the amount of the injection wells (4 - 9) about 4 to 8 million tons of CO_2 can be stored within the structure (the dynamic capacity - the higher value is approximately 80% of the static capacity of this field) for a period of over twenty years. This **would** allow for additional production of about 0.4 billion m^3 of natural gas. The implementation of such a CCS project would require to provide a few hundreds of thousands of tons of CO_2 from a medium-size emittant of Kraków or Tarnów.

4.3 Coal beds

(Janusz Jureczka, Jarosław Chećko, Iwona Jelonek, Adam Wójcicki)

Pawłowice-Mizerów site

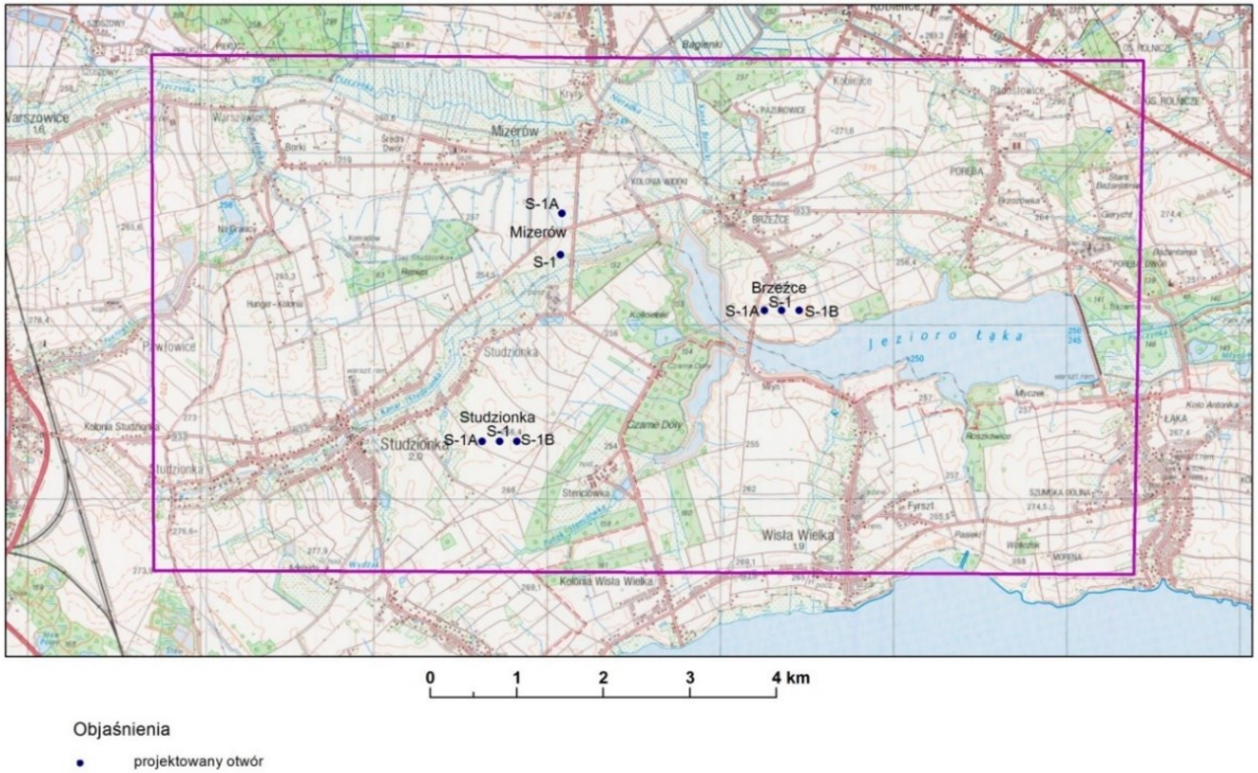


Fig. 4_24 Location of the selected site in coal beds and the injection wells

In the regional studies the area of the potential storage site in coal beds Pawłowice-Mizerów, with the possibility of enhanced coalbed methane recovery, was chosen (precise area of the site: Studzionka-Mizerów - **Fig. 4_24**), wherein as the reservoirs 405 and 510 seams were selected, with a thickness of several meters each, occurring at a depth of 1-2 km.

The study area is relatively densely covered by wells exploring Carboniferous (132 in the region of Pawłowice-Mizerów and its vicinity). According to the archive data the permeability of coals in this region of USCB is about 1 mD, and porosity - 3%. On the other hand, new measurements of permeability for selected coal seams gave permeability of 2-3 mD (horizontal and vertical). The content of methane in coal seams is 2.5-10 m^3/ton of pure coal, an average of about 5 m^3/t (CBM field of sufficient or good parameters), and the coals are characterized by a high content of vitrinite (70-90%). Presumably brine occurring within the clastic rocks of the Upper Silesian Sandstone series and the Mudstone series, where the coal seams in question occur, is the fossil water.

A static (geological) model of the productive Carboniferous (GIG - **Fig. 4_25**), based on information from 34 wells, including coal seams and barren rocks (clastic) has been constructed. The upper seam (405) is covered with an impermeable claystone-mudstone complex.

The constructed static model was the basis for simulation studies (GIG - ECLIPSE program with the option of ECBM), for selected locations of wells within blocks of the best reservoir properties (**Fig. 4_24**). A variant of the pilot injection (like the RECOPOL project, Jura et al., 2007) into the vertical wells at the locations/cases Brzeźce and Mizerów - injection of several hundreds of tons of CO_2 for 1 year, the total methane production of about 50 thousand m^3, was adopted, as well as the industrial injection (on a small scale, for a period of 1-5 years), using horizontal wells, at the Mizerów location. In the latter case, injection of 35 - 203 thousand tons of CO_2, gave the total production of 36 - 62 million m^3 of methane, which is about 500 m^3 of methane per 1 ton of CO_2 injected, which gives prospects for a cost-effective use of CO_2-ECBMR in the future.

Assumptions on construction of injection and production wells for both variants (PGI-NRI and AGH), as well as on environmental monitoring (MEERI PAS), seismology, passive tomography (GIG) and gravimetric monitoring (PBG) for the selected location of the wells were worked out.

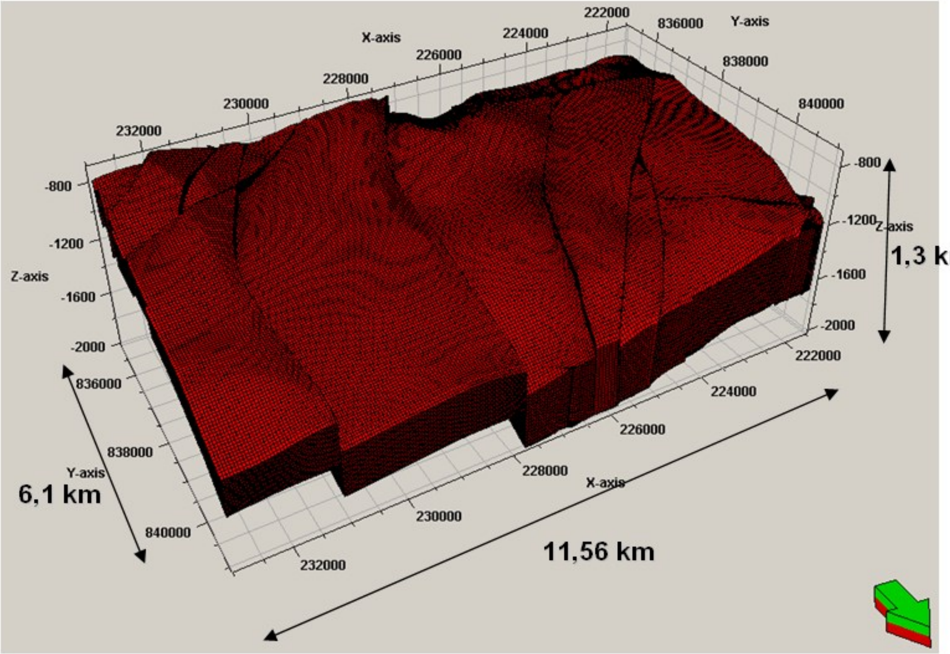


Fig. 4_25 Structure of the numerical model of coal beds

Coal beds summary

Research relating to the storage of CO_2 in deep un-mineable coal seams in conjunction with the methane recovery from these beds (ECBM technology) at recent stage is still in the exploratory phase, not only in Poland, but worldwide.

According to the regional study, favorable conditions for the location of the storage sites occur mainly in the central-southern part of the Upper Silesian Coal Basin, in the coal beds of the Upper Silesian Sandstone series and the Mudstone series. Preliminary estimate of CO_2 storage capacity was made for the (selected for the case study) site Pawłowice-Mizerów, for which a detailed structural-parametric static model of coal seams of the Upper Silesian Sandstone series was developed. The calculated (static, effective) storage capacity for the seams in question was estimated at **8.3 Mt**. Such amount of storage capacity, in connection with the methane production, can be used by smaller local industrial plants. Scenarios of CO_2 injection with coal methane recovery have been performed, of which the most promising took the injection of 200 thousand tons of CO_2, using a horizontal well, to obtain the production of about 60 million m^3 of methane. This does not mean that the dynamic capacity of the storage site of the case study - Pawłowice-Mizerów is 200 thousand tons, but that to exploit the potential of coal beds drilling of several dozen of (horizontal) injection holes would be needed there.

5. SUMMARY AND CONCLUSIONS

(Adam Wójcicki)

The results of both regional and case studies will be useful for future permit decisions of the Ministry of Environment on exploration of potential storage sites and for entities applying for permission to build new "CCS ready" power blocks, wherein identification of possible storage locations (for which the entity would apply in the future for exploration permits) and pre-feasibility studies are required.

Since we have already (or yet) no CCS demonstration projects in Poland, results of this project will be useful in the near future for CCS-ready studies, which Directive on the geological storage of carbon dioxide (pre-feasibility studies for the capture, transport and storage of CO_2 - in the latter case, at least two equivalent, initial storage scenarios and the schedule of works and expenditures on the further exploration and development of potential storage sites are needed) requires the companies applying for permits to build new power units.

Regarding the answer to the question whether the geological storage of CO_2 is possible and safe to carry on the territory of Poland in a demonstration or industrial scale, we are not able to clearly answer this question on the present state of knowledge in the case of saline aquifer structures[6] (in case of the depleted hydrocarbon fields there is rather no room for doubt, and the coal seams are of marginal significance).

The project has included indication and pre-characterization of formations and structures where storage of CO_2 would be possible, provided further surveys under exploration permits for storage sites are carried out. These results are the basis for the preparation of geological workplans on surveys for the purpose of the detailed characterization of a

---

[6] This does not mean that the storage of CO2 in these structures and formations is as dangerous as various self-proclaimed "experts" say (in Poland and elsewhere). These are even persons with the title of professor, or pretending to have such a title, but in areas rather distant from the field of geology, speaking on matters beyond their competence (and having no relevant, significant scientific achievements) who, for example, read the summary of Greenpeace propaganda brochure (Rochon, 2008) or an Wikipedia entry that something happened on a volcano in Africa (the catastrophic limnic eruption on lake Nyos in Cameroon in 1986). Greenpeace is the advocate of an (as soon as possible) eradication of the energy industry based on fossil fuels, at least on coal, and in the said booklet describes CCS as an obstacle to the development of renewable energy (it was published in 2008, when the European Commission was launching the EEPR program, which then funded CCS demonstration projects, and the RES lobby fought for subsidies - because, as a result of the crisis and the beginning of the shale gas revolution, causing the drop in prices of energy produced from fossil fuels, further subsidizing renewable energy began to raise doubts).

potential storage site, and possibly the baseline monitoring, including new exploratory wells (or CO_2 test injection wells), new seismic and other geophysical surveys.

As part of the regional studies an estimate of the potential of storage of carbon dioxide for the considered geological formations and structures has been provided. These estimates relate to the static, effective storage capacity.

The (very roughly) estimated potential for storage in saline aquifers is **11 657 million tons** for the 45 structures in the formations of Paleozoic, Mesozoic (the greatest potential, especially for the Jurassic) and Cenozoic (Miocene). If we skip the Cretaceous structures, 9 171 million tons for the 35 structures remains. Additionally, for regional Cambrian and Carboniferous aquifers the potential was estimated at **2 838 million tons**. Hence, the saline aquifers have the storage potential within **12 009 - 14 495 million tons**.

The potential for storage in the hydrocarbon structures is **784 - 1021 million tons**. These are mostly depleted gas fields; the share of the selected oil fields, of various degree of depletion, is less than 10% of the above values.

The potential for coal beds can be estimated at **20 - 100 million tons** (the first value for the possible exploration permits within the USCB, the second for the entire considered area of USCB - coal seams at depths of 1-2 km).

In summary, the storage potential for the saline aquifers is an order of magnitude higher than for the hydrocarbon structures (about 14 times), and microscopic for coal beds. The whole potential is in theory enough for half a century of industrial emissions covered by the ETS in Poland (which is about 200 million tons of CO_2 per year).

As a result of the regional studies a number of sites in the saline aquifers (including two for the purposes of CCS demonstration projects in Bełchatów and Kędzierzyn, planned when the project began, and one structure in the region of Szczecin and one in the region of Poznań), hydrocarbon fields (one oil field and two gas fields) and a site in coal beds were selected, which were then subjected to detailed analyzes in the case studies. These studies have included an initial characterization of potential storage sites in accordance with the guidelines provided in Annex 1 of the EU directive on the geological storage of carbon dioxide.

Significant substantive conclusion of the modeling conducted for the above sites within the case studies is the fact that both the capacity and the safe storage of CO_2 in a given structure significantly depend on the configuration of the injection wells (including the position within the structure and the distance between the injectors), and the amount of CO_2 injected into the well globally and per unit of time (the pressure in the reservoir and the caprock, the spatial and temporal distribution of the CO_2 plume - during and after the injection, depend on these factors, which in turn affect the intensity of the other CO_2 trapping mechanisms - mostly dissolution in the brine and to a lesser extent the chemical and physical trapping into the rock matrix).

These results were achieved through the adoption of various injection scenarios, differing in the degree of detail / the model area (as well as the methodology of its construction), the location of injection wells, the reservoir wherein the CO_2 injection was proceeded, the amount of CO_2 injected, injection time, the duration of the simulation of CO_2 behavior after the injection (and besides, the modeling on the CO_2-brine-rock reactivity was conducted).

The aim was to identify the possible behavior of CO_2 within the considered formations and structures, based on the available data. This was the first case in our country, where a number of structures - potential CO_2 storage sites were analyzed from the point of view of the requirements of the Directive on the geological storage of carbon dioxide (Annex 1). The first characterized structure was Budziszewice-Zaosie site and hence for it and its surroundings the most comprehensive and numerous analyzes were made.

It should be noted that the saline aquifer structure will never be sufficiently and accurately explored, enough to conduct credible, multi-variant simulations of injection, before the start of the injection, and the model improved by the results of new field surveys performed for more accurate exploration of the site will be more reliable than presented in this study, then the model corrected by the results of new detailed surveys done to determine the final location of the CO_2 injector(s) will be even more reliable. The model taking into account the results of any test/experimental injection (on a small scale - up to 100 kt/well) would be even more credible, and the most reliable modeling of CO_2 injection can be carried out basing on the results of monitoring of the carbon dioxide (**full scale**) injection into the storage site.

The project involving the storage of CO_2 in large scale (millions of tons of CO_2 per year) requires a prior, multi-stage exploration of the site(s). What was carried out for the saline aquifer structures within the regional and case studies is just a prelude to such an exploration, conducted in the framework of the relevant permit and including field works of increasing level of detail and costs (there is a certain analogy to hydrocarbon exploration, where there are a number of steps between finding prospects of the occurrence of the hydrocarbon accumulations to the assessment and the development). The selected storage site is the subject of a multi-stage monitoring (conducted before the start of CO2 injection, during injection and for a long period during and after the storage site operation is concluded), which is designed to detect a possible migration of CO_2 out of the storage complex (the allowed limit is up to 1% of the total amount of stored CO_2 over the entire period the storage site existence, i.e. for about 5000 years - Chadwick et al., 2008) and, even more unlikely, a leakage to the ground surface. In the case of migration of CO_2 out of the storage complex, which is a long process, first dissolution in the brine within the aquifer above the storage complex, then detaining on the impermeable rocks as well as adsorption and mineral trapping of CO_2 occur on the way, drastically reducing its stream. Hence a leak (to the ground surface) is actually possible only in case of a well integrity failure, so it is recommended to cement the new (or reconstructed) wells within the storage site, after the injection is concluded, using special cement slurries, resistant to CO_2 corrosion. On the other hand, the results of analyzes conducted under this project by AGH suggest that such work should also be done for the old, abandoned wells within the storage site, because the previously used standard cements are not resistant to long-term impacts of CO_2.

Risks related to the geological storage of CO_2 are not greater than in other cases of the use of the subsurface - the storage of hydrocarbons, exploration and production of hydrocarbons, both unconventional (there are known activities of pseudoecologists and other "experts" against shale gas production, using arguments of the same type as against the CCS) and conventional, and even, to some extent, geothermal energy (e.g., in Girona in Spain there has been a contamination of drinking water by formation waters containing heavy metals; in Basel, Switzerland, hydraulic fracturing in the framework of the geothermal project caused the earthquake; it is also worth mentioning that a large geothermal project involves reinjection of similar amount of fluid as in the case of a CCS demonstration project, i.e., one million tons per year or more).

It should be noted that the precautions taken in the selection of CO_2 storage sites, the development, operation, then in the closure and post-closure phase (after the CCS Directive and its implementation into national law), are far more restrictive than for the other aforementioned cases of the use of the subsurface.

REFERENCES

Bergen van F., Wildenborg T., 2002 - Inventory of storage potential of Carboniferous coal layers in the Netherlands. TNO Report NITG 02-031-B (GESTCO), Utrecht.

Bojarski L., 1996 – Atlas hydrochemiczny i hydrodynamiki paleozoiku i mezozoiku oraz ascensyjnego zasolenia wód podziemnych na Niżu Polskim Wyd. Geol.

Chadwick A., Arts R., Bernstone C., May F., Thibeau S., Zweigl P., 2008 - Best practice for the storage of CO_2 in saline aquifers. Keyworth, Nottingham, British Geological Survey.

Davis D., Oudinot A., Sultana A., Reeves S., 2004 - Coal-Seq 2.2: A Screening Model for ECBM Recovery and CO_2 Sequestration in Coal. Topical Report and Users Manual — ARI and US Department of Energy (www.coal-seq.com).

DIRECTIVE 2009/31/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006.

Dziewińska L., Tarkowski R., 2012 - Budowa geologiczna struktury Choszczna (niecka szczecińska) w świetle interpretacji sekcji efektywnych współczynników odbicia dla potrzeb podziemnego składowania CO2. Gospodarka Surowcami Mineralnymi T. 28, z. 1, s. 173-184.

Górecki W. (red.) 2006a - Atlas zasobów geotermalnych formacji mezozoicznej na Niżu Polskim. Atlas of geothermal resources of Mesozoic formations in the Polish Lowlands. AGH, 2006. 484s., Kraków.

Górecki W. (red.) 2006b - Atlas zasobów geotermalnych formacji paleozoicznej na Niżu Polskim. Atlas of geothermal resources of Mesozoic formations in the Polish Lowlands. AGH, 2006. 484s., Kraków.

Jura B., Krzystolik P., Skiba J. 2007 - RECOPOL and MOVECBM projects, opportunities and challenges - CO_2NET Seminar, 6-7th November 2008, Lisbon, Portugal.

Jureczka J., Dopita M., Gałka M., Krieger W., Kwarciński J., Martinec P., 2005 – Atlas geologiczno-złożowy polskiej i czeskiej części Górnośląskiego Zagłębia Węglowego. Państwowy Instytut Geologiczny, Ministerstwo Środowiska, Warszawa.

Jureczka J., Zdanowski A., Ihnatowicz A., Krieger W., Wilk S., 2011 - Węgiel kamienny. [w]: S. Wołkowicz, T. Smakowski, S. Speczik (red.) Bilans perspektywicznych zasobów kopalin Polski. Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, Ministerstwo Środowiska, Warszawa. pp. 51-63.

Jędrzejowska-Tyczkowska H. i in., 2004 - First Experience with 4D seismic in Poland; Feasibility Studies of BMB Field. EAGE 66th Conference and Exhibition, Paris, June 2004.

Lake L.W., Walsh M.P., 2008 - Enhanced Oil Recovery (EOR) Field Data Literature Search. Technical Report for Danish North Sea Partner, Danish Energy Agency, Mærsk Olie og Gas AS.

Lubaś, J. Szott W., 2010 - 15-year experience of acid gas storage in the natural gas structure of Borzęcin - Poland. Nafta-Gaz LXVI, maj 2010, pp. 333-338.

Lubaś, J. (red.), 2012 - Program wspomagania wydobycia ropy naftowej i gazu ziemnego z krajowych złóż węglowodorów przy zastosowaniu podziemnego zatłaczania CO_2. Raport z tematu dla MŚ, CAG W-wa.

May F., 2003 - CO_2 storage capacity in unminable coal beds in Germany. GESTCO Project report, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.

Pagnier H., van Bergen F., van der Meer L., 2003 - Field experiment of ECBM in the Silesian Coal Basin of Poland RECOPOL). International Coalbed Methane Symposium 2003, Tuscaloosa, Alabama (USA), May 5-9.

PGI-NRI Report, 2012 – Assessment of shale gas and shale oil resources of the Lower Paleozoic Baltic-Podlasie-Lublin basin in Poland, First report, March 2012.

Posyniak A., Rosa W., 2010 – Dokumentacja końcowa otworu wiertniczego Kaszewy-1. Archiwum PGE GiEK Bełchatów.

Rochon E. (red.), 2008 - False Hope - why carbon capture and climate won't save the climate. Greenpeace International.

Schuppers J. D., Holloway S., May F., Gerling P., Bøe R., Magnus C., Riis F., Osmundsen P.T., Larsen M., Andersen P. R., Hatzyannis G., 2003 - Storage capacity and quality of hydrocarbon structures in North Sea and the Aegean region. GESTCO WP2 Final Report, TNO, Utrecht.

Special Report of the Intergovernmental Panel of Climate Change on Carbon Capture and Storage (IPCC SRCCS) 2007 - Cambridge University Press, Cambridge; also at IPCC website: www.ipcc.ch/ipccreports/special-reports.htm.

Szewczyk J., Gientka D., 2009 – Terrestrial heat flow density in Poland - a New approach Geological Quarterly, 53(1); 125 - 140.

Tarkowski [red.], 2010 - Potencjalne struktury geologiczne do składowania CO2 w utworach mezozoiku Niżu Polskiego (Charakterystyka oraz ranking), autorzy: L. Dziewińska, S. Marek, Tarkowski R., Uliasz-Misiak B, [w:] "Studia Rozprawy i Monografie", nr 164, IGSMiE PAN, 2010, 138 s.

Tongeren van P.C.H., Laenen B., 2001– Coalbed methane potential of the Campine Basin (N. Belgium) and related CO_2-sequestration possibilities. GESTCO WP Report, VITO.

Wójcicki A., 2008 - CO_2 Storage Potential in Poland (after CASTOR WP1.2), First EAGE CO2 Geological Storage Workshop, Budapest 29-30th September (referat).

Wójcicki A., Lisowski K., Tarkowski R., Uliasz-Misiak B., 2008 - Interaktywny atlas prezentujący możliwości geologicznej sekwestracji w Polsce, w skali 1:500 000. Raport z tematu dla MŚ, CAG W-wa. Strona atlasu: http://skladowanie.pgi.gov.pl/co2atlas/atlas.phtml.

Wójcicki A. (red.), 2013 - Rozpoznanie formacji i struktur do bezpiecznego geologicznego składowania CO2 wraz z ich programem monitorowania, Raport końcowy. Strona projektu: http://skladowanie.pgi.gov.pl.

Vangkilde-Pedersen T., Anthonsen K. L., Smith N., Kirk K., Neele F., van der Meer B., Le Gallo Y., Bossie-Codreanu D., Wojcicki A., Le Nindre Y.-M., Hendriks C., Dalhoff F., Peter Christensen N. P., 2009 - GHGT-9 Assessing European capacity for geological storage of carbon dioxide – the EU GeoCapacity project, energy Procedia – Elsevier, No. 1 (2009), pp 2663-2670.

SUBJECT INDEX (TO THE FINAL REPORT, IN POLISH ONLY)

The following index summarizes the selected, most important information related to the implementation of the project, for which references are given to the individual chapters of the final report (in Polish only; about 5 kilopages) (https://skladowanie.pgi.gov.pl/twiki/bin/view/CO2/WynikiPrac).

Explanation to the references

For example,

I-1, 15, 100-101 means pages 15 and 100-101 of the chapter 1 of the regional studies (I);

and ***II-14, 44-46*** respectively pages 44-46 of the chapter 14 of the case studies (II);

see also the Table of chapters of the final report; in paper version or at the project website: https://skladowanie.pgi.gov.pl/twiki/bin/view/CO2/WynikiPrac.

---

[7] Saline aquifer formations and structures.

PARTICIPANTS OF THE PROJECT

(Executive Committee)

Name	Institution	Name	Institution	Name	Institution	Name	Institution	Name	Institution	Name	Institution
dr Adam Wójcicki	PGI-NRI	**prof. Stanisław Nagy,**	AGH-UST	**prof. Jan Lubaś**	INIG	prof. Józef Dubiński	GIG	**prof. Radosław Tarkowski**	MEERI PAS	**Tomasz Bąk**	PBG
prof. Marek Jarosiński	PGI-NRI	prof. Jakub Siemek	AGH-UST	prof. Piotr Such	INIG	prof. Jan Wachowicz	GIG	prof. Barbara Uliasz-Misiak	MEERI PAS	Agnieszka Dziasek	PBG
Katarzyna Sobień	PGI-NRI	prof. Andrzej Gonet	AGH-UST	prof. Halina Jędrzejowska-Tyczkowska	INIG	**prof. Grzegorz Mutke**	GIG	prof. Sylwester Marek	MEERI PAS	Zdzisław Żuk	PBG
prof. Grzegorz Pieńkowski	PGI-NRI	prof. Stanisław Stryczek	AGH-UST	dr Grzegorz Leśniak	INIG	dr Joanna Martyka	GIG	dr Lidia Dziewińska	MEERI PAS	Cezary Ostrowski	PBG
dr Anna Feldman-Olszewska	PGI-NRI	prof. Henryk Marcak	AGH-UST	dr Irena Matyasik	INIG	dr Jarosław Chećko	GIG	dr Magdalena Wdowin	MEERI PAS	Grzegorz Pacanowski	PBG
Hubert Kiersnowski	PGI-NRI	prof. Rafał Wiśniowski	AGH-UST	dr Wiesław Szott	INIG	Marzena Majer	GIG	prof. Krzysztof Labus	MEERI PAS	dr Marek Wojdyła	PBG
dr Anna Becker	PGI-NRI	prof. Ludwik Zawisza	AGH-UST	dr Tadeusz Szpunar	INIG	dr Magdalena Głogowska	GIG	Maria Oniszk	MEERI PAS	Krzysztof Lisowski	PBG
dr Maria Waksmundzka	PGI-NRI	dr Rafał Smulski	AGH-UST	Józef Such	INIG	Karol Kura	GIG	Katarzyna Batkiewicz	MEERI PAS		
prof. Jolanta Pacześna	PGI-NRI	prof. Czesław Rybicki	AGH-UST	Barbara Darłak	INIG	Robert Warzecha	GIG	Bogusław Liszka	MEERI PAS		
dr Krzysztof Leszczyński	PGI-NRI	Łukasz Klimkowski	AGH-UST	Sławomir Szuflita	INIG	dr Eleonora Solik-Heliasz	GIG	Wojciech Królik	MEERI PAS		
Leszek Skowroński	PGI-NRI	dr Jacek Blicharski	AGH-UST	Lidia Dudek	INIG	dr Tadeusz Bromek	GIG	Aleksandra Kutyba	MEERI PAS		
Teresa Adamczak-Biały	PGI-NRI	dr Jan Macuda	AGH-UST	Małgorzata Słota	INIG	dr Adam Lurka	GIG	dr Wiesław Sroczyński	MEERI PAS		
dr Jan Szewczyk	PGI-NRI	Rafał	AGH-UST	Małgorzata	INIG	dr Krystyna	GIG	Katarzyna	MEERI PAS		

		Sedlaczek		Włodarczyk		Stec		Luboń			
Michał Wojtowicz	PGI-NRI	Dorota Polak	AGH-UST	Krzysztof Sowiżdżał	INIG	Tomasz Urych	GIG	Tomasz Trzupek	MEERI PAS		
prof. Magdalena Sikorska-Jaworowska	PGI-NRI	Tomasz Włodek	AGH-UST	Marcin Warnecki	INIG	Michał Gut	GIG				
dr Aleksandra Kozłowska	PGI-NRI	Krzysztof Polański	AGH-UST	Jerzy Kuśnierczyk	INIG	Jacek Skiba	GIG				
Małgorzata Połońska	PGI-NRI	**prof. Wojciech Górecki**	AGH-UST	Andrzej Gołąbek	INIG	Bartłomiej Jura	GIG				
dr Marta Kuberska	PGI-NRI	dr Bartosz Papiernik	AGH-UST	Konrad Ziemianin	INIG	dr Piotr Rosmus	GIG				
dr Leszek Krzemiński	PGI-NRI	dr Anna Sowiżdżał	AGH-UST	Paweł Budak	INIG	dr Aleksandra Koteras	GIG				
prof. Katarzyna Jarmołowicz-Szulc, prof. nzw.	PGI-NRI	Marek Hajto	AGH-UST	dr Piotr Łętkowski	INIG	Michał Bednarski	GIG				
dr Magdalena Pańczyk	PGI-NRI	dr Grzegorz Machowski	AGH-UST	dr Marcin Rzepka	INIG	Robert Warzecha	GIG				
Leszek Giro	PGI-NRI	Michał Maruta	AGH-UST	dr Krystyna Żukowska	INIG	Robert Siata	GIG				
dr Grzegorz Zieliński	PGI-NRI	Andrzej Pasternacki	AGH-UST	Krzysztof Miłek	INIG	Jacek Chodacki	GIG				
Joanna Roszkowska-Remin	PGI-NRI	Grzegorz Pełka	AGH-UST	Andrzej Rychlicki	INIG	dr Przemysław Bukowski	GIG				
Piotr Lampart	PGI-NRI	Wojciech Luboń	AGH-UST	Bogdan Filar	INIG	Iwona Augustyniak	GIG				
Wanda Narkiewicz	PGI-NRI	Aurelia Zając	AGH-UST	Mariusz Miziołek	INIG	Anna Wątor	GIG				
Grzegorz Wróbel	PGI-NRI	Marzena Garncarz	AGH-UST	Barbara Piesik-Buś	INIG						
Sylwia Kijewska	PGI-NRI	Wojciech Machowski	AGH-UST	Jadwiga Zamojcin	INIG						
Katarzyna Pisaniec	PGI-NRI	Michał Michna	AGH-UST	Marcin Kremieniewski	INIG						
Paweł Poprawa	PGI-NRI	Barbara Czopek	AGH-UST	Wacława Piesik-Buś	INIG						
dr Zdzisław	PGI-NRI	Urszula Bryła	AGH-UST	Marek	INIG						

Petecki				Stadtmuller							
Jacek Chełmiński	PGI-NRI	Ewa Zubel	AGH-UST	Iwona Byś	INIG						
dr Ewa Szynkaruk	PGI-NRI	Julian Krach	AGH-UST	Mariusz Słyś	INIG						
dr Marcin Słodkowski	PGI-NRI	Anna Żołdani -Szelest	AGH-UST	Edyta Dębińska	INIG						
Maciej Tomaszczyk	PGI-NRI	Joanna Rams	AGH-UST	Łukasz Kut	INIG						
Łukasz Nowacki	PGI-NRI			Andrzej Szwagrzyk	INIG						
Krzysztof Czuryłowicz	PGI-NRI			Marta Kyś	INIG						
dr Lidia Razowska-Jaworek	PGI-NRI			Stanisław Biały	INIG						
dr Jadwiga Wagner	PGI-NRI			Władysław Socha	INIG						
Zbigniew Kaczorowski	PGI-NRI			Władysława Kędra	INIG						
prof. Jacek Motyka	PGI-NRI			Zenobia Kątna	INIG						
Anna Chmura	PGI-NRI			Irena Irlik	INIG						
Jolanta Kublik	PGI-NRI			Dorota Piróg	INIG						
Piotr Matyjasik	PGI-NRI			Szczepan Filip	INIG						
Marta Wróblewska	PGI-NRI										
Iwona Duliban	PGI-NRI										
Tadeusz Grudzień	PGI-NRI										
Małgorzata Kielan	PGI-NRI										
dr Janusz Jureczka	PGI-NRI										
Włodzimierz Krieger	PGI-NRI										
Michał Rolka	PGI-NRI										
Marek Gałka	PGI-NRI										
Sławomir Wilk	PGI-NRI										
Jan Kwarciński	PGI-NRI										
dr Zbigniew Buła	PGI-NRI										
Ryszard Habryn	PGI-NRI										

Andrzej Piotrowski	PGI-NRI										
Rafał Sikora	PGI-NRI										
dr Monika Konieczyńska	PGI-NRI										
dr Wojciech Wołkowicz	PGI-NRI										
Dariusz Choromański	PGI-NRI										
prof. Józef Chowaniec	PGI-NRI										
dr Anna Tomaś	PGI-NRI										
dr Adam Tomaś	PGI-NRI										
dr Wojciech Ryłko	PGI-NRI										
dr Leszek Jankowski	PGI-NRI										
dr Robert Kopciowski	PGI-NRI										
dr Małgorzata Jugowiec-Nazarkiewicz	PGI-NRI										
Piotr Freiwald	PGI-NRI										
Tomasz Koziara	PGI-NRI										
Piotr Owsiak	PGI-NRI										
Robert Patorski	PGI-NRI										
dr Wojciech Brochwicz-Lewiński	PGI-NRI										
Anna Majewska	PGI-NRI										
Anna Bagińska	PGI-NRI										
Kamila Janus	PGI-NRI										
Dorota Obarowska	PGI-NRI										

THE PROJECT CONSORTIUM:

Polish Geological Institute – National Research Institute (PGI-NRI; leader)

AGH University of Science and Technology (AGH-UST)

Oil and Gas Institute (INiG)

Central Mining Institute (GIG/CMI)

The Mineral and Energy Economy Research Institute of Polish Academy of Sciences (MEERI PAS)

PBG Geophysical Exploration Ltd. (PBG Ltd.)

FINAL REPORT (in Polish only, except this Summary)

https://skladowanie.pgi.gov.pl/twiki/bin/view/CO2/WynikiPrac

INTERACTIVE ATLAS (WEBGIS – in Polish and English)

http://skladowanie.pgi.gov.pl/co2polska/polska.phtml