CO_2 Emissions and Geological Storage Options in Bulgaria

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Abstract. In CO_2 emissions inventory for Bulgaria are included all 42 large industrial sources (>0.1 Mt/year). The Energy sector gives the largest portion of country CO_2 emissions - 33.7 Mt/y or almost 65 %. The thermal power plants produced 25.3 Mt/y (48.5 %) and combined power & heating plants – 8.4 Mt/y (16.1 %). In the country there are 4 zones with a high concentration of industrial CO_2 sources and emissions - they produced totally 46 Mt/y CO_2 which equates to 88 % of all industrial CO_2 emissions.

The large presence of thick sedimentary succession and the high exploration rate of Northern Bulgaria are favourable preconditions for assessment of CO_2 storage opportunities and development of CO_2 storage activities. In Southern Bulgaria the sedimentary spreading is restricted in area and thickness and related with numerous small intra-mountain young basins.

The presented Bulgarian CO_2 storage capacity estimation is based on large data base, including mainly original seismic and borehole results, integrated with our knowledge on the subsurface and with a unified way of calculating the capacity in HC fields, aquifers and coal beds, accepted in the frame of EU GeoCapacity project.

The largest capacity of potential CO_2 storage options in Bulgaria related with aquifers, coal fields have considerably less opportunities, while the possibilities to use depleted hydrocarbon fields practically there are not.

The main problem for the CO_2 geological storage in Bulgarian is that the selected and estimated country storage options are located far from major CO_2 sources. Main storage capacities related to Northern Bulgaria, while the main concentrations of country industrial CO_2 emissions are mainly in Southern Bulgaria.

Key words: Bulgaria, CO_2 emissions, Geological storage options, Storage capacity

Introduction

Bulgaria is a small country in SE Europe - occupies 110 994 km^2 of territory on the Balkan Peninsula and has population about 8 millions. According to Kyoto Agreement ratified in 2002, Bulgaria is responsible to reduce CO_2 equivalent emissions with 8 % as compared to the base 1988 year, when were recorded 100.28 Mt/year. Reduction of 8 % means 8.02 Mt, so the Kyoto limit of 92.261 Mt/year CO_2 equivalent emissions should be achieved in the 2008 – 2012 period.

The industrial collapse in the country after democratic changes in 1990 has reduced significantly the produced CO2 emissions and they became vastly less than the fixed Kyoto limit. However, if the Government intentions to turn Bulgaria into energy centre on the Balkan Peninsula take place, the emissions from new build thermal power and industrial plants will increase significantly and may reach and exceed the Kyoto limit of 92 Mt/year.

The large presence of thick sedimentary succession in Bulgaria and the high exploration rate of Northern Bulgaria are favourable preconditions for assessment of CO_2 storage opportunities and development of CO_2 storage activities.

The first estimation of CO_2 storage capacity for Bulgaria was made as a part of the CASTOR project (2004-2005). This assessment has been updated, enlarged and elaborated in the frame of EU GeoCapacity project (2006-2008).

CO_2 emissions inventory

The industrial CO_2 emissions in Bulgaria from all 42 large point sources (>0.1 Mt/year) are 52.2 Mt/y (estimation in 2006). Total number of monitored combustion plants (CP) in the country is larger, about 130. However, most of them have yearly CO_2 emissions less then 0.1 Mt/y and their total CO_2 amount is not more than 4-5 % of annual industrial CO2 production in the country. Fig. 1 shows the distribution of all 42 large industrial CO_2 sources included in the estimation and the basic concentrations of CO2 emissions in Bulgaria.

Generally 7 industrial groups of CO2 emissions exist in the country. They are: I - Power (5 plants); II - Power & Heating (13 plants); III - Refineries (1); IV - Iron & Steel (4 plants); V - Cement (5 plants); VI - Ammonia & Chemicals (10 plants) and VII – Others, mainly lime & ceramics (4 plants). Their contribution to country CO_2 industrial emissions is seen from Fig. 2.

The Energy sector, incorporating the first two groups, gives the largest portion of country CO_2 emissions – 33.7 Mt/y or almost 65 %. The thermal power plants

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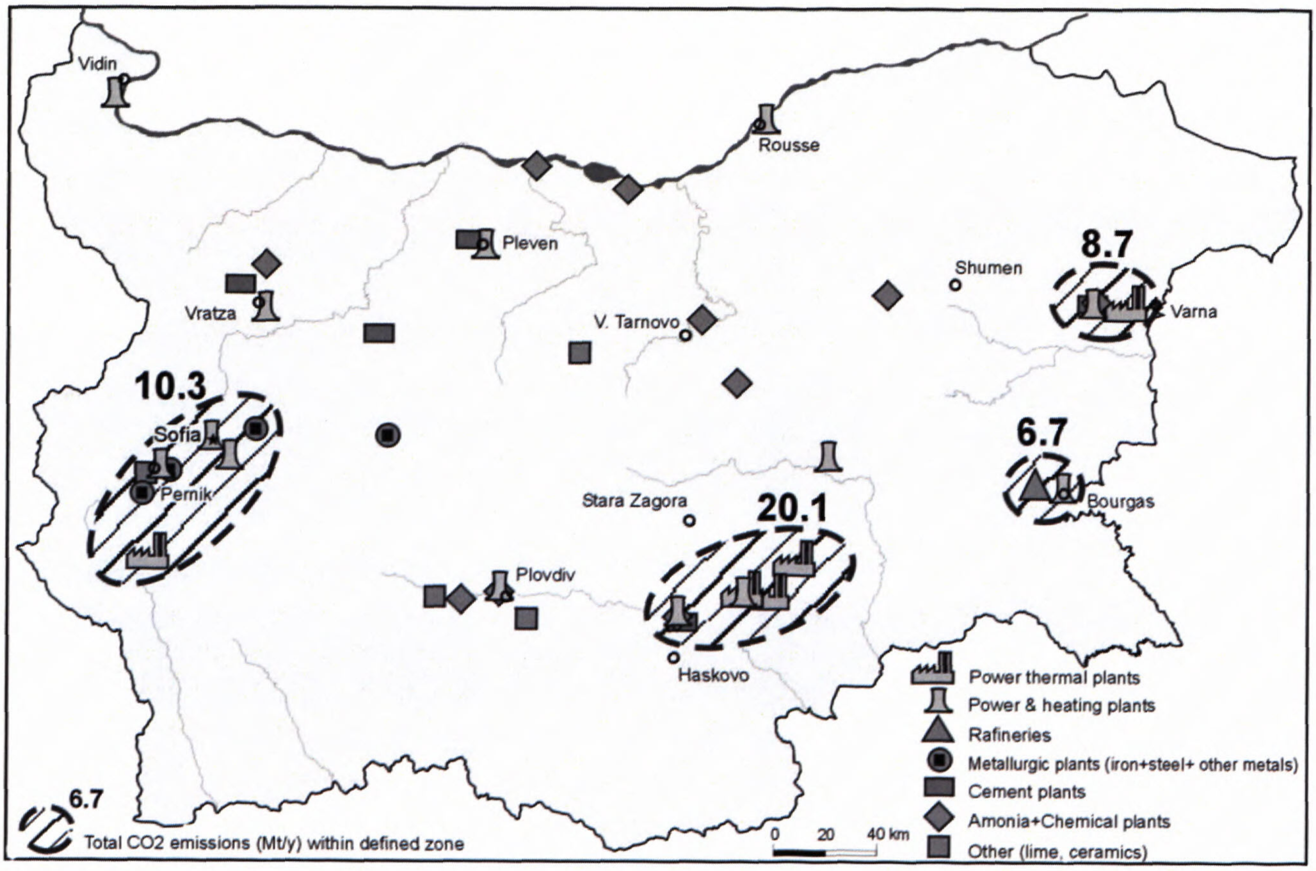

Fig. 1 Distribution of all large industrial CO_2 sources and basic concentrations of CO_2 emissions in Bulgaria.

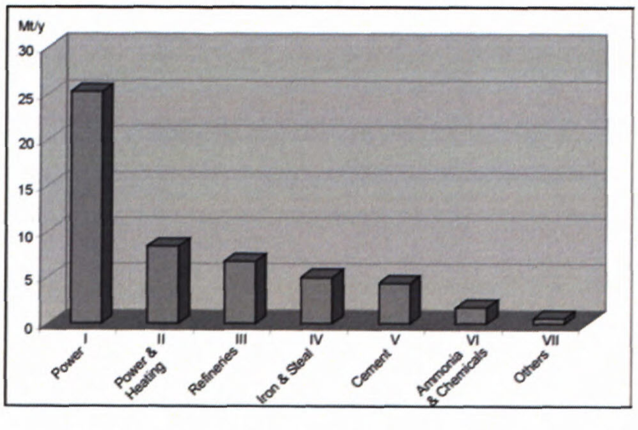

Fig. 2 Contribution of industrial groups to country CO_2 emissions.

produced 25.3 Mt/y (48.5 %) and combined power & heating plants – 8.4 Mt/y (16.1 %). For thermal power plants, the basic fuel is coal from local mines or imported, while the combined power & heating plants use mainly gas.

The largest CO_2 emitters in the country are all 5 thermal power plants, the refinery near to Bourgas and the steel plant near to Sofia (Fig. 1). They produced totally 36.7 Mt/y CO_2 or 70 % from country CO_2 industrial emissions.

In Bulgaria there are 4 zones with a high concentration of industrial CO_2 sources and emissions - they produced totally 46 Mt/y CO_2 which equates to 88 % of all country CO_2 emissions (Fig. 1). The highest CO_2 concentration (20.1 Mt/y or 38.5 %) is located in the middle of Southern Bulgaria and related with the largest producing coal field "Maritza East". This zone comprises 3 of the largest thermal power plants, as well as some other big industrial emitters. The other 3 zones related with Sofia–Pernik, Varna and Bourgas areas.

In general for the country the number of larger CO_2 emitters and the amount of produced CO_2 are much bigger in Southern Bulgarian (Fig. 1).

Geological settings

Bulgaria has an extensively varied and complex geological structure (Atanasov et al. 1984; Georgiev & Dabovski, 1997). Several major tectonic units are recognized, they are: Moesian platform, Alpine thrust-folded belt with Tertiary foredeep (named Kamchija depression), Sakar and Strandzha orogenic zones and a system of small syn- to post-orogenic Tertiary extensional basins (Figs 3, 4, 5, 6, 7). In addition, the offshore area covers and some parts of the western periphery of the Western Black Sea basin.

Two branches of Alpine orogenic belt and their foreland can be seen in Bulgaria (Fig. 3). The northern branch, represented by the Balkanides (Balkan and Forebalkan), crosses the country in the middle from west to east; Moesian platform is foreland. The southern branch comprises the Kraishtides, Srednogorie and Rhodope massif and could be considered as a pre-Alpine basement of the Balkanides (Georgiev & Dabovski, 1997).

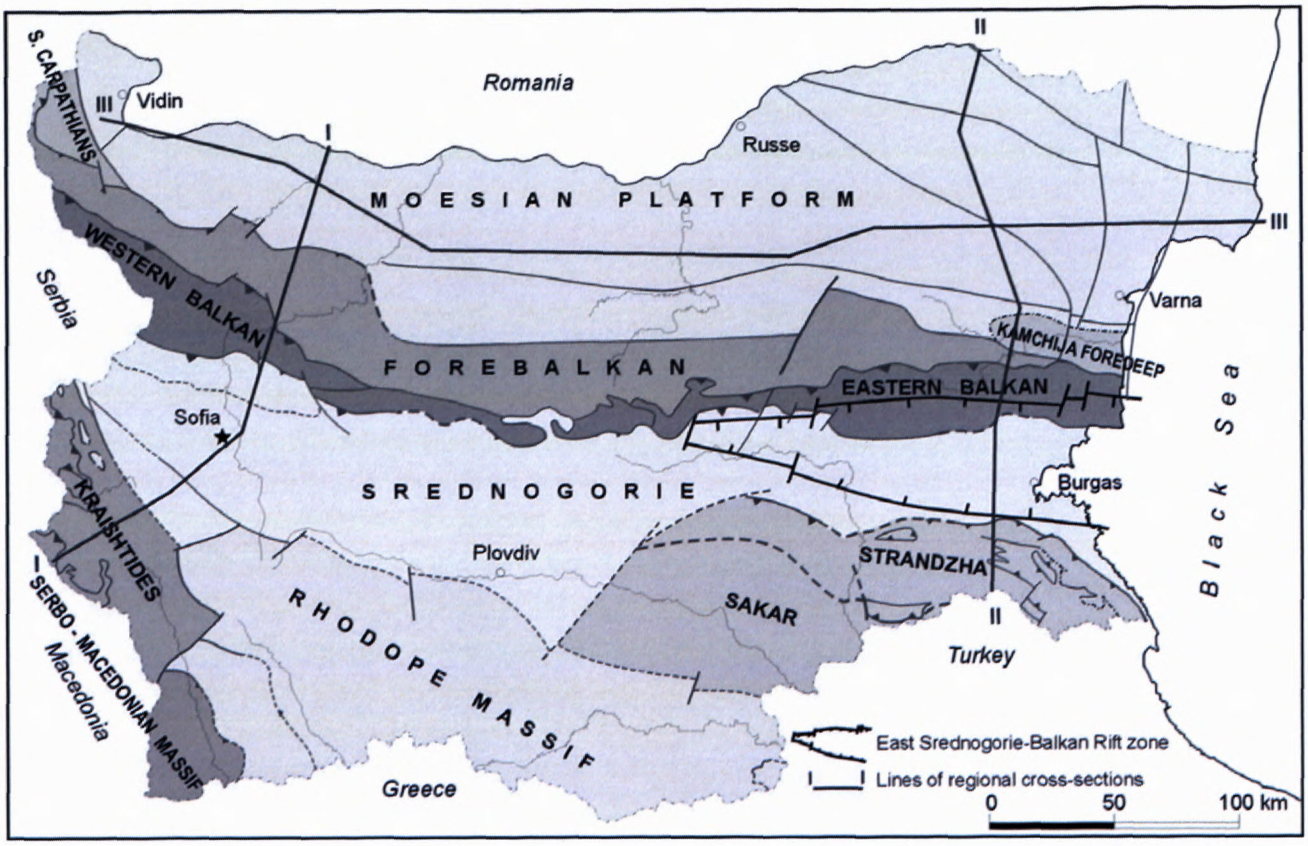

Fig. 3 Major tectonic units in Bulgaria (by Georgiev & Dabovski, 1997 – modified).

The Moesian Platform, which southern part extended in Northern Bulgaria, forming the foreland of the Balkan thrust-folded belt, is composed of up to 4-5 km thick relatively un-deformed, dominantly shallow-marine Mesozoic sediments, that rest on a gently folded Palaeozoic basement (Figs 4, 5, 6, 7). Totally, the Phanerozoic sedimentary succession in Moesian platform has a thickness of 4-13 km. Major unconformities, occurring at the base of the Triassic, Jurassic, Upper Cretaceous and Eocene (Fig. 8), are related to major compressional events within the Alpine thrust belt.

Five sedimentary zones (tectonic units) with increased sedimentary thickness are present in Bulgarian part of Moesian platform (Fig. 4):

- The Southern Moesian platform margin (SMPM) subsided with accelerates rates during the Jurassic-Early Cretaceous time (Figs 5, 6, 8).
- The Lom basin has a similar evolution as SMPM, but the accelerate subsidence in it continuing during the Tertiary also (Figs 3, 4, 5). By these features the Lom basin is considered lately as a westernmost zone of SMPM (Georgiev & Dabovski - 1997).
- The Alexandria basin, which small SE part is spread in Bulgaria, developed during the Middle-Late Triassic.
- The Varna basin actually represent the eastern slope of North Bulgarian arch, which was involved in accelerate subsidence mainly during the Triassic and Late Cretaceous – Tertiary (Figs 4, 7).
- The Kamchija basin corresponds to a post-Middle Eocene foredeep that is filled with late Eocene-Oligocene and Neogene clastics and clays. Towards the East, this foredeep deepens and merges offshore with the Western Black Sea basin.

The northern branch of Alpine orogenic belt (Balkan–Forebalkan) consists of a stack of dominantly north-verging thrust sheets (Figs 3, 5, 6), formed during long displaying multiphase compression, which began in the Late Triassic and culminated toward the end of the Early Cretaceous and to the end of the early Middle Eocene (Georgiev & Dabovski, 1997).

The Balkan (Stara Planina) thrust-folded belt is a major tectonic unit in Bulgaria, which is a comparatively narrow stripe, consisting of strongly folded and northward over-thrusted Mesozoic and early Tertiary sediments (Figs 3, 5, 6). The Western Balkan is composed mainly by Paleozoic and Triassic mixed sedimentary, metamorphic and magmatic sequences, the tectonic style is higher (Figs 3, 5). While, in the Eastern Balkan dominated the Upper Cretaceous and Paleogene sedimentary sequences, the tectonic style is lower (Figs 3, 6, 8).

The Forebalkan is the northernmost unit of the Northern Alpine orogenic belt, through which the structural transition between Balkan and Moesian platform takes place (Figs 3, 5, 6). Tectonically this unit is closer to Balkan, only it has lower style. However, by sedimentary succession it is closer to Moesian platform, what means that it is the southernmost strip of SMPM, which is folded by northward-directed orogeny in the Balkan. A series of en-echelon narrow folds were thrust over the SMPM.

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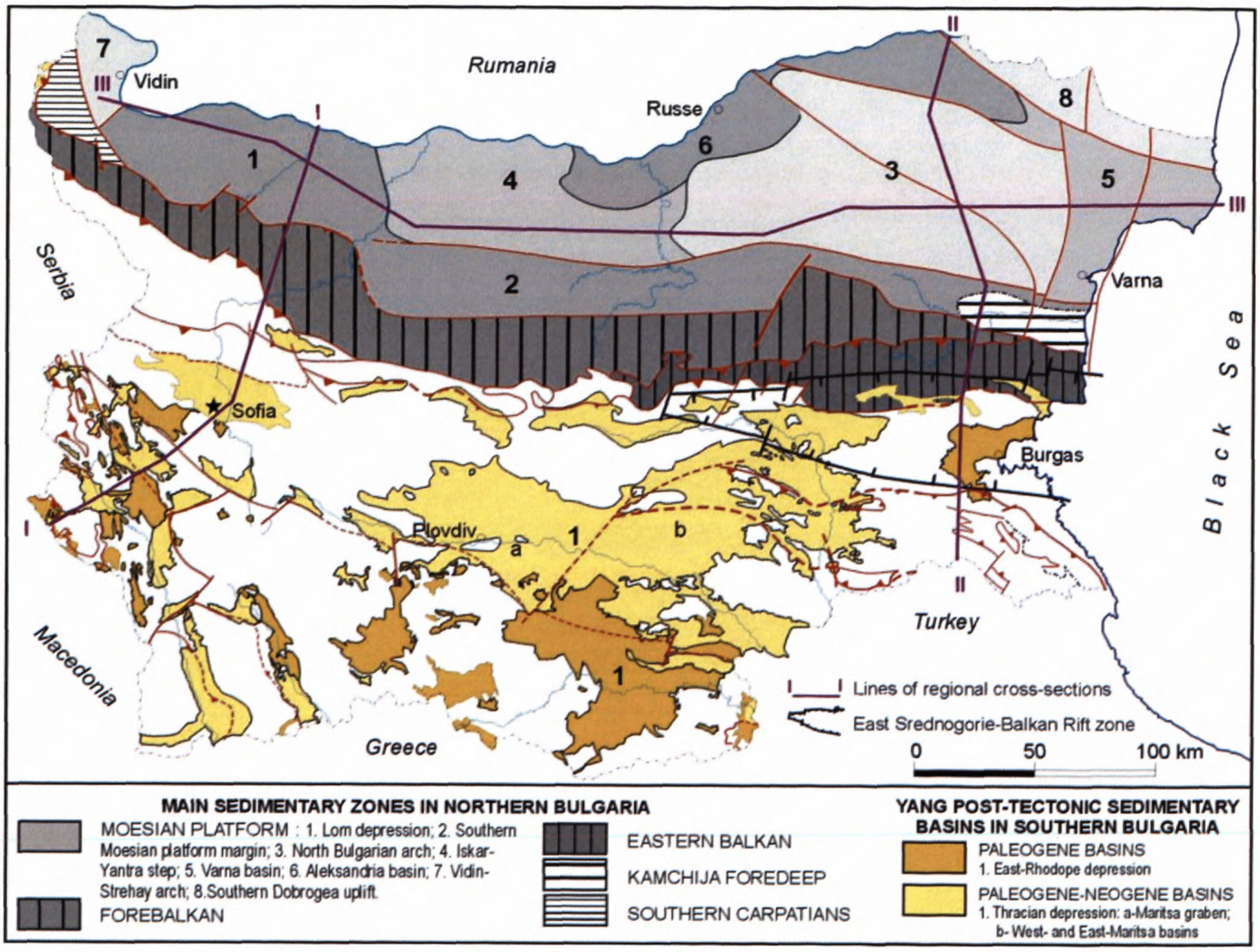


Fig. 4 Main sedimentary basins and zones in Bulgaria (composed by Georgiev & Dabovski, 2007 – no published).

In the Forebalkan are distinguished three longitudinal units by differences in sedimentary succession, tectonic and morphologic features (Georgiev et al., 1993). They are separated by transverse oriented small depressions. The Western Forebalkan is typical post-platform orogen (Bokov, 1968), made-up during the Illyrian tectonic phase in Middle Eocene. In the Central Forebalkan a very thick (up to 3 km and more) Upper Jurassic flysch sequence controlled the thrust-tectonic processes in Mid Cretaceous (Austrian phase) and Middle Eocene (Illyrian phase). Eastern Forebalkan is structurally shaped by salt tectonics during mainly the Mid Cretaceous (Austrian phase) in the Upper Triassic evaporates, thick above 1000 m (Georgiev, 1996).

The Rhodope Massif is dominating by high-metamorphic and magmatic rocks. Recent concepts consider it to be made up of several overlapping nappes.

The Srednogorie is separated from the Balkanides to north and from the Rhodope Massif to south by Early Alpine wrench and normal faults. This zone contains two large groups of rocks: the lower one consists mainly of metamorphics (amphibolites, gneisses, gneisses, marbles), the upper one consists of rhythmic volcano-clastic sequences and molasses thick of over 3000 m.

The zone of Kraishtides belongs to southern Alpine orogenic branch in Bulgaria. It is considered by many Bulgarian geologists as a lineament of high ranking folding, wrenching and faulting. This zone is one of the most seismically active on the Balkan Peninsula.

The Strandzha unit is the southernmost, topmost basement-cover nappe of Eastern Bulgaria. Its basement is composed of Precambrian high-grade and Palaeozoic low-grade metamorphic rocks. The sedimentary cover comprises Triassic platform carbonates and Lower-Middle Jurassic sandy-calcareous and shaly-silty series (autochthonous), which are topped by slices of exotic nappes, consisting of Palaeozoic and Triassic deposits (allochthonous).

In Southern Bulgaria the sedimentary spreading is restricted in area and thickness and related with numerous small intra-mountain young basins in the Srednogorie zone, between the Kraistides and the Rhodope and in the Rhodope zone (Figs 4, 5, 6). Only Thracian depression is larger in spreading and sedimentary thickness, which exceeds 800–1000 m in some parts of Maritsa graben and West-Maritsa basin.

In the *East Srednogorie – Balkan rift zone* the thickness of sedimentary succession grow vastly (Figs 4, 6, 8), because several spatially superimposed rift basins developed during the Permian-Early Triassic, Early Jurassic, Late Jurassic (?) and Late Cretaceous (Georgiev et al., 2001).

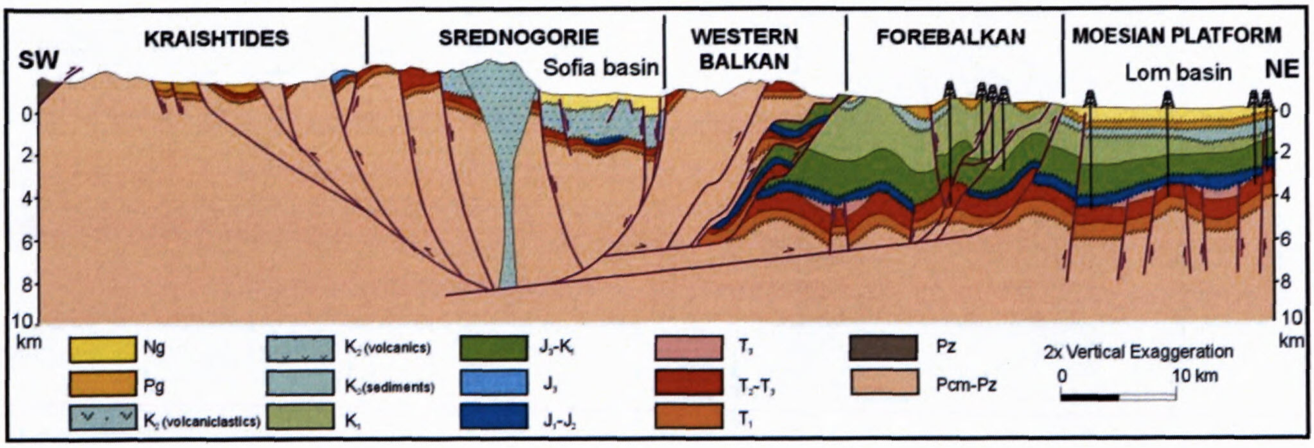


Fig. 5 Regional geological cross-section along line I-I (Figs 3 and 4), giving an overview for the differences in geological structure and sedimentary spreading in western part of Northern and Southern Bulgaria (Georgiev & Dabovski, 2004 in Cavazza et al.–eds., 2004).

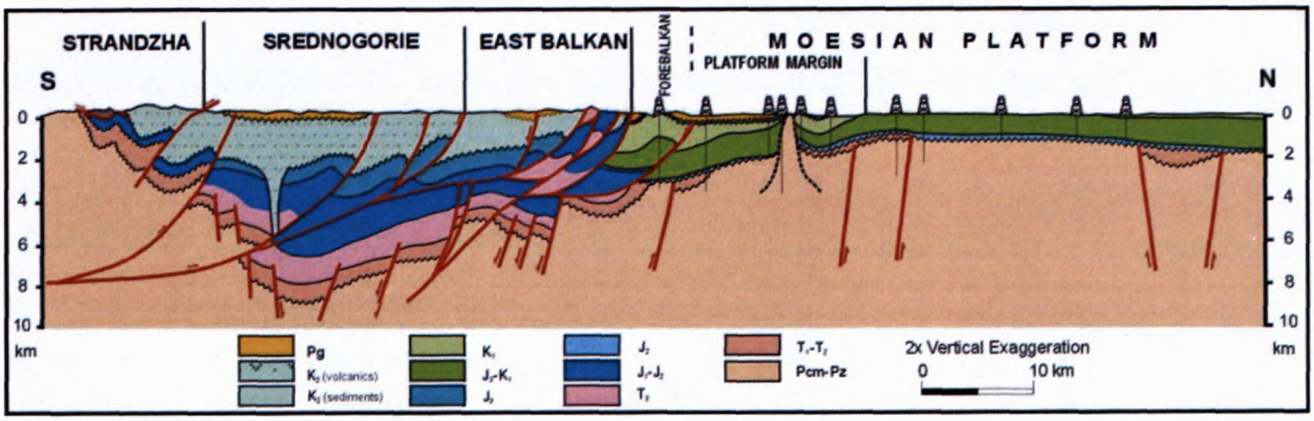


Fig. 6 Regional geological cross-section along line II-II (Figs 3 and 4), giving an overview for the differences in geological structure and sedimentary spreading in eastern part of Northern and Southern Bulgaria (Georgiev et al., 2001).

The Bulgarian offshore covers the easternmost fragments of Moesian platform and Balkanides, as well the western periphery of the Western Black Sea basin and of the young Tertiary Bourgas basin. Most of them have promising sedimentary features for local and zonal spreading of deep saline aquifers.

The seismicity of Bulgarian territory is shown by Fig. 9. The made seismic zoning (Bonchev et al. 1982) is based on a large range of initial geological, geophysical, seismological and other necessary information. The evaluation of seismicity was made by the ability to produce earthquakes of different energetic level depending on the character and intensity of tectonic processes, as well taking in mind the distribution and magnitude of recorded earthquakes.

The expected seismic source zones (SSZ) (Fig. 9) are traced through extrapolation along the earthquake sources of a given magnitude interval, along the zones of the lineaments. Furthermore, they extend also along the intersecting lineament up to the point of its next intersection, within the contour and depth of active layer. It may be assumed that such approach gives the most accurate estimation of expected SSZ on Bulgarian territory.

Recent and current volcanic activity on Bulgarian territory is not marked. However, several stages of volcanic activity in geological evolution were recorded in sedimentary succession. Volcanic manifestation is marked in Late Permian – Early Triassic, Late Cretaceous (Turonian-Santonian), Paleogene (Eocene-Oligocene) and Neogene (by basalt intrusions).

Estimation of CO_2 Geological Storage options

The industrial CO_2 emissions can be captured, transported and stored in suitable underground storage reservoirs. The most promising options to store CO_2 in geological formations are: in empty (depleted) oil and gas fields; in aquifers (deep saline water bearing layers) and in un-mined coal seams.

The presented Bulgarian CO_2 storage capacity estimation (Table 1) is based on large data base, including mainly original seismic and borehole results, integrated with our knowledge on the subsurface and with a unified way of calculating the capacity in HC fields, aquifers and coal beds, accepted in the frame of EU GeoCapacity project.

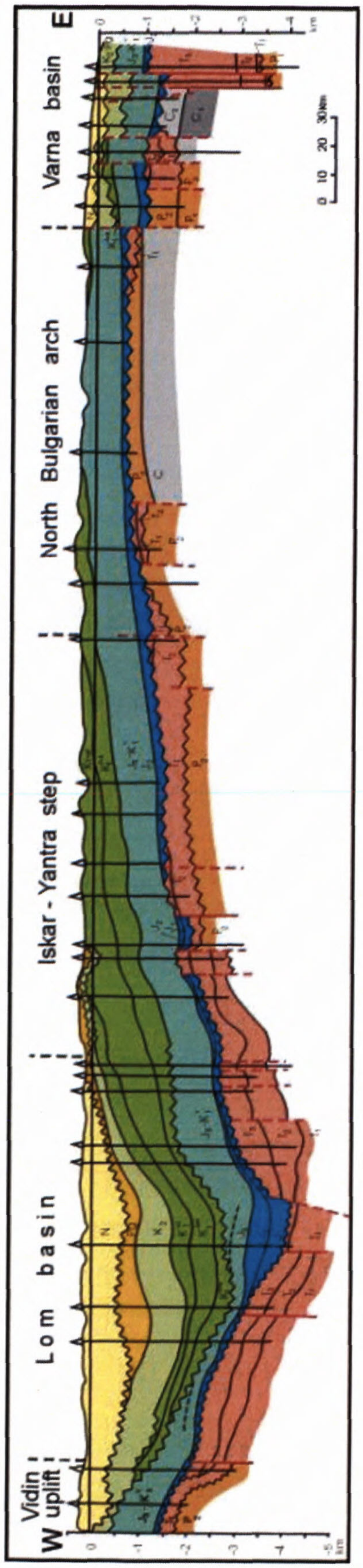


Fig. 7 Regional geological cross-section along line III-III (Figs 3 and 4), giving an overview for the Mesozoic-Tertiary sedimentary thickness variations in the Moesian platform (by Kalinko, ed., 1976 - updated).

Table 1. Capacity of potential CO_2 storage options in Bulgaria

Options	Storage capacity in Mt
Depleted hydrocarbon fields	6
Deep saline aquifers	2660
Coal seams	27
total	**2693**

In Hydrocarbon fields

The estimation of CO_2 storage capacity in Bulgarian hydrocarbon fields is based on evaluation of all discovered 12 economic fields (Fig. 10). However most of them are out of right depth interval for effective CO_2 storage, which is 800 – 2500 m. Only in two gas fields, respectively Tchiren and Galata, the depth window for the reservoirs is favorable. But Tchiren field was converted into sub-surface gas storage in 1974 and still operating.

So, only Galata gas field (located offshore) was considered for estimation of CO_2 storage capacity. Nevertheless that this field is small, it suggests good opportunities for CO_2 storage (excellent reservoir parameters and depth). However there is a big interest for conversion of this field after depletion into sub-surface gas storage.

The storage capacity of the gas fields has been estimated assuming a 1:1 volumetric replacement ratio between hydrocarbons and CO_2. The CO_2 density varies with depth as a function of pressure and temperature and has been estimated using diagrams.

In Aquifers

Aquifers or deep saline water bearing layers offer enormous CO_2 storage potential, because they usually have larger spreading and good reservoir qualities. Important requirement to them is to have effective seals, presented by no permeable geological formations.

The presence of reservoir strata, horizons and levels in sedimentary succession of main tectonic units in Bulgaria is pictured in Fig. 8. Generally speaking, in the sedimentary successions of different basins and zones (Fig. 4) dominated not-permeable and semi-permeable formations and the presence of reservoir strata, horizons or levels is usually with local or zonal spreading.

The assessment of aquifers and their potential for CO_2 storage in Bulgaria was made after detailed study and analyses of:

- the presence of appropriate lithology for good reservoirs;
- the presence of favourable seismic facieses;
- the received amount of fluid flow during the tests in the boreholes;
- the presence of negative anomaly in SP log curve;
- the mud circulation louse during the drilling (mud engulf);
- the lab analyses of reservoir parameters porosity and permeability;
- the buried depth of reservoir formations – is it effective for CO_2 storage?

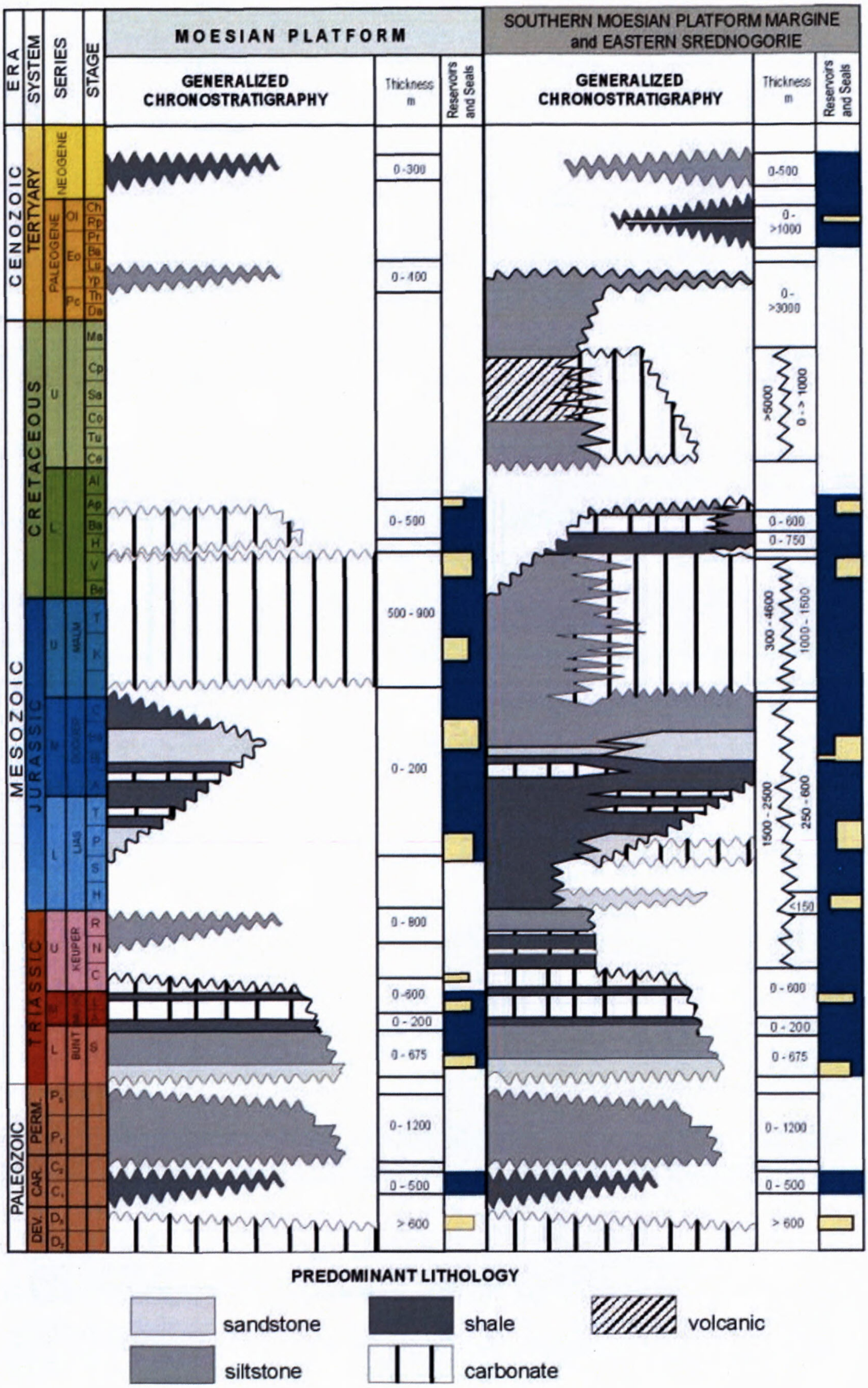


Fig. 8 A schematic Litho-Stratigraphic chart for sedimentary succession in the Moesian platform, Southern platform margin and Eastern Srednogorie-Balkan zone with reservoir / seal distribution (Georgiev & Dabovski, 2000 - improved).

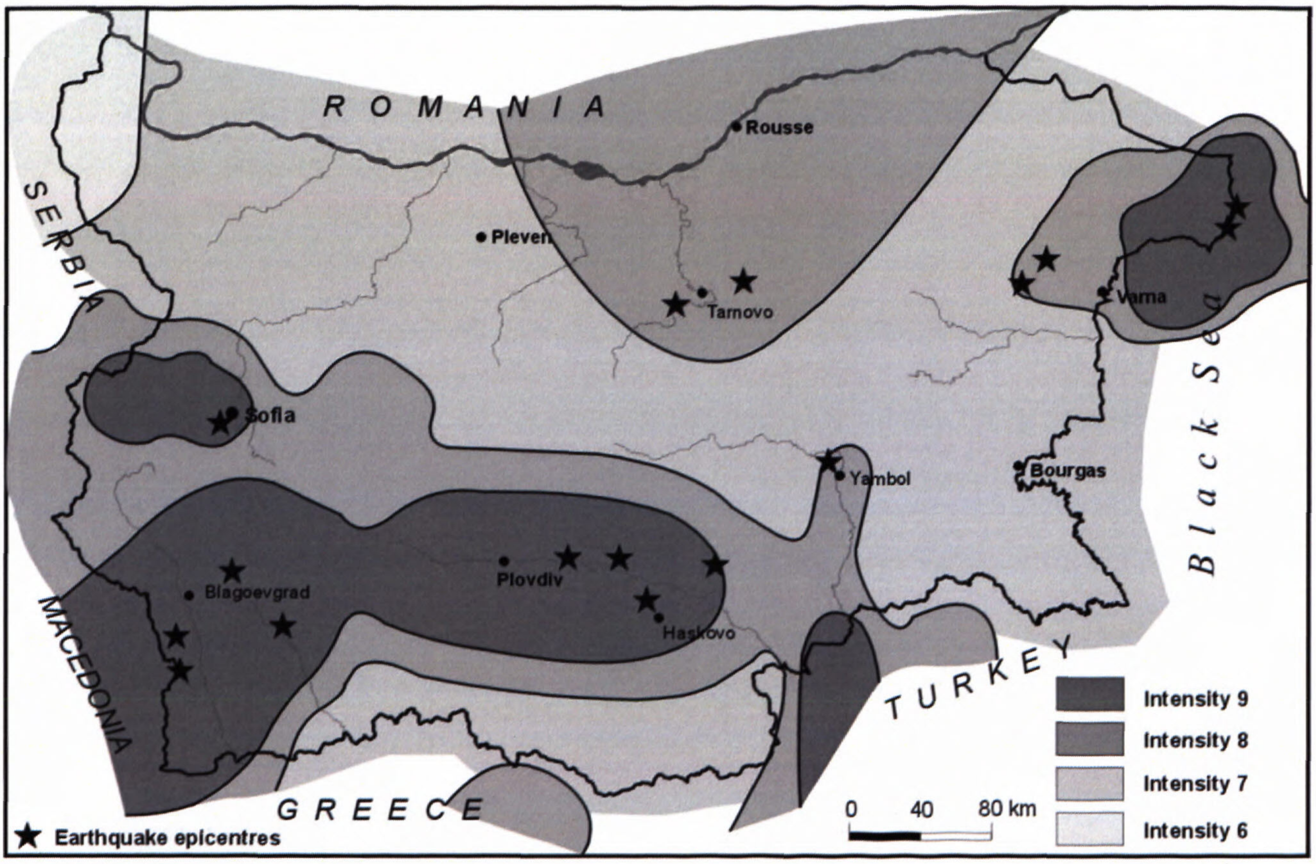
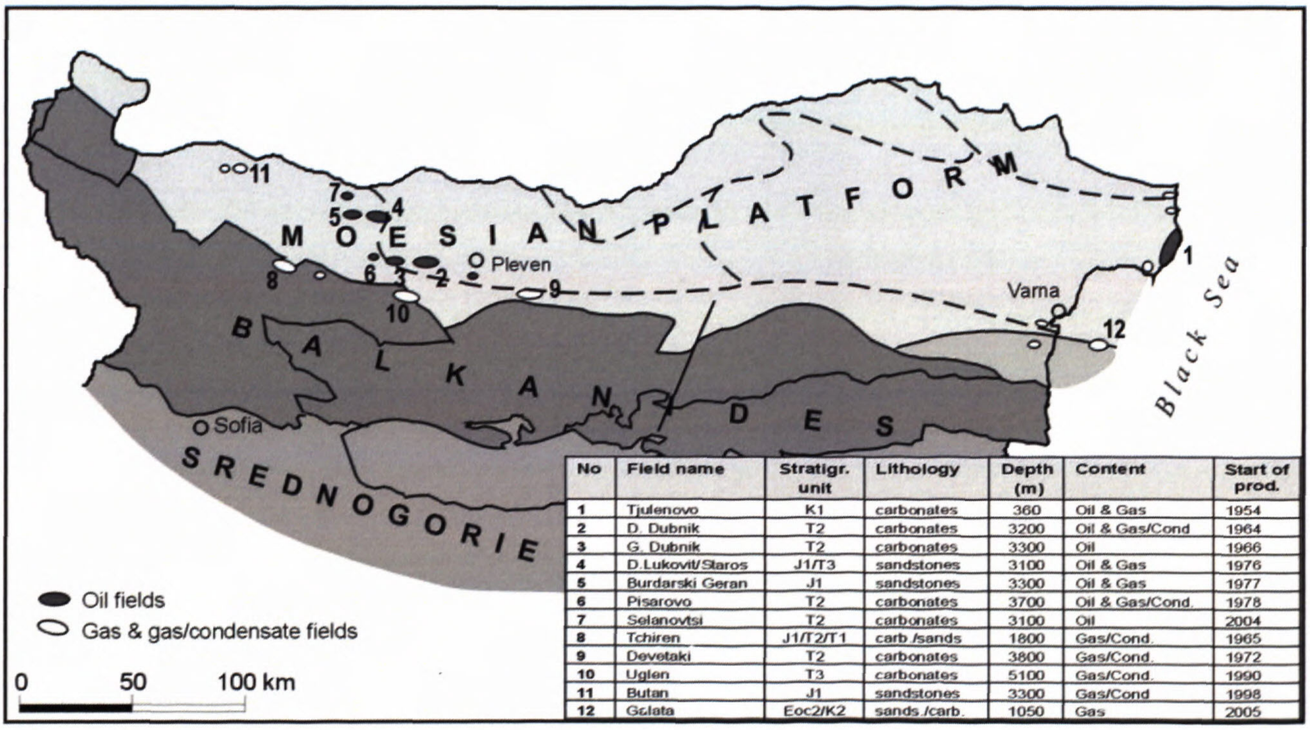


Fig. 9 Recorded stronger earthquakes and prognosis seismic intensity (by MSC-64) in Bulgaria (by Bonchev et al., 1982 – modified and updated).



No	Field name	Stratigr. unit	Lithology	Depth (m)	Content	Start of prod.
1	Tjulenovo	K1	carbonates	360	Oil & Gas	1954
2	D. Dubnik	T2	carbonates	3200	Oil & Gas/Cond	1964
3	G. Dubnik	T2	carbonates	3300	Oil	1966
4	D.Lukovit/Staros	J1/T3	sandstones	3100	Oil & Gas	1976
5	Burdarski Geran	J1	sandstones	3300	Oil & Gas	1977
6	Pisarovo	T2	carbonates	3700	Oil & Gas/Cond.	1978
7	Selanovtsi	T2	carbonates	3100	Oil	2004
8	Tchiren	J1/T2/T1	carb./sands	1800	Gas/Cond.	1965
9	Devetaki	T2	carbonates	3800	Gas/Cond.	1972
10	Uglen	T3	carbonates	5100	Gas/Cond.	1990
11	Butan	J1	sandstones	3300	Gas/Cond	1998
12	Galata	Eoc2/K2	sands./carb.	1050	Gas	2005

Fig. 10 Summary of Bulgarian economic hydrocarbon fields.

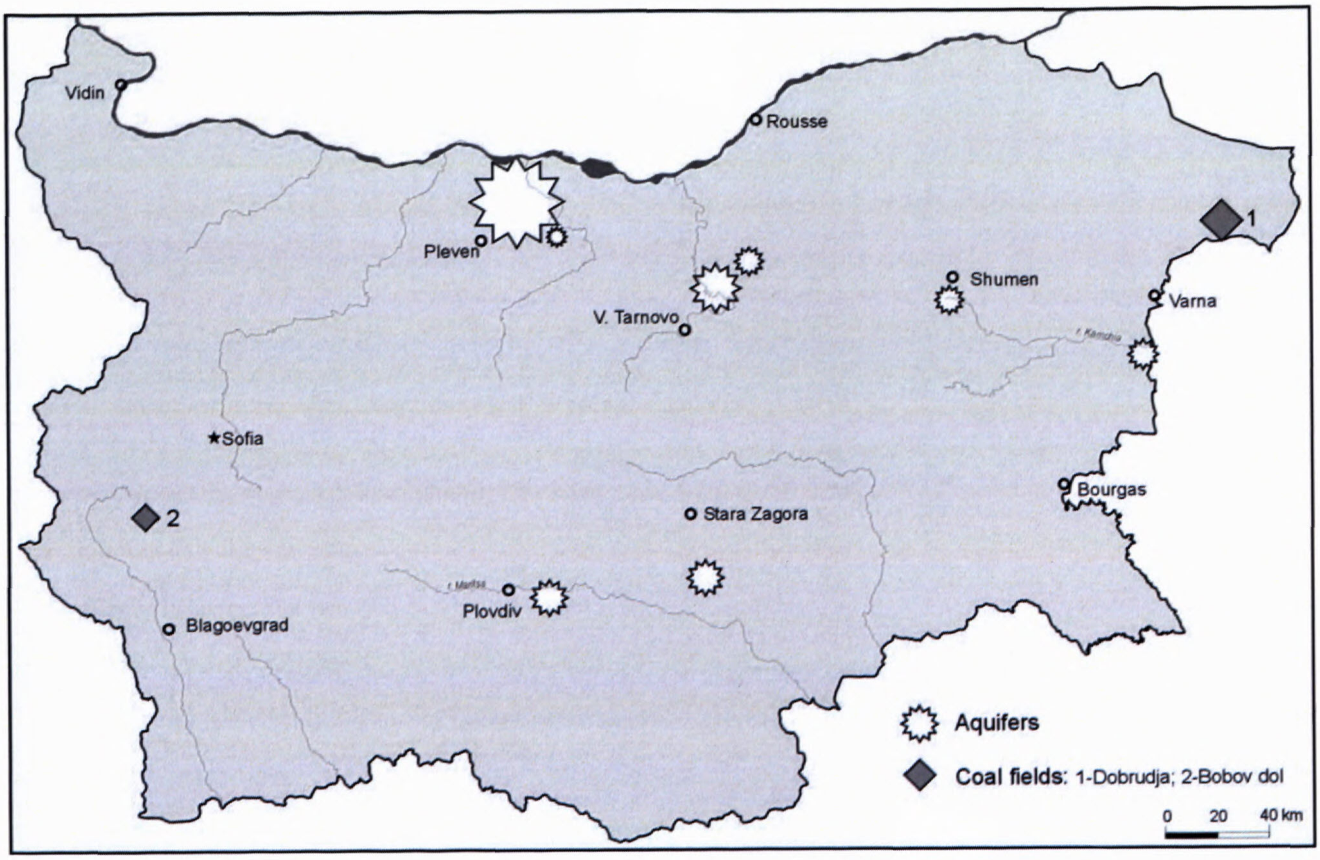


Fig. 11 Location of selected and estimated aquifers (zonal and structural) and coal fields in Bulgaria.

Volumetric storage capacity was calculated using methodology of Brook at al., 2003 and Bachu et al., 2007, accepted in EU GeoCapacity project, expressed by the formula:

$$\mathbf{M_{CO2} = A \times h_{ef} \times \phi \times \rho_{CO2} \times S_{eff}}$$

where:

M_{CO2} - storage capacity within a geological structure
A - area of aquifer
h_{ef} - effective thickness of aquifer reservoir
ϕ - reservoir porosity
ρ_{CO2} - CO_2 density at reservoir conditions
S_{eff} - storage efficiency factor

The most promising potential for CO_2 storage in Bulgaria related with some karstified and fractured carbonate reservoirs in the Devonian and Upper Jurassic – Valanginian, and some coarse-grained clastic reservoirs in the Lower Triassic, Middle Jurassic and Middle-Upper Eocene stratigraphic units (Fig. 8). All they were proved by received results from numerous drilled oil and gas exploration wells.

The evaluation of CO_2 storage capacity in deep saline aquifers in Bulgaria is based on estimation of 2 individual structures and 6 local zones, shown on Fig. 11. They related respectively with Devonian, Lower Triassic, Middle Jurassic, Upper Jurassic - Valanginian and Middle-Upper Eocene reservoirs (Fig. 8). Six of selected aquifers are located in Northern Bulgaria, other two in Southern Bulgaria.

In Coal seams

Most of un-mined coal reserves in Bulgaria occur at shallow depth, no favorable for safety injection of CO_2. Deeper occurrence of coal-bearing formations (>800 m), suitable for CO_2 storage, exists only in two fields - Dobudja and Bobov Dol (Fig. 11). In GeoCapacity project was made first evaluation of geological conditions in order to estimate CO_2 storage feasibility and capacity in coal seams within these two fields.

The CO_2 storage capacity in coal field (S) is a function of PGIP (producible gas in place), CO_2 (gas) density and CO_2 to CH_4 exchange ratio (ER) (Bergen & Wildenborg, 2002):

$$S = PGIP \times CO_2 density \times ER$$

CO_2 storage capacity ***S*** denotes quantity of CO_2 which could replace PGIP, to the extent specified by ER (hard coal has usually the ratio of about 2, brown coal and lignite may have higher ratios).

PGIP means coal bed methane reserves for CO_2-Enhanced Coal-Bed Methane Recovery with the use of CO_2 storage.

Main conclusions

The largest capacity of potential CO_2 storage options in Bulgaria related with aquifers, coal fields have considerably less opportunities, while the possibilities to use depleted hydrocarbon fields practically there are not.

The duration of the estimated CO_2 storage country capacity (Table 1) with regard to annual industrial CO_2 emissions (if they save the level from 2006 - 52.2 Mt/y), is for more than 50 years.

The main problem for the geological storage of Bulgarian industrial CO_2 emissions is that the selected and estimated country storage options are located far from major CO_2 sources. Main storage capacities related to Northern Bulgaria, where the sedimentary succession is thick several kilometers and aquifers with limited spreading (structural and zonal) are present. However, the main concentration of industrial CO_2 is mainly in Southern Bulgaria, where the storage capacities are considerably less.

Some of the selected and estimated geological CO_2 storage options, as both coal fields and aquifers near to Plovdiv and V. Tarnovo (Fig. 11) are located in zones with heightened seismicity (Fig. 9), which made them risky in some extent.

The selected and estimated geological CO_2 storage options need further investigations and qualification based on: (1) larger utilization and deeper analyses of available wells and seismic information and (2) some new seismic data and wells.

The presented estimation of geological CO_2 storage options can be characterized as a slightly conservative, because some of the used values for some calculative parameters are a little bit less than expected. So, in further development of investigations and qualification of selected options there are real opportunities for increasing of national CO_2 geological storage potential.

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