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CO_2 storage potential of sedimentary basins of Slovakia, the Czech Republic, Poland and the Baltic States

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It has been increasingly realised that geological storage of CO_2 is a prospective option for reduction of CO_2 emissions. The CO_2 geological storage potential of sedimentary basins with the territory of Slovakia, the Czech Republic, Poland and the Baltic States is here assessed, and different storage options have been considered. The most prospective technology is hydrodynamic trapping in the deep saline aquifers. The utilisation of hydrocarbon (HC) fields is considered as a mature technology; however, storage capacities are limited in the region and are mainly related to enhanced oil (gas) recovery. Prospective reservoirs and traps have been identified in the Danube, Vienna and East Slovakian Neogene basins, the Neogene Carpathian Foredeep, the Bohemian and Fore-Sudetic Upper Paleozoic basins, the Mesozoic Mid-Polish Basin and the pericratonic Paleozoic Baltic Basin. The total storage capacity of the sedimentary basins is estimated to be as much as 10,170 Mt of CO_2 in deep saline aquifer structures, and 938 Mt CO_2 in the depleted HC fields. The utilisation of coal seams for CO_2 storage is related to the Upper Silesian Basin where CO_2 storage could be combined with enhanced recovery of coal-bed methane.

Key words: CO_2 geological storage, saline aquifer, coal bed, EOR, ECBM.

INTRODUCTION

Most of the energy used to meet human needs is derived from the combustion of fossil fuels, such as coal, natural gas, oil shale, or shale gas which release carbon dioxide into the atmosphere. According to Intergovernmental Panel on Climate Change (IPCC, 2007), the annual amount of CO_2 transferred to the atmosphere and attributable to human economic activity equals 27 Gt; about 30% of 27 Gt is absorbed in land or in ocean as, according to IPCC, about 70% of this anthropogenic CO_2 is supposed to remain in the atmosphere. As a result of human activities, CO_2 concentration in the atmosphere has risen from pre-industrial 280 ppmv to 396.8 ppmv by February 2013 and may reach 1100 ppmv by 2100 in a case continued business as usual scenario (White et al., 2003; http://co2now.org/). For the past decade 2003–2012 the average annual increase is 2.1 ppm per year, while the average for decade 1993–2002 is 1.7 ppm per year (http://co2now.org/). In 2010, 33 Gt of CO_2

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were produced globally (Peters et al., 2011). The atmospheric concentration of CO_2, a greenhouse gas, is increasing, causing trapping of solar heat and subsequent global warming (e.g., Hansen et al., 1981). Global warming studies predict that climate changes, resulting from increase of atmospheric concentration of CO_2, will adversely affect life on Earth (Mackenzie and Lerman, 2006).

Carbon management consists of a broad portfolio of strategies to reduce CO_2 emissions via CO_2 capture and geological storage (CCS), enhanced efficiency of power generation and use, application of low carbon fuels, and the employment of renewable energy sources (Lokhorst and Wildenborg, 2005).

Carbon dioxide is already being captured by the oil and gas and chemical industries. Once CO_2 has been captured, it needs to be stored securely for thousands of years. CO_2 has been used for enhanced oil recovery (EOR) since the 1950s (Crawford et al., 1963). Research related to storage of CO_2 for environmental purposes began only 10–15 years ago. CO_2 storage in geological media can be safely undertaken within national boundaries in most countries, thus avoiding international political issues. Geological sinks for CO_2 include depleted oil and gas reservoirs, unminable coal seams, and deep saline porous formations. Together, these can hold worldwide hundreds to thousands of gigatonnes of carbon dioxide, and the technology to inject CO_2 into the ground is well established. CO_2 is stored in geological formations by a number of different trapping mechanisms, with the particular mechanism depending on the formation type (Bradley et al., 1991; Blunt et al., 1993; Winter and Bergman, 1993; Bachu et al., 1994; Law and Bachu, 1996; Gunter et al., 1997; Herzog et al., 1997; Bruant et al., 2002; Bachu and Adams, 2003; Pashin and McIntyre, 2003; Lokhorst and Wildenborg, 2005).

The present study has been performed within the frames of the EU GeoCapacity and CO2NET EAST projects supported by the European Commission's 6th and 7th Framework Programmes (Willscher et al., 2007). Geological sinks potentially suitable for CO_2 storage were evaluated using a common approach. The region studied is one of the largest CO_2 producers per capita in Europe. In the countries considered, the stationary sources of CO_2 that are listed in the European Union Emission Trading Scheme produce 16.9% of European emissions (year 2005). This averages 8.1 Mt CO_2 per capita in 2007, with the largest emissions per capita reported from Estonia and the Czech Republic – 15.2 and 12.1 Mt CO_2 respectively, while Latvia and Lithuania account only for 3.4 and 4.5 Mt CO_2 (World Bank Data, http://data.worldbank.org/indicator/EN.ATM.CO2E.PC).

CO_2 STORAGE TECHNOLOGIES

Various types of formations are considered suitable for CO_2 storage, though the maturity of different storage technologies differs. The carbon dioxide can be trapped in a geological formation in the following ways:

– methane displacement in coal beds (Gunter et al., 1997; Pashin and McIntyre, 2003);
– storage in salt caverns (Bradley et al., 1991);
– storage in depleted hydrocarbon reservoirs (Winter and Bergman, 1993), in particular when applying the enhanced oil recovery techniques (Blunt et al., 1993);
– storage in deep saline aquifers through hydrodynamic trapping (Bachu et al., 1994);
– mineral trapping (Bachu et al., 1994; IPCC, 2005; Teir et al., 2010).

Selection of a particular technology depends on geological conditions of the sink and on economic feasibility. In most of sedimentary basins, the traps in the deep saline aquifers represent the most prospective approach. Storage in salt deposits and mineral trapping are considered to be still uneconomic and too little studied, though the progress in developing those technologies is generally encouraging. Storage of CO_2 in coal seams is an attractive method due to the possibility of additional recovery of coal-bed methane combined with CO_2 storage. It should be, however, noted that coal storage technologies are still immature and not applicable at a commercial scale at present.

Storage of carbon dioxide in deep reservoirs, including hydrocarbon (HC) fields, is regarded as the most advanced technology and is ready to use.

REQUIREMENTS FOR GEOLOGICAL MEDIA

The hydrodynamic trapping of CO_2 in deep saline aquifers is considered as a nearly mature technology and is the main near-future option for geological storage of carbon dioxide. The prospective formations comprise water-saturated porous layers, at present not used for any other purpose. The high salinity renders the water unsuitable for use for drinking or for irrigation.

A number of parameters, such as pressure, temperature, reservoir properties and availability of traps define the storage potential of an aquifer. Depending on the formation pressure and temperature, CO_2 can be stored as compressed gas or in supercritical state (P > 73.8 bars, T > 31°C). At depths greater than ~800 m the carbon dioxide will be in supercritical state, which enables its efficient injection and brings advantages for both pipeline engineering and filling the deep pore space. Therefore, thermobaric conditions of P = 73.8 bars, T = 31°C are considered as the lower limit for the geological storage of CO_2.

CO_2 can be stored in structural and stratigraphic hydrodynamic traps. The capability of an aquifer to transfer and store CO_2 is controlled by the depositional environment, structure, stratigraphy and pressure/temperature conditions of a reservoir. Critical factors for CO_2 storage in the deep saline aquifers are:

– the regional water flow system;
– the thickness, lateral extent and continuity of the aquifer;
– the porosity, permeability and homogeneity of the aquifer;
– the tightness of the seal above the aquifer, including the faults that are potential pathways for CO_2 escape to the overlaying reservoirs;
– the capability of overburden layers above the reservoir seal to delay or diffuse leakage.

ASSESSMENT OF CO_2 STORAGE POTENTIAL OF GEOLOGICAL SINKS

Different approaches have been used to calculate the storage potential of deep saline aquifers, HC fields, and coal seams.

In a saline aquifer, the pore volume available for CO_2 storage (the effective storage capacity) depends on the geometric volume of the structural or stratigraphic trap down to the spill point, as well as on its porosity, sweep efficiency and the irreducible water saturation (CSLF, 2007):

$$M_{CO_2} = A \times h \times \varphi \times \rho_{CO_2} \times S_{eff} \times (1 - S_{Wirr}) \quad [1]$$

where: M_{CO_2} – effective storage capacity; A – area of trap; h – average thickness of trap multiplied by the net-to-gross ratio; φ – average aquifer porosity; ρ_{CO_2} – CO_2 density at saline aquifer conditions; S_{eff} – sweep efficiency (fraction of porewater that can be replaced by injected CO_2); S_{Wirr} – irreducible water saturation.

Of the various options for storing CO_2, the use of depleted oil and gas fields has a number of attractions. These fields are known to have held gases and liquids for millions of years, and their geology is known. Depleted and semi-depleted fields provide an opportunity for storing CO_2. It is a proven technology. In the oil industry, CO_2 flooding has been used worldwide as a Tertiary Enhanced Oil Recovery (CO_2-EOR) mechanism for about 40 years, particularly for reservoirs with pressures above the minimum miscibility pressure where miscible displacement of the residual oil by CO_2 would occur. The storage capacity of hydrocarbon fields has been estimated assuming 1:1 volumetric replacement ratio between hydrocarbons and CO_2:

$$M_{CO_2} = \rho_{CO_2 r} \times URp \times B \quad [2]$$

where: M_{CO_2} – hydrocarbon field effective storage capacity; $\rho_{CO_2 r}$ – CO_2 density at reservoir conditions (best estimate); URp – the volume of proven ultimate recoverable oil or gas; B – the oil or gas formation volume factor.

Injection of CO_2 into deep unminable coal seams is an alternative option for geological storage of CO_2. Some seams already hold naturally occurring carbon dioxide. All coals have varying amounts of methane adsorbed onto pore surfaces. The differences in adsorption behaviour of CO_2 and CH_4 can be used for CO_2 storage with simultaneous production of coal-bed methane from seams that are considered unmineable under actual technical or economical conditions. The process is called enhanced coal-bed methane recovery (ECBM). Carbon dioxide has a greater affinity to coal than methane. Coal can adsorb approximately twice as much CO_2 as methane. Some studies have shown that this rate may be as high as 10:1 (Mazzotti et al., 2009). One ton of coal can adsorb about 30–35 m^3 of CO_2 at pressures in excess of 5 to 8 MPa (Cook et al., 2000). One molecule of methane can be exchanged by 1.5 to 6 molecules of CO_2 depending on the available pressure (van Bergen and Pagnier, 2001). Two parameters are important for CO_2-ECBM potential – the producible gas in place (PGIP) and the CO_2 storage capacity, which is a function of PGIP, CO_2 density and CO_2 to CH_4 exchange ratio (ER). PGIP denotes the coal bed methane reserves for CO_2-ECBM economic use (it differs from regular estimations of CBM reserves assuming the use of standard production measures). CO_2 storage capacity (S) denotes the amount of CO_2 which replaces the PGIP, to the extent specified by the ER (hard coal usually has a ratio of about 2; brown coal and lignite may have higher ratios):

$$S = PGIP \times CO_2 \text{ density} \times ER \quad [3]$$

The standard approach of calculating PGIP estimates the volume and mass of coal within a seam, taking into consideration the methane content of the coal, the recovery factor and the completion factor:

$$PGIP = \text{coal volume} \times \text{coal density} \times CH_4 \text{ content} \times \text{completion factor} \times \text{recovery factor} \quad [4]$$

The depth range corresponds to the supercritical state of CO_2 and depths where sufficient data are available and/or suitable reservoir properties occur.

CBM (and CO_2) is trapped in coal in different forms (Klibáni and Němec, 2001), such as (1) gas sorption in micropores; (2) gas sorption in meso- and macropores; (3) free gas; (4) gas dissolved in pore water (Henry´s law). The first two mechanisms trap up to 90% of the total content of methane in coal seams. The amount of adsorbed gas in most of the coals is commonly 2.5–40 m^3 per ton.

CO_2 STORAGE POTENTIAL OF SEDIMENTARY BASINS

VIENNA BASIN (CZECH AND SLOVAK PARTS)

The Vienna Basin (Fig. 1) is a pull-apart feature that subsided nearly 5.5 km. The basin is subdivided tectonically into a system of horsts and grabens (Royden, 1985; Piller et al., 1996). It was initiated as a piggy-back depocentre on the Alpine nappes in the Lower Miocene. The escape of the Western Carpathians triggered the pull-apart mechanism in late Early Miocene that also affected the Danube Basin (discussed below). Thus, the two basins shared a similar subsequent tectonic

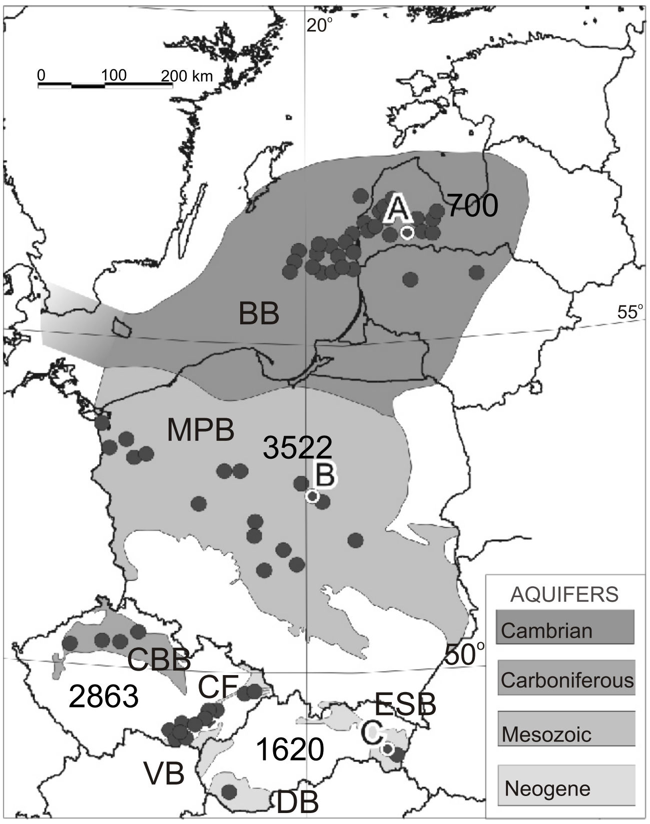
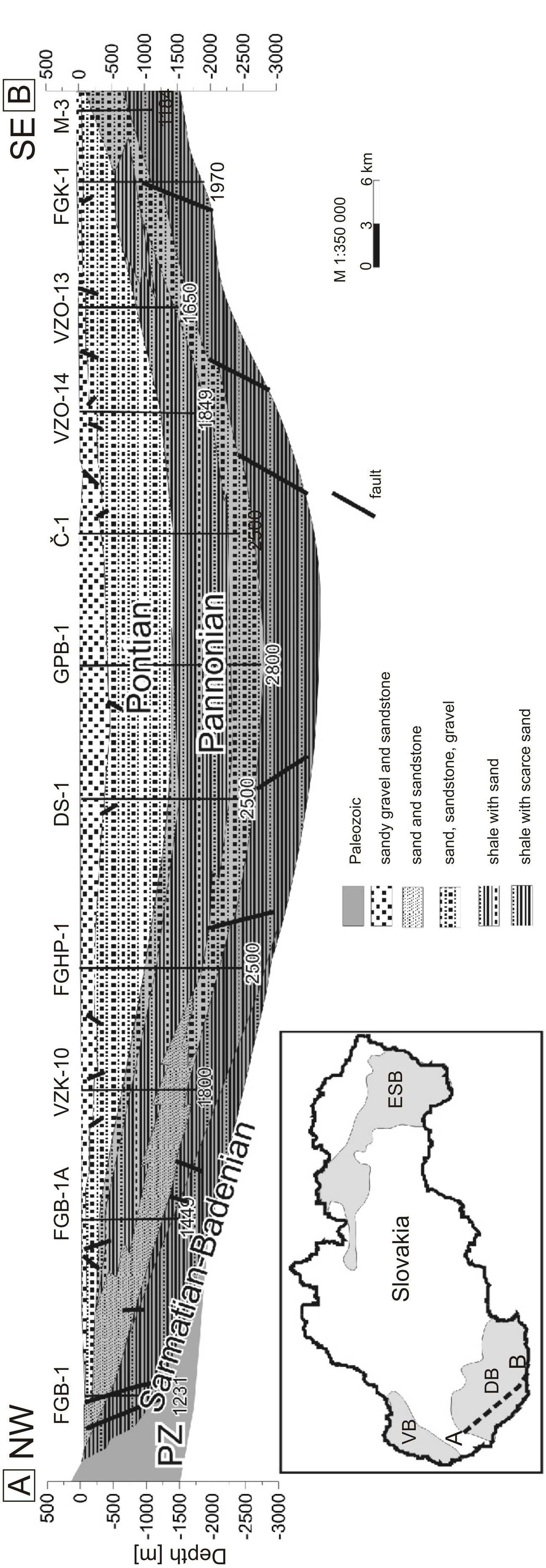


Fig. 1. Prospective aquifers and estimations of CO_2 storage capacity per country (Mt CO_2)

Dots – locations of prospective storage sites; BB – Baltic Basin, CBB – Central Bohemian basins, CF – Carpathian Foredeep, DB – Danube Basin, ESB – East Slovakian Basin, MPB – Mid-Polish Basin, VB – Vienna Basin; contours of aquifers matching hydrostatic pressure and temperature conditions for CO_2 storage (>7.8 MPa and >31°C) are shown only; A, B, C – selected structural traps (white-black dots) indicated in Figure 5



history. The syn-rift subsidence was replaced by post-rift thermal sag and cessation of fault tectonics and subsidence rate in the Late Miocene. Only in the east (e.g., Zohor–Plavecký Mikuláš), sinistral transtension maintained rapid, fault-controlled subsidence of grabens.

The Neogene fill of the Vienna Basin is composed of Eggenburgian to Pontian sequences that overlap the Alpine–Carpathian units and flysch nappes (Piller et al., 1996).

The main prospects of the Vienna Basin are related to HC fields. Some of the reservoirs are practically depleted, especially the shallow ones. Deeper structures in the Vienna Basin are still producing, as e.g., the reservoirs Hrušky (oil and gas), Týnec (oil), Gajary (oil and gas) and others. Most of the structures in the Vienna Basin represent tectonic traps in the Neogene sedimentary infill (Pícha et al., 2006). Reservoir bodies are mostly represented by Miocene (Badenian, Sarmatian) sandstones. Miocene oil and gas accumulations occur in the depth interval of 150–2000 m. Reservoir rocks are sandstones and conglomerates (2–30 m, in some places up to 60 m thick). Porosity of sandy layers ranges from 10 to 29%, permeability from 50 to 250 mD. The storage capacity of sixteen major hydrocarbon fields discovered in the Slovakian and Czech parts of the Vienna Basin is as high as 93.1 Mt CO_2.

DANUBE BASIN

The Danube Basin is situated in the SW part of Slovakia (Fig. 1). Together with the Vienna Basin it represents the north-western part of the Pannonian Basin system. The pre-Cenozoic basement is composed of Austro-Alpine and Slovak-Carpathian terrains as well as of Transdanubicum in the south-east (Rasser and Harzhauser, 2008). The depth of the Danube graben basin exceeds 8.5 km. It was established as a fault-controlled rift basin owing to wrench faulting induced by NW–SE compression during the late Early Miocene. Pull-apart depocentres opened in some parts of the basin (e.g., Blatná). The extensional regime was unstable. The extension direction changed to NW–SE in Middle Miocene, which led to unroofing of some basement blocks and high activity of N–S, NNE–SSW and NE–SW striking, predominantly low-angle normal faults. The Pannonian and Pontian reservoir siliciclastics deposits (that accumulated along the northern margin of Lake Pannon) were deposited in the post-rift thermal sag phase that subsequently gave way to tectonic inversion during the Pliocene, induced by SW–NE compression, which, however, did not interrupt the subsidence. In this case, the structural extension-to-compression history resembles the tectonic scenario of the Mid-Polish Mesozoic Basin. The structures, however, lack evidence of salt tectonics; therefore the geometry of the structural traps is somewhat different.

Two prospective large deep saline aquifers were defined in the geological section of the Danube Basin (Fig. 2). The lower, Pannonian formation is composed of sands, sandstones and gravels, with subordinate clay intercalations (Hrušecký et al., 1996). The depth of the formation exceeds 3000 m in the central part of the basin. The temperature is in the range of 80–140°C. The younger, sandy Pontian formation has more fa-

Fig. 2. Geological cross-section of Danube Basin (Slovakia) (after Franko et al., 1995; with some modifications)

Locations of Neogene basins of Slovakia and geological profile A–B (hatched line) are shown in the left corner of the figure; other explanations as in Figure 1

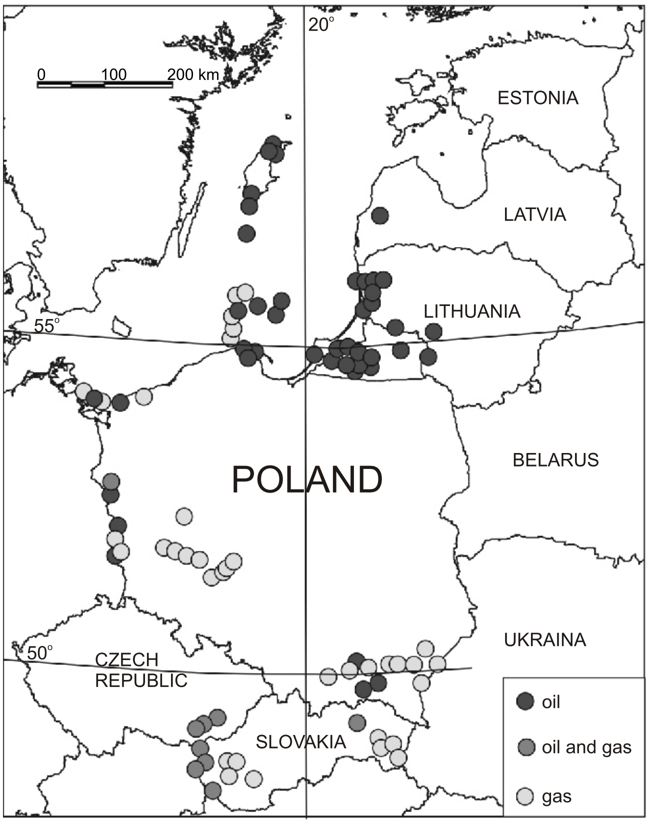


Fig. 3. Hydrocarbon fields considered for CO_2 storage

vourable thickness, depths, temperatures, and reservoir properties (Franko et al., 1995). The average porosity of the Pannonian formation is 6%, while that of the Pontian formation is 12%. However, the Pontian formation has a more complex syn-sedimentary architecture showing a highly fragmented pattern. Furthermore, it underlies an important Quaternary drinking-water aquifer that is considered as a risk factor for CO_2 leakage, as the basin is strongly faulted and fault sealing potential has not been proven.

Apart from saline aquifer structures, the HC fields might be prospective targets for storing CO_2. The HC fields have been intensely exploited. Presently there is the only one producing gas field. The total capacity of thirteen HC fields of the Danube Basin (Fig. 3) is assessed at 9.9 Mt CO_2, which is a negligible amount from the emissions reduction point of view.

EAST SLOVAKIAN BASIN

The East Slovakian Basin, locked between the Western and Eastern Carpathians, reaches 9 km in thickness. The Neogene sediments are up to 7000 m thick in the deepest part of the basin (Fig. 1; Kováč et al., 2007). The Carpathian nappes compose the basement of the basin. The tectonic and structural style of the depression changed in the course of basin history (Kováč et al., 1995). Initial Lower Miocene sedimentation took place in a forearc setting and was subject to NE–SW compression that finally led to fragmentation of the depocentre. The horizontal compression was associated with normal and strike-slip faulting. Upper Lower Miocene sediments filled the pull-apart depressions of the early rifting phase. The prospective Sarmatian reservoir accumulated during a backarc syn-rift phase that was also marked by extensive volcanic activity.

Shales and sandstones are the dominant lithologies. Two prospective saline aquifers have been identified. The lower, Sarmatian aquifer is composed of predominant sandstones characterized by good reservoir properties. The formation also contains impermeable claystones and volcanoclastic layers. The thickness of the Sarmatian sedimentary fill varies from 92 to 1030 m, but the average effective thickness (reservoir layers) is only 127 m. The average depth of the Sarmatian aquifer is 1050 m; the average porosity of the sandstones is 18%. The second, Pannonian saline aquifer comprises the lower part of the Pannonian formation. The aquifer is composed of basal conglomerates and sandstones about 25 m in thickness; the porosity averages 22%. The aquifer is sealed by a thick package of shales. Average aquifer depth is 794 m.

Some prospective structures have been identified, such as the Bzovik uplift, that can store 830 Mt of CO_2 (Kucharič, 2009). The storage potential of the Danube and East Slovakian basins remains an object of further study due to insufficient coverage by industrial seismic profiles and drilling; accordingly, only a limited number of structures were identified in the aquifers. Assuming a theoretical regional storage efficiency coefficient of 4%, the regional potential of the Pannonian and Pontian aquifers of the Slovakian part of the Pannonian Basin is 1360 and 8165 Mt of CO_2 respectively. The capacities of the Sarmatian and Pannonian aquifers of the East Slovakian Basin are evaluated as high as 2940 and 416 Mt of CO_2 respectively.

A number of HC fields were discovered in the East Slovakian Basin. Reservoirs are located mainly in the Badenian and Sarmatian volcanoclastic sedimentary formations. The capacity of nine major HC fields of the East Slovakian Basin was evaluated at 49.9 Mt CO_2.

CARPATHIAN FOREDEEP BASIN

The Neogene Carpathian Foredeep represents a narrow depression limited to the SE by the deformed Carpathian Flysch Zone. The autochthonous sedimentary formations comprise important oil and gas fields and large aquifer structures. The sediments filling the basin are of Eocene, Oligocene and Miocene age. The average porosity of reservoir rocks is in the range of 15–20% and the permeability is 50–200 mD. Seventeen potentially suitable deep saline aquifer sites were identified in the Czech part of the foredeep.

The Carpathian Foredeep comprises a number of hydrocarbon fields. Miocene deposits represent the reservoir rocks. Sixteen depleted/depleting gas and oil fields have been evaluated for CO_2 storage, most of them of moderate size. Most of the HC reservoirs are depleted or almost depleted (80–90%) and some of them have been transformed into natural gas underground storage sites (e.g., Dolní Dunajovice).

In the Czech Republic, the most important producing oil and gas reservoirs are located in the Carpathian Flysch Zone (Hladík et al., 2008). In this area the production layers are related to Jurassic and Carboniferous strata underlying flysch nappes. There are also some gas fields in Miocene deposits (Ždánice area) and small oil reservoirs were discovered in the crystalline basement (Ždánice, Lubná–Kostelany).

The storage capacity of the HC fields is very different, ranging from 4.17 Mt in the Uszkowce field to 244.6 Mt in the Przemyśl field (Poland). The total storage potential of HC fields was evaluated at 434.6 Mt CO_2, mostly in the Polish part, where they belong usually to the Carpathian Neogene Foredeep zone along the Carpathian Front containing Miocene reservoirs. Some HC fields are related to the basement of the foredeep comprising Mesozoic and Paleozoic reservoir layers, especially in the western part (Karnkowski, 1999).

CZECH CRETACEOUS BASINS

Czech Cretaceous basins comprise several large aquifers, such as the Bohemian Cretaceous Basin in central and east Bohemia or the Cenozoic and Cretaceous deposits of south Bohemia comprising the Budějovice and Třeboň basins (Malkovský, 1987). However, these basins are too shallow to be considered as prospective for CO_2 storage. Furthermore, the Cenomanian–Santonian deposits of the Bohemian Cretaceous Basin, one of the largest depressions in the Czech Republic, are important groundwater reservoirs used for water supply and therefore are also unsuitable for CO_2 storage.

UPPER PALEOZOIC BOHEMIAN BASINS

Upper Paleozoic basins, located in the central and northern part of the Czech Republic and southwesternmost Poland, contain prospective Permian–Carboniferous formations comprising deep saline aquifers of Early Carboniferous–Late Permian age (Holub and Tásler, 1978). Two main fault systems define the structural framework of the basins. Faults that were active during Late Paleozoic sedimentation might have considerably influenced the lateral lithofacies pattern. NW–SE trending faults are most common. They show kinematic features of normal faults with some dextral strike-slip component. This fault population was recurrently activated, essentially during Cretaceous Alpine compressional faulting. The second fault family, striking NE–SW, is also likely of synsedimentary origin. These are mostly normal faults showing offset amplitudes of several tens to hundreds of metres. The largest amplitudes are defined in marginal parts of the basins. The relative vertical displacements on these synsedimentary faults reach up to several hundreds of metres. An example of a large-scale border fault is the Litomeřice Fault Zone. It was established in the Late Paleozoic and was repeatedly active during the Cretaceous and mainly in Cenozoic times, when it represented a part of the NE-trending Eger rift comprising a system of depocentres and a volcanic range (a large Doupov stratovolcano emerged along this fault zone, and partly covered the Žatec Basin). Post-volcanic hydrothermal activity gave rise to several bentonite deposits associated with tuff deposition.

The basins contain large structures that might be prospective for CO_2 storage. The Central Bohemian basins represent a chain of fluvial-lacustrine depocentres comprising several prospective aquifers as well as coal-bearing layers (e.g., Pešek et al., 2001).

Only structures with favourable sealing, suitable depth and significant pore volume were considered for CO_2 storage. Altogether, five potentially suitable structures were identified within these basins.

The Permian–Carboniferous Central Bohemian and Lower Silesian basins are partly covered by thick (up to 900 m) sedimentary units of the Bohemian Cretaceous Basin. Reservoir bodies comprise mainly Upper Carboniferous (Westphalian) sandstones sealed by Stephanian and Lower Permian shales. The structures are of complex geometry, and sufficient information about their properties is lacking in most of the basins. The

Fig. 4. Coal seams (black polygons) and theoretical CO_2 storage capacities in coal per country (Mt CO_2)

assumed porosity of aquifers for calculating CO_2 storage capacities was 15%. The assumed average permeability is in the range of 1–80 mD. The theoretical storage capacity of the Central Bohemian basins was assessed at 471 Mt CO_2.

The Central Bohemian basins contain coal fields that might be considered for potential CO_2 storage (Fig. 4). The Slaný, Peruc and Mělník–Benátky fields have been evaluated at a basin scale.

UPPER SILESIAN BASIN

The Upper Silesian Coal Basin is a large and complex paralic-limnic sedimentary structure that is located in the north-east Czech Republic and south Poland. Coal seams occur here within Namurian and Westphalian sediments (Upper Carboniferous) that have a potential for CO_2 storage in coal seams and for application of enhanced coal-bed methane recovery technologies. It should be mentioned that coal mining methane (CMM) is exploited together with coal (usually at a depth range of 300–1000 m), for safety reasons in producing collieries as a secondary resource. The majority of CBM is, however, produced from unmineable coal seams or from abandoned mines. For example, the production of CBM from the Czech part of the basin reaches 40 mil. m^3 per year.

For the purposes of CO_2 storage, the unmined coal measures were considered. Storage capacities are based on estimations of producible gas in place (PGIP) calculated for the favourable depth range. The total effective CO_2 storage capacity of 33 sites was assessed as high as 469 Mt. Estimated storage capacities of individual fields vary from 0.3 Mt (Moszczenica) to 46.1 Mt (Żory-Suszec, both in Poland). The regional storage capacity at the depth range 1–2 km was assessed at 1254 Mt.

FORE-SUDETIC MONOCLINE

The Fore-Sudetic Monocline represents the western flank of the larger Mid-Polish Mesozoic Basin. It contains a number of HC fields (Fig. 3). There are numerous gas fields situated in the Rotliegend and Zechstein deposits. Due to its deep burial and the Early Permian volcanic activity, most of the Fore-Sudetic Basin is overmature. In the HC area, two principal depositional episodes of Triassic–Jurassic and Late Cretaceous ages are recognized. The reservoirs are usually comprised of fluvial and aeolian deposits of the Rotliegend and, especially in the northern part, carbonates of Zechstein (Karnkowski, 1999).

The storage capacity of HC fields varies from 2.4 Mt (Gorzysław) to 91.9 Mt (Żuchlów). Most HC fields are depleted to over 90% of reserves, especially the largest ones.

The size of hydrocarbon fields is highly variable. The Barnówko–Mostno–Buszewo (BMB) structure of about 150 km^2 in size is the largest oil and gas field developed in Poland (Górski et al., 1999); its storage capacity has been evaluated at 34.2 Mt. Total storage capacity of HC fields of the Fore-Sudetic Monocline was assessed as high as 240 Mt.

MID-POLISH BASIN

The Mid-Polish Mesozoic Basin is one of the largest sedimentary depocentres in Europe (Dadlez, 2006). It comprises large aquifers of Early Cretaceous, Early Jurassic and Early Triassic age. Tectonic analysis of the Mid-Polish Basin indicates an initial Late Permian–Early Triassic syn-rift phase with subsequent extensional rejuvenation during the Late Jurassic (Stephenson et al., 1995) that correlates with intensified rifting and wrench activity within the Arctic–North Atlantic rift system and along the northern Tethyan margin (Stephenson et al., 2003). In contrast, accelerating tectonic subsidence beginning in the Cenomanian was a precursor of compressional deformation in the basin that culminated in Alpine-related basin inversion during the latest Late Cretaceous and earliest Cenozoic.

The Lower Cretaceous reservoir consists mainly of Barremian–Middle Albian sandy and carbonate-sandy deposits. They are separated by series of low- and non-permeable siltstones and mudstones. The Barremian–Middle Albian sandstones represent a potential reservoir for CO_2 storage. They are overlain by Upper Cretaceous limestones and chalk characterized by low permeability (Górecki, 2006). The total thickness of the Lower Cretaceous succession varies from several metres at the peripheral zones of the basin to several hundred metres (500 m) in the centre (Leszczyński, 2012). The effective porosity is of order of 20–40%. Pore water salinity attains 100 g/l.

Lower Jurassic aquifers are predominantly composed of sandstones of Hettangian, Sinemurian, Domerian, Late Pliensbachian and Late Toarcian age. They are separated by deposits of low permeability. The total thickness of the Lower Jurassic succession ranges from ~10 metres in the basin periphery to 400–1200 m in the centre (Górecki, 2006). The best properties for CO_2 storage have been identified in the Upper Toarcian and Lower Aalenian sandstones overlain by Upper Aalenian shaly seal rock. The Upper Pliensbachian aquifer is sealed by Lower Toarcian shales. Commonly, the open porosity ranges from 15 to 20%. Pore water salinity reaches 200 g/l.

Middle Buntsandstein sandstones compose the major part of the Lower Triassic aquifer. They are sealed by Röt silty and clastic-carbonate-evaporitic deposits referred to as the Upper Buntsandstein. The total thickness of the Lower Triassic unit changes from several tens of metres to over 1600 m (Górecki, 2006). The average effective porosity of aquifer sandstones is about 10%. The porewater salinity of the Lower Triassic aquifer varies from several g/l in the marginal parts to over 350 g/l in the central parts of the basin.

Numerous tectonic trap structures have been defined in the Mesozoic aquifers, mainly related to salt structures. Some of these may prove to be geological structures adequate for CO_2 storage. 18 prospective local anticlines and tectonic grabens have been examined – 7 structures in Lower Cretaceous, 7 structures in Lower Jurassic and 4 structures in Triassic formations. These relatively well explored structures likely comprise only a part of storage capacity potential of the basin which is still being studied in new domestic research projects. The storage capacity of individual structures varies from 64 to 575 Mt of CO_2. The total storage capacity of these 18 structures amounts to 3522 Mt of CO_2. This would allow storage 11-years' CO_2 emissions from Poland (referring to the emission level of 2004; Tarkowski et al., 2008).

BALTIC BASIN

The Baltic Basin is a part of the East European Platform. It comprises Lithuania, Latvia, Estonia, the Kaliningrad District of Russia as well as parts of Poland, Sweden and Denmark (Šliaupa et al., 2004, 2005, 2008).

A number of large aquifers have been identified within this basin. However, except for a very small part of the Mesozoic Mid-Polish Basin located offshore, only the saline Cambrian aquifer matches the basic requirements for CO_2 storage (Šliaupa et al., 2008). The main deficiency of the other aquifers is the absence of structural traps that are large enough.

The Cambrian reservoir represents the base of the Baltic Basin sedimentary infill. The depths vary from outcrops in Estonia to more than 2 km in west Lithuania and 4 km in north Poland (Podhalańska and Modliński, 2010). The reservoir is composed of quartz arenites with subordinate siltstones and shales. The thickness of the aquifer is in the range of 10–70 m (average 40–60 m). Porosity is 3–26%, decreasing with depth. The Cambrian sandstones are confined by a 200–2000 m thick Ordovician–Silurian shale package that ensures reliable sealing of the reservoir. Temperature (>31°C) and pressure (>7.8 MPa) conditions favourable for CO_2 geological storage have been identified in the southern Baltic Sea, the Kaliningrad district, northeastern Poland, central and west Lithuania and Latvia. Detailed geological and geophysical data, collected during extensive oil exploration in the past, has enabled identification of a number of local structures in the Cambrian reservoir. The main deformation took place during the latest Silurian–earliest Devonian that was induced by docking of Laurentia to Baltica (Sliaupa et al., 2004). They structures are, however, mostly of small size. For instance, only two structures in Lithuania have a storage capacity exceeding 1 Mt (8 and 21 Mt CO_2 respectively).

The prospective storage area is confined to central Latvia and the Latvian offshore region. Sixteen onshore and sixteen offshore large Cambrian structures, each with estimated storage capacity exceeding 2 Mt CO_2, have been identified in this area (Fig. 1; Shogenova et al., 2009a, b). The average effective porosity of Cambrian sandstones is 20–25%, permeability reaches hundreds and thousands of mD, mineralization of groundwater is 85–126 g/l and water temperature is 17–25°C. Thickness of the reservoir sandstones is 20–70 m (Shogenova et al., 2011). The total capacity of large structures is estimated as high as 400 Mt of CO_2 onshore and 300 Mt offshore, with the potential of the largest uplifts reaching 40–70 Mt of CO_2.

The Baltic Basin represents a proven HC province (Fig. 3). In total, about 40 HC accumulations have been discovered (Brangulis et al., 1993; Šliaupa et al., 2004). Most of them are oil accumulations, but offshore Poland, gas accumulations occur as well. In the Kaliningrad district, oil production began in 1975. Currently 5–6 Mbbl/year are produced from the onshore fields. Lithuanian onshore oil production started in 1991. It reached its production peak in 2004 with 2.8 Mbbl. There is light oil and gas production in the Polish sector of the Baltic Sea (Pikulski et al., 2010). In the northern part of the basin, there is small-scale oil production in Gotland. In Latvia, several small oil accumulations have been discovered. Only minor, brief oil production took place in 1990. The oil and gas fields are generally small in size and most of them are depleting. Therefore, the EOR option is considered as a prospective CO_2 application technique for the region. The net (and gross) CO_2 volumes required for EOR have been evaluated. The total potential of Lithuanian oil fields is 4.3 (9) Mt CO_2, Kaliningrad onshore 29.1 (58) Mt and offshore 7.7 (15) Mt, Polish offshore 7.4 (15) Mt. The CO_2 storage potential was evaluated at 5.7 Mt in Lithuania, 26 Mt onshore Kaliningrad, 7 Mt offshore Kaliningrad, 7 Mt for Polish offshore oil fields and 16 Mt for gas fields.

In Polish part of the basin, excluding seven known HC fields, forty Cambrian traps of various size have been identified (Domżalski et al., 2004) as prospective for hydrocarbon prospecting. The storage capacity of these structures have yet not been assessed but they might be comparable to those described of Latvia. One problem might be integrity of the caprock, because of locally intense faulting there.

DISCUSSION

The present study shows that the main potential for geological storage of carbon dioxide emissions in the countries considered is related to deep saline aquifers. The sedimentary basins discussed are of very different type, size and age that range from Cambrian to Neogene. Despite the considerable differences in geological evolution, the storage potential figures evaluated for particular basins are quite comparable.

The prospective traps identified at the first study stage of deep saline aquifers are of explicitly structural nature. Structures show very different kinematic features that relate to various tectonic types of the basins considered.

The Baltic Sedimentary Basin represents the largest depocentre among the basins analysed. Yet, the cratonic setting of the basin results in only weak tectonic structuring of the sedimentary infill, owing to a mechanically strong lithosphere (Ershov and Šliaupa, 2000) and long distance to the tectonic stress source systems. Activity of these systems is the principal reason for the formation of major structural traps in the Baltic Basin. Due to low tectonic forces and a stiff lithosphere, the structures are generally small in size. The amplitudes of local uplifts are commonly in the range of 10–20 m. Therefore, the storage capacity of the structures identified is low and cannot be considered as prospective for CO_2 storage (Šliaupa et al., 2005). Only central Latvia and the adjacent offshore area have been subject to strong deformation within the Liepaja–Saldus Ridge, comprising local uplifts of considerable size producing structures with high storage capacity (Šliaupa et al., 2008). The structures are classified as transpressional fault-controlled anticlines (Fig. 5A). The regionally differentiated deformation was related to variations in the lithosphere strength of the basin. The more deformed central Latvia is confined to the locally weakest and thickest (~60 km) part of the Earth's crust. Therefore, only Latvia has a large storage potential, while other countries situated within the Baltic Basin are devoid of prospective traps.

The Mid-Polish Mesozoic Sedimentary Basin is situated in a different tectonic setting, straddling the zone where the East European Craton and the younger West European Platform are juxtaposed, i.e. the Teisseyre-Tornquist Zone (TTZ). The TTZ represents a pre-weakened zone that is sensitive to acting tectonic forces. Therefore, the basin in general, and the tectonic structures in particular, are of much larger magnitudes than those of the cratonic Baltic Basin. The Mid-Polish depocentre was established in the Late Permian. Multiphase tectonic activity, changing from extensional to compressional regimes, has resulted in the complex geometry of the tectonic structures (Krzywiec, 2006). Furthermore, they are associated with intense salt tectonics (Fig. 5B). Therefore, the structural traps identified in central Poland are of much larger size and have larger storage volumes; some of them exceed more than 10-fold the size of the Latvian structures.

The sedimentary basins located south of the Baltic and Mid-Polish depocentres are of much smaller size due to tectonic fragmentation.

The tectonic history was complex in the Central Bohemian Upper Paleozoic basins. The potential sinks represent largely fault-bounded depocentres with a generally flat basin floor. The basin fill, arranged in a large brachysyncline superimposed by lower-order brachyanticlines, is dissected by numerous faults and associated structures.

The other group of small sedimentary basins is represented by Neogene extensional depressions comprising the Vienna, Danube and East Slovakian basins. They bear similarities in tectonic evolution, structuring style and sedimentation. Structures representing series of extensional fault-blocks formed that are considered prospective for storage of CO_2 (Fig. 5C). The second important reservoir of Pannonian age is representative of the post-rift subsidence phase that was associated with tectonic extension and fault activity. As in the Danube Basin, the East Slovakian depression was subject to tectonic inversion and slight folding during the Pliocene.

A conflict of interests should be noted. In this instance, the Danube Basin is the largest reservoir of potable water in the central Europe. The sources are located in the Quaternary cover of thickness of up to 500 m and in the upper part of the Neogene succession comprising Pannonian and Pontian aquifers. Furthermore, they contain large sources of saline geothermal water at depths exceeding 1500 m. At this depth, the average temperature is about 60°C. It is estimated that the recoverable amount of geothermal energy is 150 MWt across the whole basin (Franko et al., 1995). These issues are relevant also to other sedimentary basins of similar hydrogeological characteristics in Europe. The priorities depend on development of energy sector, demands on potable water, as well as CCS technology progress.

Another type of aquifer sink is related to foredeep basins located along the northern margin of the Carpathian orogen. A number of prospective structural traps have been identified in the Carpathian Foredeep, up to 40 km across, in the Czech Republic. The initial re-collisional basin was established in the Oligocene through to the early part of the Early Miocene (Nehyba and Šikula, 2007). The flexural bending phase and deposition of a syn-orogenic clastic wedge started in the mid Early Miocene due to the onset of thrusting in Carpathians. This climaxed in the late Carpathian time and was followed by Early

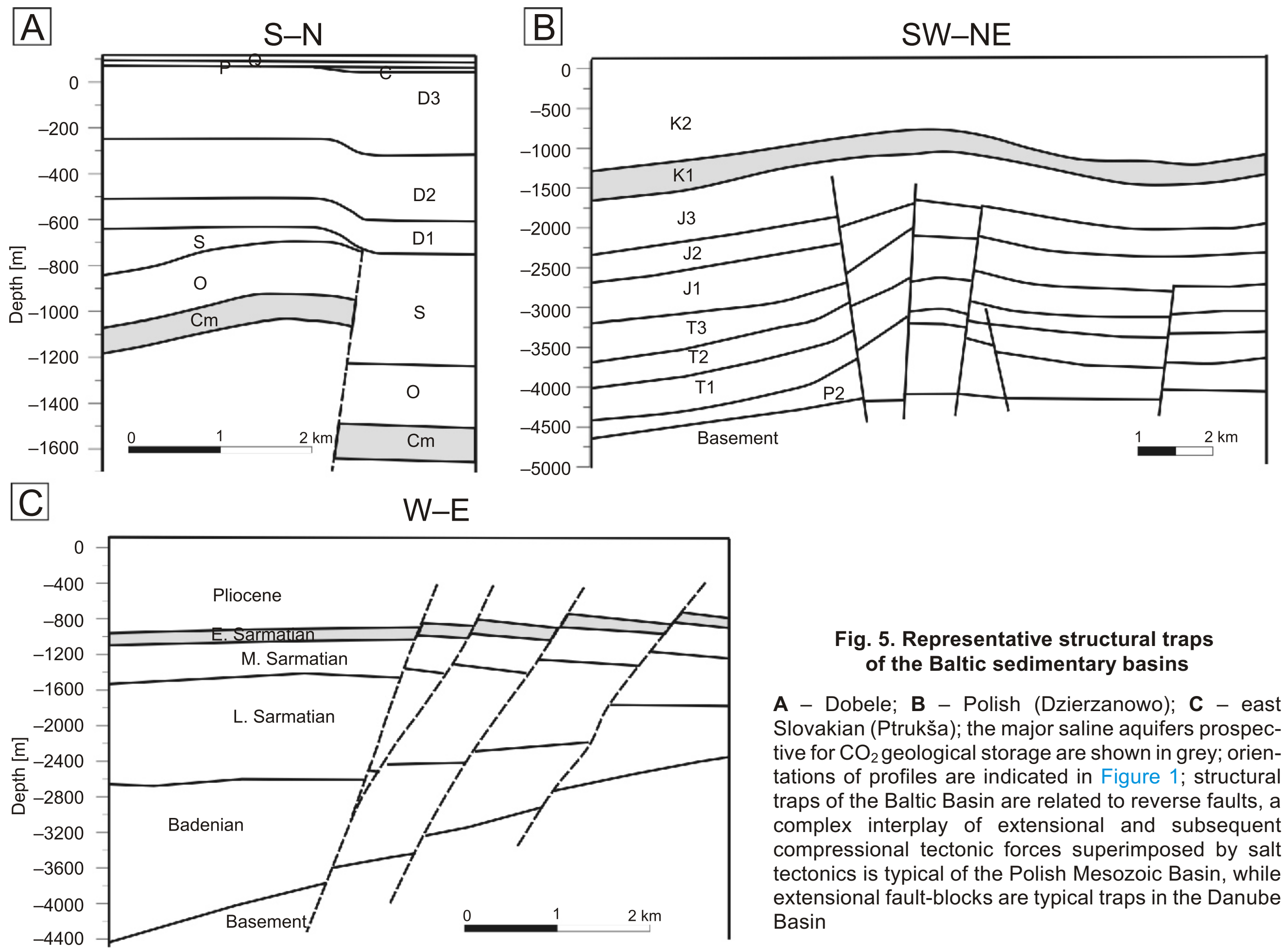


Fig. 5. Representative structural traps of the Baltic sedimentary basins

A – Dobele; **B** – Polish (Dzierzanowo); **C** – east Slovakian (Ptrukša); the major saline aquifers prospective for CO_2 geological storage are shown in grey; orientations of profiles are indicated in Figure 1; structural traps of the Baltic Basin are related to reverse faults, a complex interplay of extensional and subsequent compressional tectonic forces superimposed by salt tectonics is typical of the Polish Mesozoic Basin, while extensional fault-blocks are typical traps in the Danube Basin

Badenian postcollisional deposition. Foredeep subsidence was associated with the onset of formation of compressional structures, many of which are considered to be prospective for CO_2 storage in the Czech territory. The structural traps suitable for CO_2 storage in south Poland were formed in a similar tectonic setting (Oszczypko, 1998; Oszczypko et al., 2006). Syn-sedimentary faults controlled the lateral pattern of lithofacies. The faulting was complex in the foredeep, that shows both flexural extension related to the Late Badenian–Sarmatian reactivation of the basement fault zones and thrusting compression. Proven structural traps are related to anticlinal bends comprising a passive-roof duplex, and to detachment folds above the roof back-thrust (Oszczypko et al., 2006). Some prospective structures are located in the Mesozoic and Paleozoic basement.

The depths of potential structural traps are different in various sedimentary basins. The critical minimum depth is approximately 780 m – the depth at which CO_2 can be usually injected in the supercritical state that is important for efficient storage operation. There is no maximum depth limit; the deepest considered structure in the study region is located at a depth of 2,630 m (Fig. 6). Identified prospective structures are located mainly in the depth range 800–1600 m (88%) with a peak at depths of 1000–1200 m (40%). Such a shallow setting of the majority of the prospective sites is largely related to the impact of depth (and temperature) on the reservoir properties of siliciclastic deposits, showing a systematic decreases in porosity and permeability with depth. An essential requirement for a reservoir body is favourable petrophysical properties, as high gas injection rates are required for effective operation of CO_2 storage sites.

Only siliciclastic reservoirs have been considered in the present study. Employment of carbonate reservoirs for CO_2 storage is still a matter of discussions (e.g., Lagneau et al., 2005; Andre et al., 2007). The sandy reservoirs considered are highly variable in terms of mineral composition (quarz arenites, arkoses, greywackes), sedimentary environment (continental, marine) and diagenetic attraction. For example, Cambrian, Jurassic and Cretaceous marine reservoirs of the Baltic and Mid-Polish basins are characterized by a generally simple syn-sedimentary architecture, while Permian–Carboniferous and Neogene continental and marine deposits in the south showing very complex sedimentation patterns. The sedimentation history accordingly influences the quality of a storage site. The range in porosity of prospective structures considered is 0.08–0.30 (Fig. 7). Most potential sites (76%) have porosities of 0.12–0.24. The range of permeability is 10–1300 mD, mostly 50–300 mD (Fig. 7).

The storage capacity estimates of the potential structures identified depend considerably structure size and reservoir properties. In most cases, the size of prospective structures identified ranges from small to medium with an estimated storage capacity of 2–100 Mt of CO_2 (Fig. 8). Only two structures exceeding 500 Mt were discovered in the region. Such small structures relate primarily to limited tectonic activity (e.g., the Baltic and Mid-Polish basins) and to the small size of sedimentary basins, resulting in a fragmentation of depocentres (e.g., the Vienna, Danube and East Slovakian basins).

The alternative storage options related to utilisation of HC and coal fields are of considerably lower potential in the countries studied. The HC traps on cratonic Baltic Basin are small.

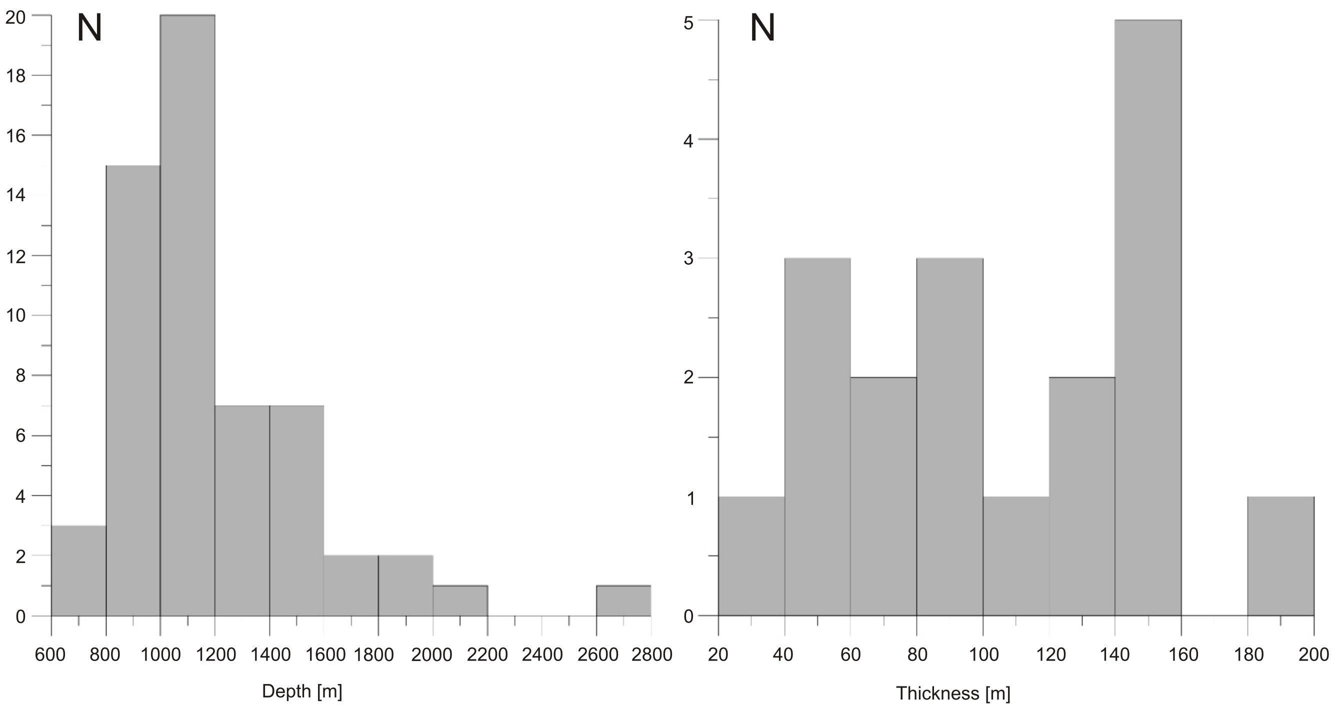


Fig. 6. Depths and thicknesses of reservoirs of prospective aquifer structures

N – number of structures

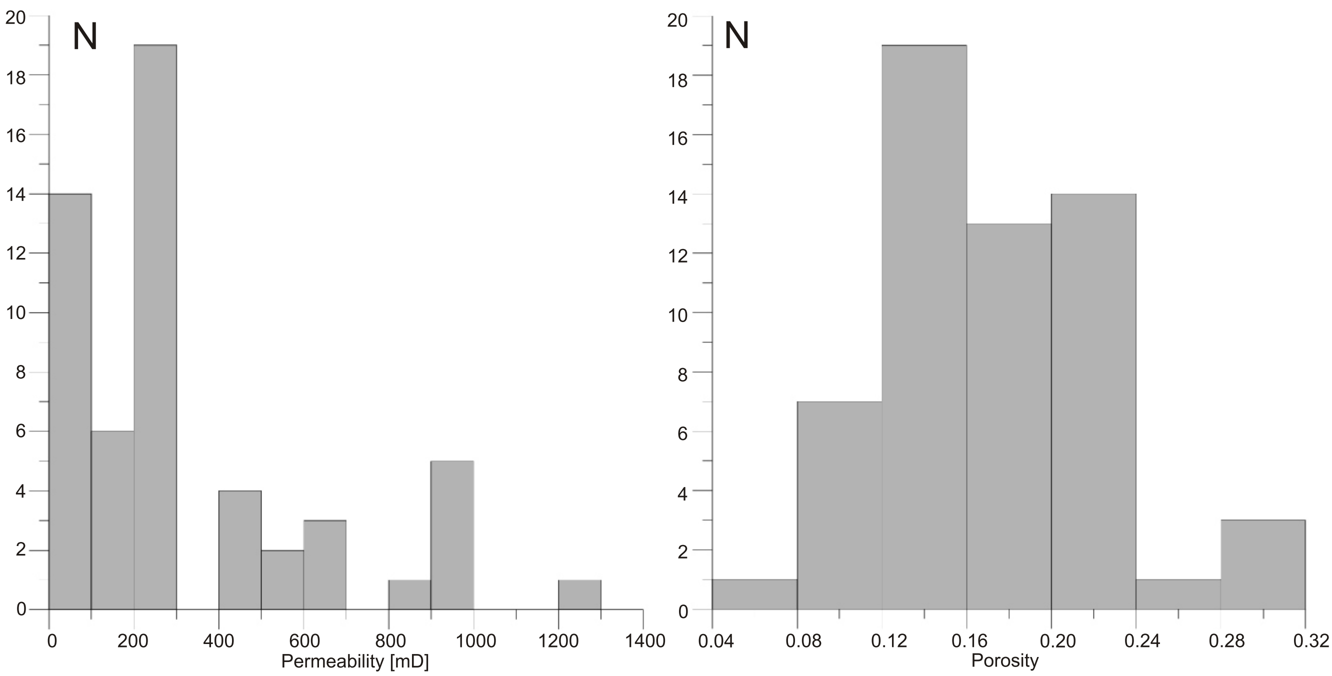


Fig. 7. Permeability and porosity of prospective reservoirs

Explanations as in Figure 6

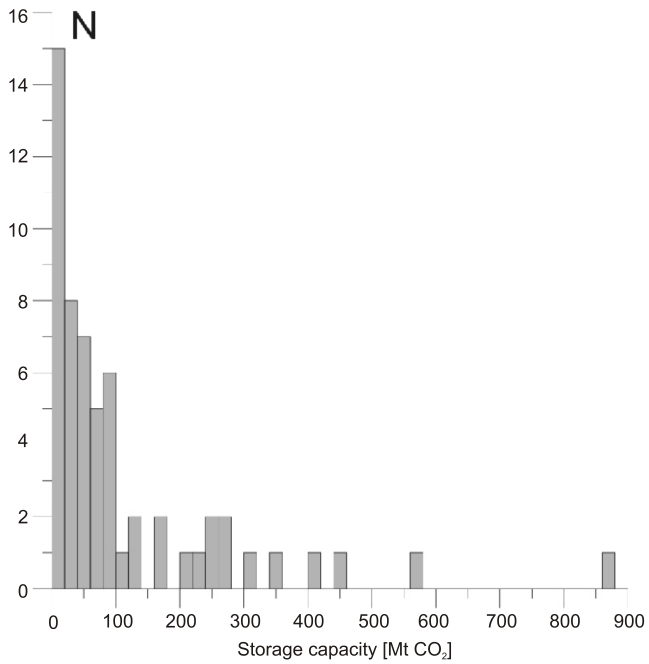


Fig. 8. Storage capacities of prospective structures

Explanations as in Figure 6

Furthermore, extensive diagenetic cementation of Cambrian sandstones and a predominance of fracture-type reservoirs makes it practically impossible to apply tertiary oil recovery using CO_2. The oil fields of Poland, the Czech Republic and Slovakia show better reservoir properties and are larger. Therefore, CO_2-EOR might be considered as an attractive technique for the hydrocarbon industry. Pilot studies are required to demonstrate the applicability of this technology in these countries, as only Hungary and Croatia have applied this approach in Europe so far. On the other hand, HC fields of Poland, the Czech Republic and Slovakia are dominated by gas accumulations, while oil fields are scarce. There is no proven technology developed for enhanced gas recovery (EGR), therefore the prospects of most of HC fields remain in question (van den Burgt, 1990; Polak and Grimstad, 2009). Only a few HC fields are sufficiently large in size to be considered prospective for storing CO_2 (e.g., the Żuchlow field, 91.9 Mt CO_2). In most cases, the fields are structural traps. Also, some structural traps of pinch-out type have been considered in the Fore-Sudetic Monocline. Such traps are interesting in terms of their large size and thickness (Górski et al., 1998).

The storage potential of coal seams is also limited and is defined as a prospective technique only in Poland and the Czech Republic. This potential is considered as a combination of CO_2 geological storage and enhanced recovery of coal-bed methane (CO_2-ECBM). The methane content of a coal deposit depends on the process of coalification and the overall geological history of the deposit. The amount of stored gas that can be extracted is a function of the intrinsic features of the reservoir, such as water saturation, fractional permeability, pressure, and the specific features of the coal, i.e. sorption equilibrium, permeability, microstructure, and so on.

The Upper Silesian Basin (USB) may represent a suitable option for CO_2 storage in coal seams. Other coal basins, not discussed above, are too shallow (e.g., the brown-coal basins in northern Bohemia) or too sparsely explored (the Central Bohemian Paleozoic basins). The total effective storage capacity of 40 blocks selected in the USB has been estimated at 797 Mt CO_2. The reserves of CBM that might be recovered by applying CO_2-ECBMR technology have been assessed at about 14 Bcm in the Czech Republic and 118 Bcm in Poland. This approach could significantly increase domestic CBM production in these countries.

However, it should be taken into consideration that the technology of CO_2 storage in coal seams is still immature. It is commercially applied only in the San Juan sedimentary basin in the USA, where the use of CO_2 for enhanced recovery of methane is related to exceptionally good reservoir properties of coal, e.g. permeability exceeding 10 mD. The European coal fields, including the countries studied, usually have worse properties that will require development of more advanced techniques for enhancing the recovery of methane using carbon dioxide.

CONCLUSIONS

The six countries studied are characterized by very different geological conditions. Slovakia and the Czech Republic possess a number of small sedimentary basins, whereas Poland and the Baltic countries include the large Mid-Polish and Baltic basins. Four countries have prospective CO_2 storage potential; a very low capacity has been; however, assessed for Lithuania, while in Estonia there are no prospects of in-site storage. The largest capacities are estimated for deep saline aquifers. The aquifer capacity was calculated as being able to accommodate up to 9, 10 and 75 years of annual CO_2 emissions from large point sources in Poland, the Czech Republic and Slovakia respectively, while Latvia has potential for about 200 years of emission. The total storage potential of all countries studied is 5950 Mt CO_2 (Table 1). It should be noted that precision of storage capacity estimates for individual countries is different, depending on the availability of geological and geophysical data. Methodologies suggested by CSLF (2007) and US DOE (2007) were applied for calculations. Realistic (practical) storage capacity was assessed for Latvia, Lithuania and Poland that are constrained by detailed drilling and geophysical frameworks, while less precise effective capacity was estimated for Slovakia and the Czech Republic.

Depleted and depleting hydrocarbon fields of Lithuania, Poland and the Czech Republic have small potential, in the range of several years of CO_2 emissions (from 0.4 to 4 years), while no suitable HC fields were identified in Slovakia, Latvia and Estonia. Coal beds have even less potential. Capacity estimate in Poland and the Czech Republic is only 2.2 and 0.7 years respectively of the countries' emissions from large point sources.

Table 1

Total storage capacity of geological sinks and stationary emission rates of large sources (>0.1 Mt/y) of central European countries [Mt CO_2]

Saline aquifers	HC fields	Coal beds	CO_2 emissions from large sources
4677	804	469	309

The employment of HC and coal fields is considered as a prospective option if in combination with enhanced HC and methane recovery.

From practical point of view, storage of CO_2 in deep saline aquifers and depleted HC fields is considered as the near-future solution for reducing CO_2 emissions, while more advanced techniques should be developed for utilisation of coal seams.

The present study shows that Poland, the Czech Republic and Slovakia can use geological formations for storage of CO_2 emitted from key point sources located close to potential traps, whereas Latvia can use deep aquifers for storing all CO_2 emitted from major sources of that country. Moreover, it can provide storage space for neighbouring Lithuania and Estonia, that do not have suitable geological storage conditions. It is therefore concluded that geological storage of CO_2 can contribute significantly to the portfolio of emission reduction measures, providing thus the time required for development of more advanced, low-carbon technologies.

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