

## Annex B: Selection of geothermal areas

### 1. Geological, Hydrogeological and Geothermal Framework of Bulgaria

#### 1.1 Geology

The territory of Bulgaria covers parts of two major geologic domains: the northern part of the Alpine orogenic belt in the Balkans, and its foreland constituted by the Moesian platform in northern Bulgaria (Figure 1).

The Alpine orogenic belt consists of dominantly north-verging thrust sheets and fold structures formed through multiple compressional events in Late Triassic, mid-Jurassic, mid-Cretaceous, Late Cretaceous, and mid-Eocene times, followed by crustal extension, collapse of the orogen, and development of Cenozoic intra-orogenic basins.

Two orogenic systems can be distinguished within the Alpine belt across the territory of Bulgaria: the Carpathian and the Balkan systems. The Carpathian orogenic system mostly underlies a thick cover of Neogene and Quaternary deposits and is poorly exposed only in northwesternmost Bulgaria (Zagorchev et al., 2009). The Balkan orogenic system occupies a large part of the Bulgarian territory between the Moesian platform and the Carpathian orogenic system to the north, and the Vardar zone to the southwest and south. It is subdivided into three main tectonic zones: Balkan, Srednogie, and Morava-Rhodope (Figure 1)

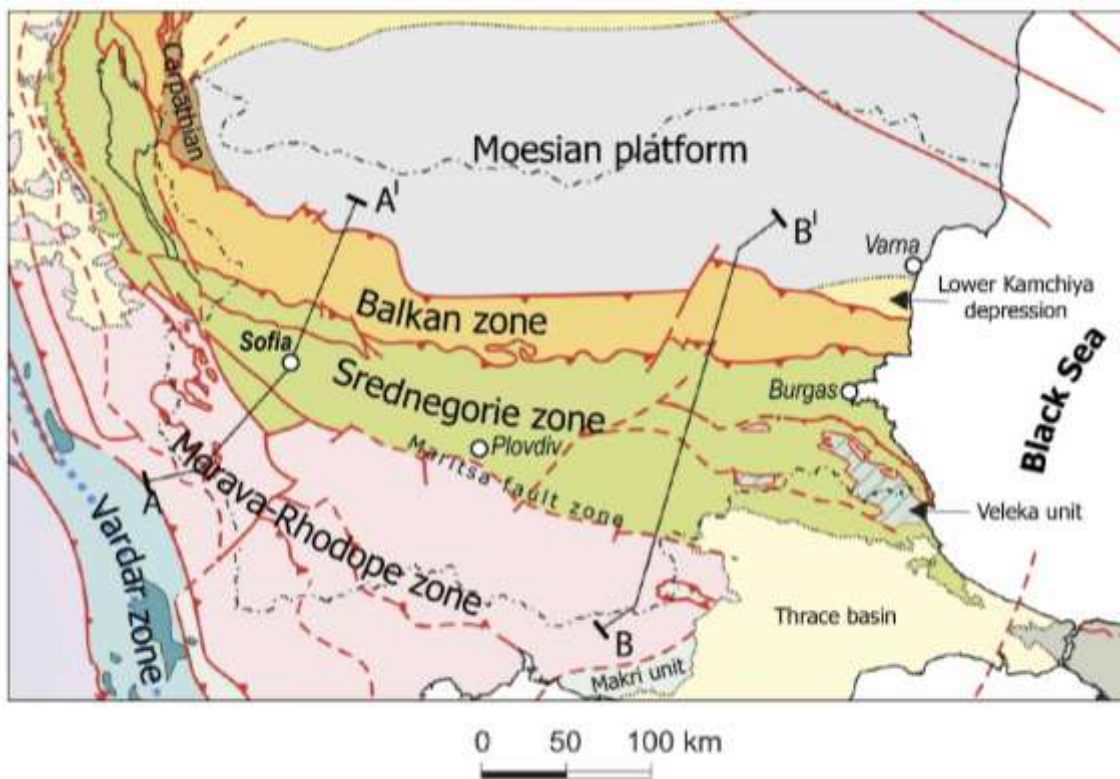


Figure 1- Tectonic scheme of the central part of the Balkan Peninsula (from Zagorchev et al., 2009). See sections A-A' and B-B' in Figure 2 and 3).

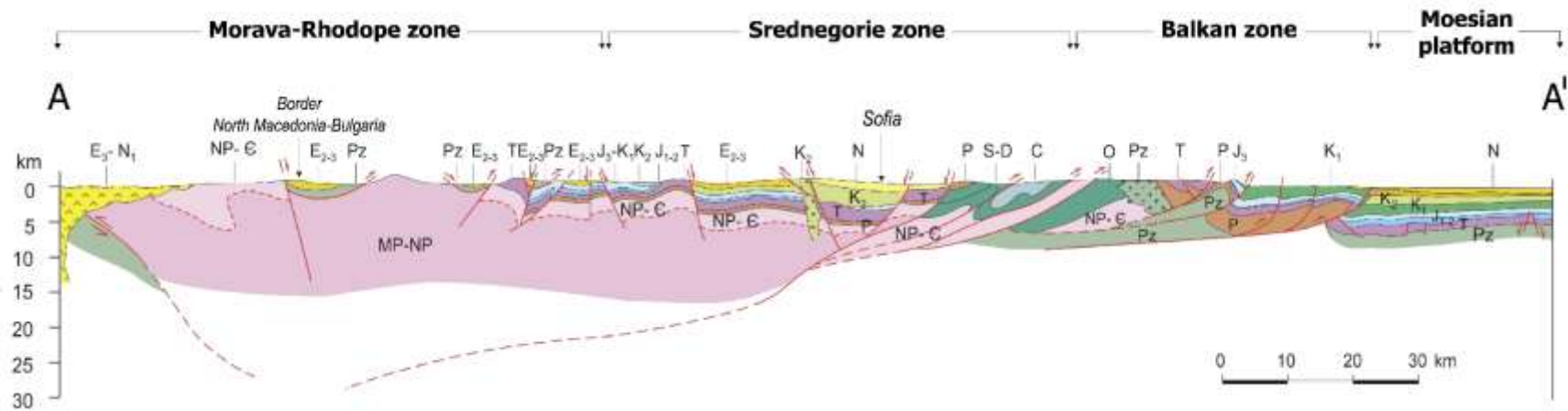


Figure 2- Section A-A' through western Bulgaria (from Zagorchev et al., 2009).

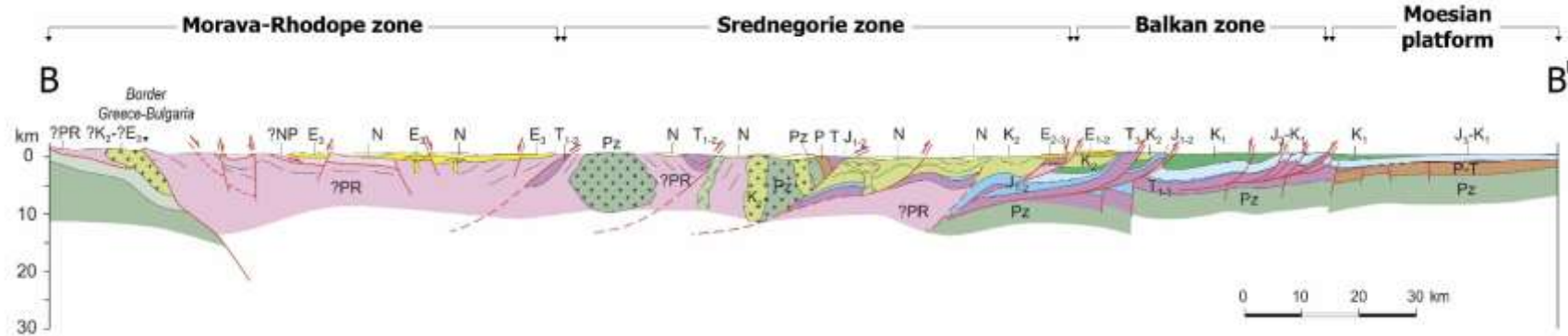


Figure 3- Section B-B' through eastern Bulgaria (from Zagorchev et al., 2009).

The Balkan zone forms the external northern parts of the Alpine orogen. Its northern boundary is represented by a complex system of flexures and north-verging thrusts that override the Moesian platform. The southern boundary of the Balkan zone, with the Srednogorie zone, is likewise a system of north-verging mid-Eocene reverse faults and thrusts, largely covered by Cenozoic deposits. According to Zagorchev et al. (2009), the typical features of the Balkan zone are: (1) wide occurrence of Triassic and Jurassic-Lower Cretaceous platform carbonates overriding from the Moesian platform; (2) development of Upper Jurassic-Lower Cretaceous and Upper Cretaceous-Palaeocene flysch associations; (3) almost full absence of Mesozoic magmatic products; (4) main and final compressional events towards the end of the Middle Eocene, preceded by Late Cretaceous, mid-Cretaceous and weak Triassic deformations.

The Srednogorie zone occupies the central and southeastern parts of Bulgaria. Its northern boundary with the Balkan zone is traced by north-verging mid-Eocene reverse faults and thrusts, while its southern boundary with the Morava-Rhodope zone is defined by a system of faults known as the Maritsa fault zone (Figures 1, 2, and 3). This zone is divided into three main segments: western, central, and eastern, differentiated by their tectonic evolution (

Figure 4). Despite these differences, the Srednogorie zone shows common geological and structural features, such as: (1) the basement is represented by Precambrian metamorphic rocks locally covered by a Neoproterozoic-Cambrian diabase-phyllitoid complex, and Palaeozoic metasediments and metavolcanics; (2) wide distribution of Mesozoic sediments, particularly Upper Cretaceous volcano-sedimentary succession; (3) presence of Palaeozoic granitoid plutons; (4) large areas of the Srednogorie zone are covered by Cenozoic deposits.

The Morava-Rhodope zone includes several tectonic units, such as the Struma, Morava, Pirin-Pangaion, Ograzhden, Rila-Rhodope, and Mandritsa-Makri (

Figure 4). Although these units had a relatively independent pre-Late Cretaceous tectonic evolution, Zagorchev et al. (2009) unified them into one main zone due to the following common characteristics: (1) widely exposed high-grade metamorphic basement complexes, as typically occur in internal parts of orogenic belts; (2) frequent Late Cretaceous and Tertiary intrusive bodies; (3) development of isolated Palaeogene basins filled by continental and shallow marine sediments and felsic-intermediate volcanic rocks; (4) main mid-Cretaceous compressional deformations followed by Late Cretaceous-Tertiary extension; (5) thickened continental crust (50-52 km) in the central parts of the zone, thinning to 34-37 km in SE and NW direction.

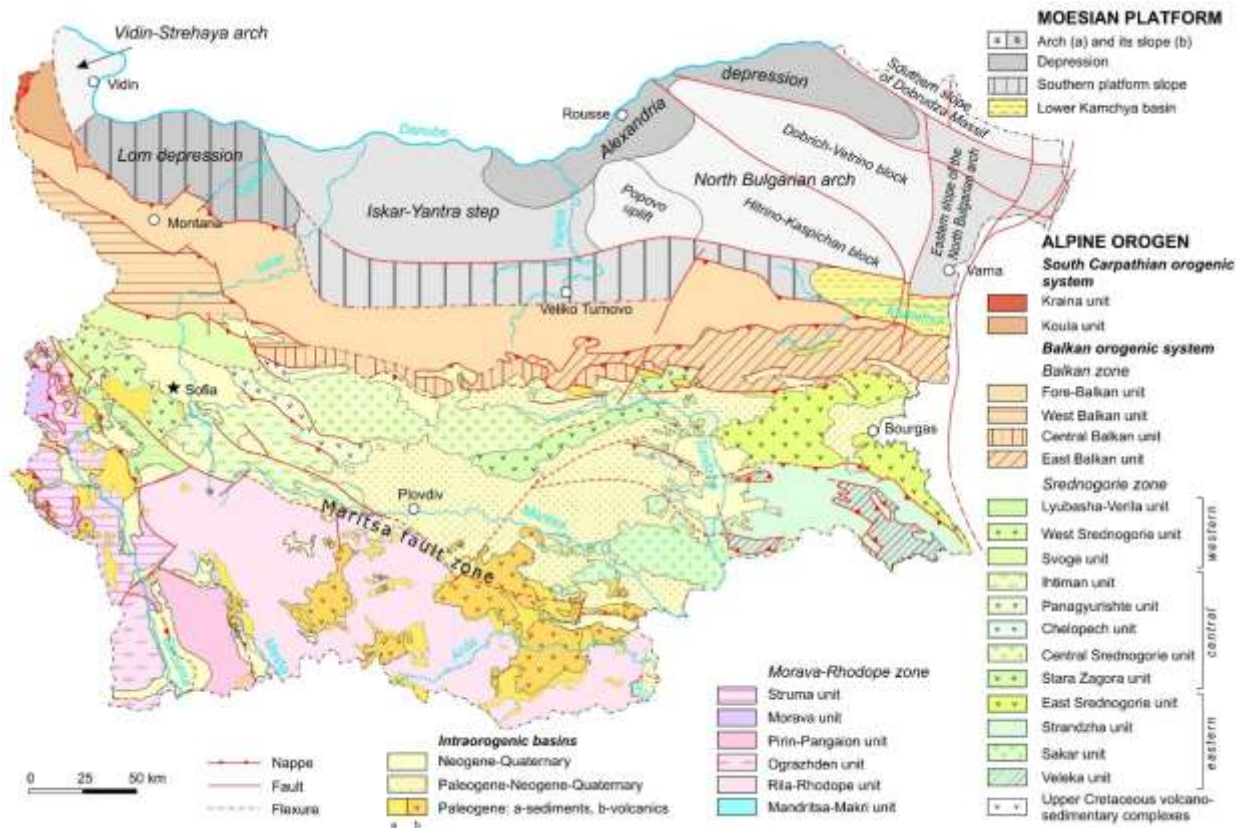


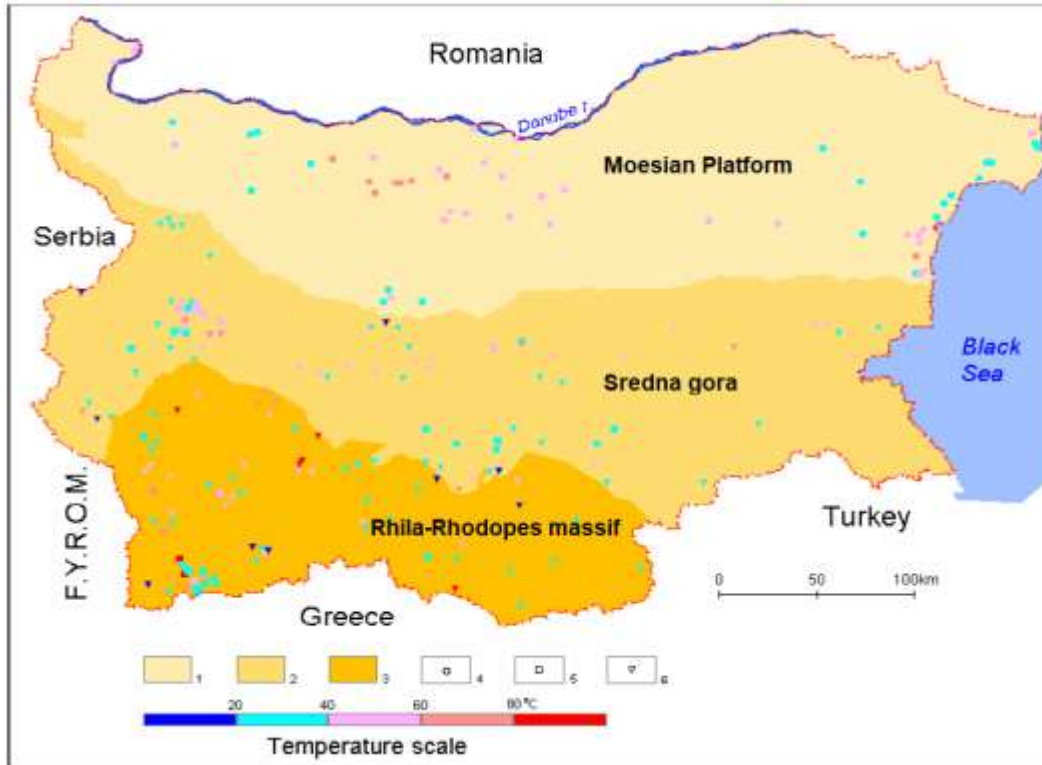
Figure 4 - Tectonic scheme of Bulgaria showing major tectonic units and units of lower rank (from Zagorchev et al., 2009).

The Moesian platform is dominated by vast positive (arches) and negative (depressions) structures that are faulted into horsts and grabens blocks, as shown by the tectonic scheme in

Figure 4. The geological section of the Moesian platform within the territory of Bulgaria is represented by a slightly folded Paleozoic basement covered by sub-horizontal Upper Paleozoic, Mesozoic, and Cenozoic, mainly shallow-marine terrigenous-carbonate and carbonate platform successions up to 7-8 km thick (Figure 2 and Figure 3).

### 1.2 Hydrogeology and geothermal context

Bulgaria is divided into three major zones with distinct hydrogeological characteristics: Moesian platform, Sredna Gora zone, and Rhila-Rhodopes massif (Figure 5).



**Figure 5 – Major hydrogeological units of Bulgaria (from Bojadgieva et al., 2010).**

Legend: 1. Moesian platform (stratified reservoirs); 2. Sredna Gora, including the Balkan zone (secondary stratified reservoirs, fractured reservoirs); 3. Rhila-Rhodopes massif (predominantly fractured reservoirs); 4. Major wells and discovering stratified reservoirs in the Moesian platform region; 5. Hydrothermal waters from fractured reservoirs in Southern Bulgaria; 6. Hydrothermal waters from secondary stratified reservoirs in Southern Bulgaria.

Within the thick sedimentary cover of the Moesian platform, static aquifers with a thickness of up to 1,000 m are hosted in limestone and dolomite formations, that constitute conductive hydrothermal systems with permeability resulting from fracturing and karstification. These aquifers are penetrated by hundreds of deep oil and gas exploration wells (some of them 6,000 m depth). The aquifer's temperature reaches more than 100°C at the bottom of some boreholes (Vidin, Slanotran, Pleven, etc.). However, the deep waters are reportedly characterized by high salinity, which hinders its utilization due to a high scaling potential. More than 2,000 of these wells (exploratory and exploitation ones) have been decommissioned and cemented to avoid mixing of deep highly saline waters (TDS up to 150 g/l) with fresh water contained in overlying shallower aquifers. (Penev and Shterev, 2000; Hristov et al., 2019)

In the Sredna Gora zone, the complex geological structure defines a heterogeneous hydrogeological context where a combination of unstratified (fault-fractured), stratified, and mixed aquifers systems take place in fractured massifs of intrusive and metamorphic rocks, Upper Cretaceous volcano-sedimentary deposits, and post-orogenic Neogene-Quaternary grabens filled up with terrigenous deposits. The thermal waters occurring in this zone are exclusively of meteoric origin, have very low mineralization (usually below 1 g/l), and their temperature vary between 25 and 100°C (Penev and Shterev, 2000).

The Rhila-Rhodopes zone is mainly composed of Precambrian metamorphic and granite rocks, fractured by a dense system of seismically active faults. The occurrence of thermal waters in this region is often associated with major faults along which meteoric waters that have infiltrated and heated at depth, up-flow to form natural hot springs. In some cases, the up-flowing thermal water accumulates to form

relatively shallow aquifers in recent unconsolidated sediments (secondary reservoirs), deposited in graben depressions. More rarely, there are cases where karstified limestone and marble formations become secondary collectors for thermal water. Boreholes have been drilled in many of the geothermal sites in the Rhila-Rhodopes zone to increase the extraction of thermal water. The salinity of most natural hot springs and boreholes is lower than 1 g/l TDS (Hristov et al., 2019).

## 2. Geothermal resources of the Moesian platform and Fore-Balkan zone

The Atlas of Geothermal Resources in Europe (European Commission, 2002) describe the regional hydrothermal aquifers found in the Moesian platform and the Fore-Balkan zone. Few additional investigations and drillings have been performed in the last 20 years, therefore the Atlas still represents the main source of regional information about geothermal resources in northern Bulgaria. Three main aquifers were identified as summarized further below. These are hosted in carbonate formations and are mostly characterized by high salinity and very limited recharge; therefore they are interpreted as static hydro-geothermal systems (Shterev and Zagorchev, 1996). Some parts of the shallower aquifer on the Black Sea coast are however reported to have a non-negligible natural flow and a low water salinity, indicating a local meteoric recharge.

### 2.1 Devonian-Carboniferous (Givetian-Tournaisian) aquifer

This is the deepest and least known geothermal reservoir in the Moesian platform and probably extends over a large portion of the platform basement. Figure 6 indicates its currently inferred extension, where it was found at depths varying between 2,500 and 6000, emplaced in a thick (up to 1,800 m) sequence of limestones and dolomites likely permeable at some levels due to secondary dolomitization and karstification. This seems to be confirmed, at least on a local scale, by old oil and gas wells drilled on the banks of the Danube near Gomotartsi (NW of Vidin) and near Shumen, that reached permeable and productive levels in such formations. The aquifer temperature varies from 50°C up to 150 °C depending on formation depth.

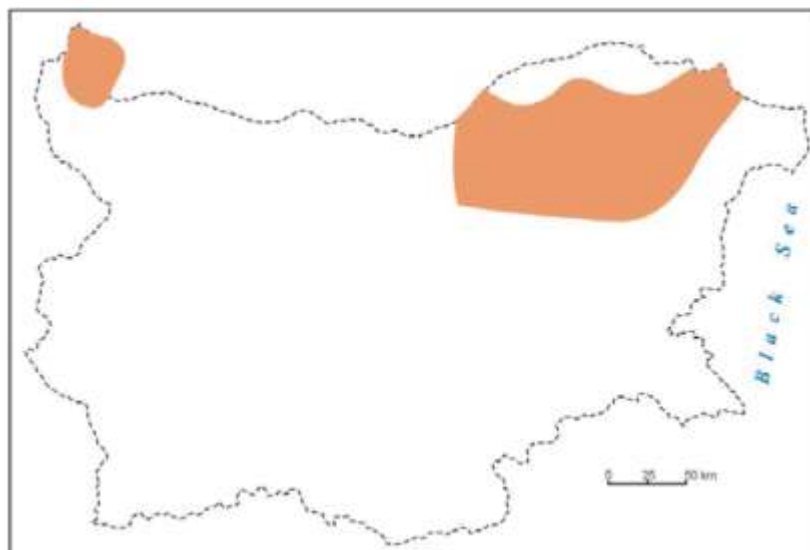
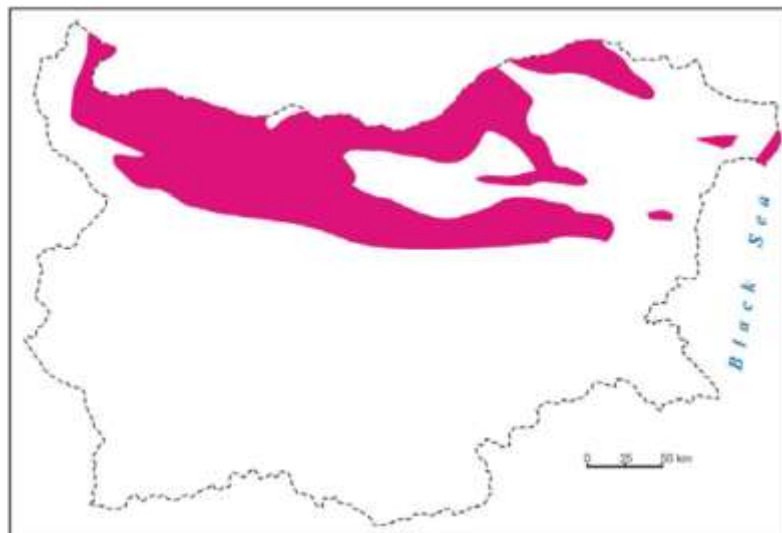


Figure 6 – Location of Middle-Upper Devonian carbonate aquifers in Northern Bulgaria (Shterev and Georgiev, 2011).

The current knowledge and the regular lithostratigraphic set-up of the Devonian-Carboniferous formations suggest that this aquifer may contain large volumes of hot saline waters and brines. Shterev and Georgiev (2011) reported for the middle-upper Devonian aquifers indicated in Figure 6 an estimated recoverable thermal energy between 5 and 25 GJ/m<sup>2</sup> with water T between 50 and 150°C (European Commission, 2002).

## 2.2 Middle - Late Triassic (Anisian – Carnian) aquifer

Limestones and dolomites of Anisian to Carnian age (Doyrentsi Formation) form a potential reservoir of thermal brines with thickness variable between 100 and 800 m, situated at depths between 1,500 m and 4,000-5,000 m. The aquifer temperature varies from 40°C up to 140 °C depending on formation depth. This carbonate complex is widespread (Figure 7) and well-studied with respect to its areal distribution, lithostratigraphy, and structural features; however, its hydrogeologic and geothermal characteristics are less known and needs further investigation (European Commission, 2002).



**Figure 7– Location of Middle-Late Triassic carbonate aquifers in Northern Bulgaria (Shterev and Georgiev, 2011).**

Shterev and Georgiev (2011) reported for the middle-late Triassic aquifers depicted in

Figure 7 an estimated recoverable thermal energy between 1 and 10 GJ/m<sup>2</sup> with water T between 40 and 140°C.

## 2.3 Upper Jurassic – Lower Cretaceous (Malm-Valanginian) aquifer

The Malm-Valanginian aquifer is the best-studied and most important geothermal reservoir in Bulgaria. Its characteristics were documented in detail in the Atlas of Geothermal Resources in Europe, as well as by other authors, including in recent studies that evaluated its geothermal potential in the central region of north Bulgaria (Gerginov et al., 2022; Trayanova et al., 2020).

The aquifer is located at depths between 800 m and 3,000 m and extends over 11,000 km<sup>2</sup> throughout north Bulgaria, subdivided into two main zones with distinctive characteristics, respectively defined as the Danube and the Black Sea zones.

### **Malm-Valanginian aquifer – Danube Zone**

This part of the Malm-Valanginian aquifer consists of three areas in the western Moesian platform and the Fore-Balkan zone, respectively named Vidin, Vratsa, and Pleven (see Figures 8 and 9), which contain static saline geothermal reservoirs with temperatures variable between 40°C and 90-100 °C. The extension and characteristics of the geothermal reservoir in these three areas are known with different degrees of accuracy.

The characteristics of the Malm-Valanginian aquifer in the Vidin and Vratsa areas are poorly known, therefore the extension and properties reported in Figures 8 and 9 are approximate and mainly based on inferences.

In the Vidin area, the top of the geothermal aquifer was estimated to progressively deepen from 300 m depth in its northern part to 1,300 m in the south, with a thickness of about 900 m. The piezometric level is between 5 m and 15 m (above ground level) along the Danube riverbank, the maximum reservoir temperature is expected to be around 60 °C, and the aquifer salinity seems to be quite high, with values up to 50-60 g/l. The geothermal resources were preliminarily estimated for this area at  $5.9 \times 10^{18}$ J (European Commission, 2002).

In the Vratsa area, the geothermal aquifer is located at a considerable depth of 1,000-2,100 m, generally deepening toward the SE with a thickness of about 1,000 m. The temperature ranges from 50 °C to 90 °C, being higher in its eastern part, where the geothermal reservoir is deeper. Other properties of the aquifer are poorly known, as well as its continuation to the E is unclear (Figure 8). The geothermal resources were preliminary estimated at  $4.7 \times 10^{18}$  J (European Commission, 2002).

The Pleven area has a larger and more constrained extension and was reported by the European Commission (2002) as the most important area for the development of geothermal resources in Bulgaria. The geothermal aquifer is located at depths of 600-2,400 m, with a total thickness varying between 600 and 800 m in its northern-central part and increasing to 1,000-1,200 m along the western and southern border of the area. The temperature and salinity also increase from NE to SW, consistently with the aquifer depth and thickness, from 30°C to 90°C, and 1 g/l to 20-25 g/l. Some recharge by freshwater (meteoric) seems to occur in the shallower NE part of the aquifer. The piezometric level reaches and even exceeds the ground level in zones along the Danube River, while in the southern portion of the Pleven area, located at higher elevations, it is located at 50 m to 200 m beneath ground level. (European Commission, 2002). Many tested boreholes in the Pleven area indicated a significant yield of the Malm Valanginian aquifer, particularly from the Drinovo Formation (dolomites and dolomitic limestones up to 600 m thick) which is deemed to be particularly permeable. According to preliminary estimations reported by the European Commission (2002), a wells doublet<sup>1</sup> in the Pleven area may produce between 40 l/s and 190 l/s of thermal water, and 10 to 30 MWt of thermal energy. The geothermal resources in the region were estimated at  $59 \times 10^{18}$ J. The geothermal potential of the area around Pleven was assessed by Petrov et al. (1998) by distinguishing the resource that may be extracted by conventional wells (including available and potential

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<sup>1</sup> A doublet is a pair of wells, one abstraction and one injection, used to extract geothermal energy from the subsurface.

thermal capacity), and that which may be exploited by wells doublets<sup>2</sup>, reporting an estimated potential of 1,052 Mwt, of which 792 Mwt corresponding to wells doublets, assuming a final T of 15°C. The same data were subsequently validated and reported by COWI (2005).

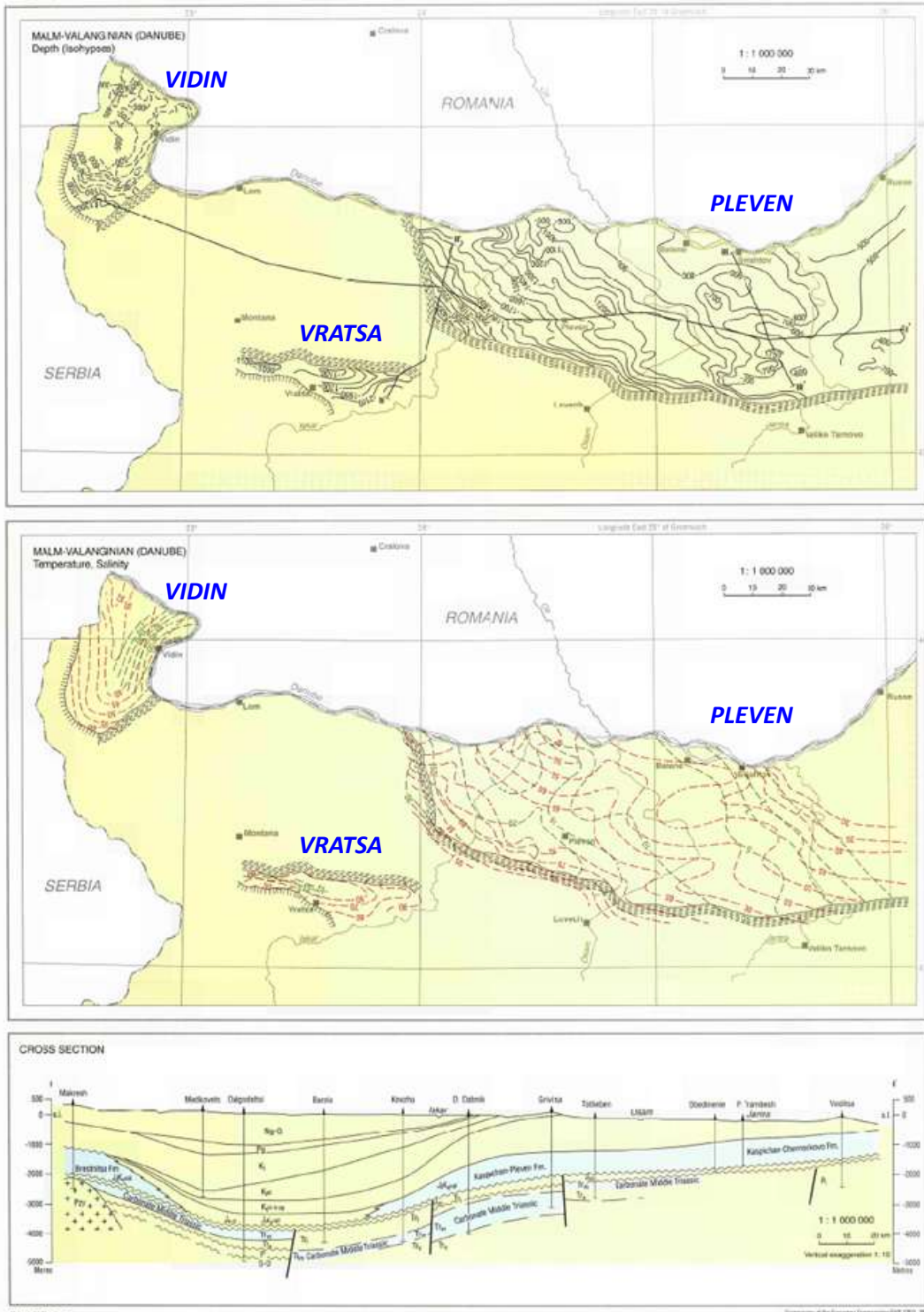


PLATE 11

<sup>2</sup> The number of doublets was evaluated assuming a distance between wells of 1,000 m and a doublet drainage area of 25 km<sup>2</sup>



Figure 8 - Malm-Valanginian aquifer, Danube zone. Maps of depth to reservoir top, temperature, water salinity, and E-W cross-section (from European Commission, 2002; modified).

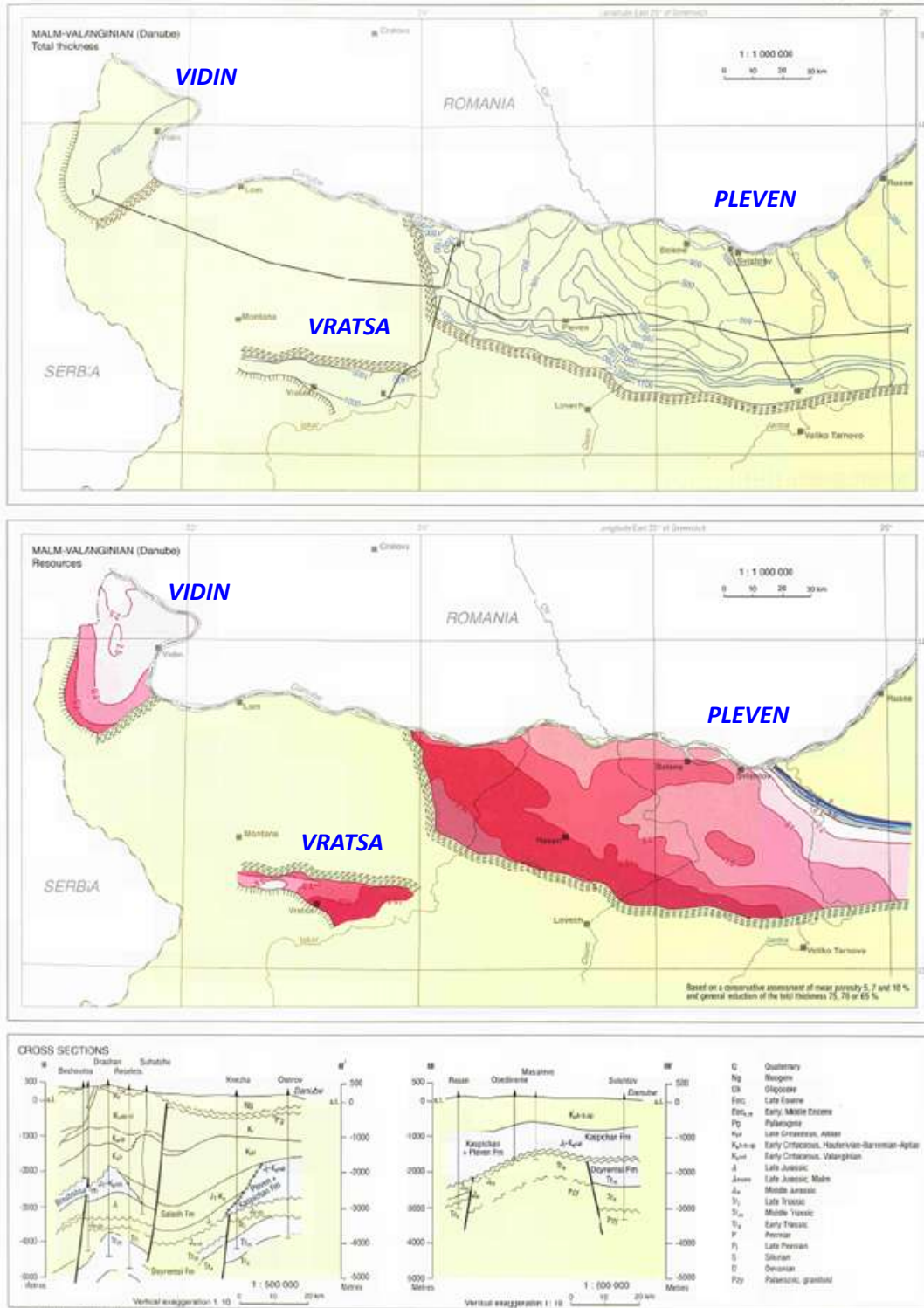




Figure 9 - Malm-Valanginian aquife, Danube zoner. Maps of total reservoir thickness, geothermal resources and N-S cross sections (from European Commission, 2002; modified).

A recent, more detailed, assessment of the geothermal resource potential of the Malm-Valanginian aquifer in the Pleven area was published by Gerginov et al. (2022). This study comprised the region between the Iskar River on the W and the Yantra River on the E, encompassing the cities of Svishtov, Pleven, and Lovech, and it was based on the review and analysis of data from about 250 deep boreholes drilled for oil and gas exploration (Figure 10).

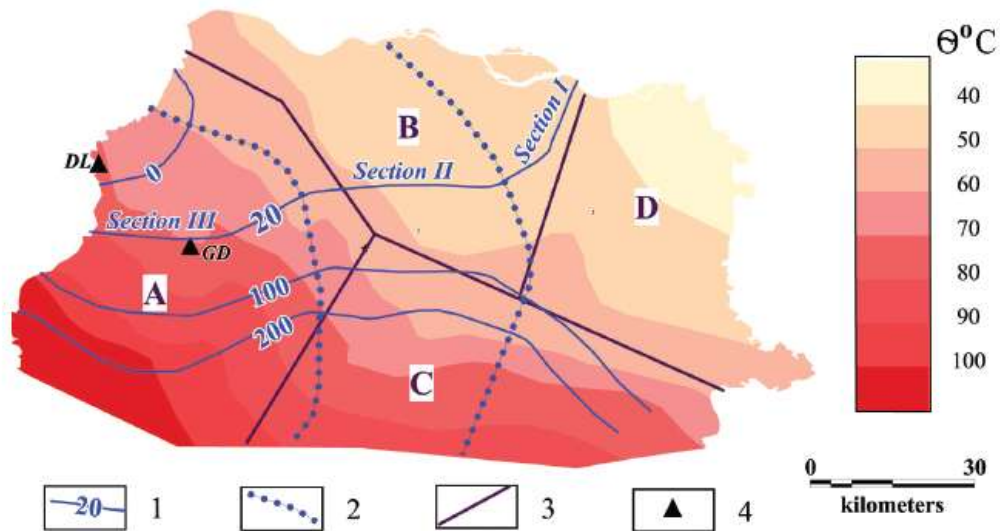


Figure 10 - Map of the Malm-Valanginian aquifer assessed by Gerginov et al. (from Gerginov et al., 2022)

Gerginov et al. (2022) evaluated the extractable heat reserves in the studied region by applying the doublet well method developed by the Geological Institute at the Bulgarian Academy of Sciences for the evaluation of the heat reserves in Bulgaria (Petrov et al., 1998). Compared with the previously mentioned assessment conducted for the Atlas of Geothermal Resources in Europe (European Commission, 2002), this evaluation is improved by taking into account measured hydrodynamic properties of the aquifer to evaluate the actual well flow rates that can be obtained under real exploitation conditions. The key parameters and results obtained by Gerginov et al. (2022) are summarized hereafter.

- The temperature distribution at the top of the aquifer and the equipotential lines are shown in Figure 11 where the studied area is divided into 4 blocks (A, B, C, and D) with reasonably uniform properties. Table 1 reports the average values of temperature, transmissivity, hydraulic gradient, and thermal water resources evaluated along 3 sections shown in Figure 11 (I, II, and III). The transmissivity values reported in Table 1 are among the few data of this type available in the reviewed literature.

- As already indicated by the European Commission (2002), the main Malm – Valanginian aquifer is hosted in carbonate formations (limestone and dolomite), characterized by high permeability derived from paleokarst processes that occurred during a sedimentation pause after the Valanginian age. However, Gerginov et al. (2022) report a reduction in transmissivity with depth so that the aquifer yield is lower in its deepest and higher temperature parts.
- The groundwater level is mostly below the ground surface (thus requiring well pumping), except in the northeastern area close to the Danube River, where it is close to the ground level (see Figure 11).



Sections and blocks for evaluating the heat potential of the Upper Jurassic–Lower Cretaceous aquifer: 1, equipotential lines; 2, section boundary; 3, block boundary; 4, geothermal power plant (GD – Gorni Dabnik, DL – Dolni Lukovit).

Figure 11 - Temperature map at the top of the Malm-Valanginian aquifer and equipotential lines (equivalent freshwater total head) map (from Gerginov et al., 2022). Note: GD-Gorni Dabnik shall be read DD-Dolny Dabnik.

Table 1- Malm - Valanginian aquifer. Average values of temperature, hydraulic transmissivity, hydraulic gradient, and renewable water resources (Q) by sections (from Gerginov et al., 2022). See locations in Figure 11.

Section	Temperature °C	Transmissivity m <sup>2</sup> /d	Hydraulic gradient –	Renewable resources L/s
I	50	1500	0.0003	110
II	55	140	0.003	530
III	65	40	0.4	740
			Σ Q	1380

- Table 2 lists for each of the 4 blocks indicated in Figure 11 the estimated average aquifer temperature, thickness, individual doublet yield, and total yield. A constant well doublet distance of 1 km was used by Gerginov et al. (2022), with water level drawdown at production wells in the range of 5 to 30 m and thermal breakthrough exceeding 50 years.

**Table 2 - Malm - Valanginian aquifer. Average values of aquifer temperature and thickness; calculated individual and total yield from well doublets by blocks (from Gerginov et al., 2022). See locations in Figure 11.**

Block	Temperature °C	Thickness m	Individual yield L/s	Total yield L/s
A	65	900	7	6300
B	50	700	20	25 000
C	70	1100	10	8000
D	45	800	30	22 500

Note: The total number of doublets n is 3,700, corresponding to 900, 1250, 800, and 750 for the individual blocks A, B, C, and D (see location in Figure 11).

- Table 3 lists the thermal energy extractable, computed for the 4 blocks (A, B, C, and D) indicated in Figure 11. For reference, the equivalent avoided fossil fuel consumption and its value considering the crude oil price in 2021 is also included in the table. The huge extractable thermal energy and corresponding avoidable annual oil costs are due to the evaluation approach conducted by Gerginov et al. (2022) which assumes covering the entire blocks with a regular network of production and reinjection wells reproducing a 5-spot well pattern.

**Table 3 - Malm - Valanginian aquifer. Extractable thermal energy (per year) by blocks for a temperature drop to 15°C (from Gerginov et al., 2022). See locations in Figure 11.**

Section	Thermal energy TJ	Equivalent fuel t	Price* USD
A	41 543	992 427	70 462 317
B	115 399	2 756 785	195 731 735
C	58 029	1 386 264	98 424 744
D	89 022	2 126 660	150 992 860
Total	303 993	7 262 136	515 611 656

\* At 71\$/t average crude oil price in 2021

The thermal power from the 4 blocks as a function of the temperature drop is shown in Figure 12. The highest thermal power is obtained from blocks B and D because of the higher doublet flow rate evaluated for those blocks (see Table 2).

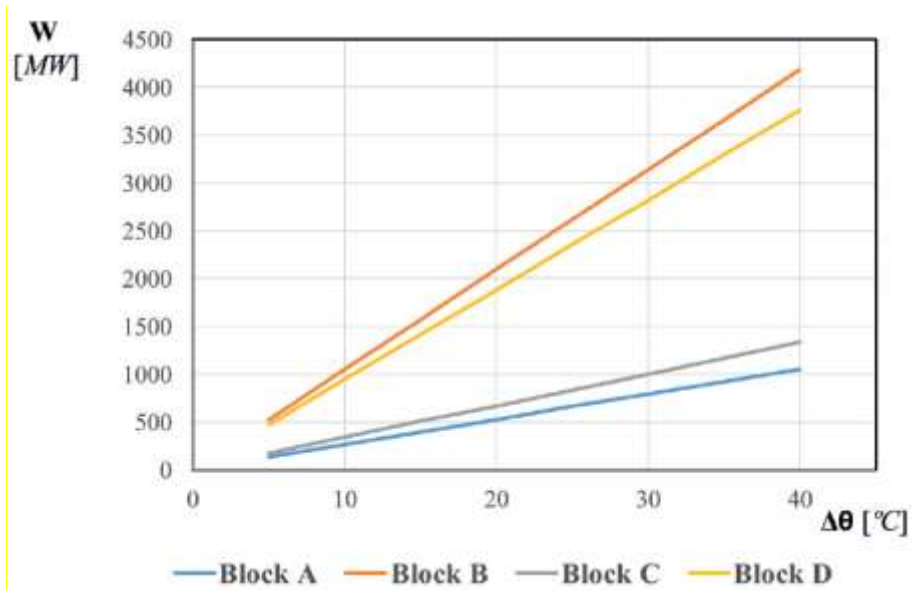


Figure 12– Thermal power extractable from the 4 blocks A to D as a function of temperature drop (Gerginov et al., 2022).

The thermal power values estimated by Gerginov et al. (2022), as presented in Figure 12, cannot be compared directly with the previously reported estimate of 792 MWt by Petrov et al. (1998) for the Pleven area, because of different assumptions in the calculations. While the assumed well distance is the same in both studies ( $D = 1,000$  m), the Petrov et al. (1998) extractable energy calculations refer to a final temperature of  $15^{\circ}\text{C}$ , with a doublet drainage area of  $25\text{ km}^2$ . Gerginov et al. (2022) did not specify the doublet drainage area in their paper but, considering the number of well doublets and the surface of the different blocks considered in their study (see Figure 11 and Table 2), an average doublet drainage area of  $3\text{ km}^2$  can be inferred. Assuming in Figure 12 a temperature drop of  $20^{\circ}\text{C}$ , the thermal power for the 4 blocks studied by Gerginov et al (2022) is about 5,180 MWt. Considering the difference in the doublet drainage area used by Gerginov et al. (2022) vs. Petrov et al. (1998) (i.e.  $3\text{ km}^2$  vs.  $25\text{ km}^2$ ), the corresponding thermal power calculated by Gerginov et al. (2022) is about 622 MWt, slightly less than 80% of Petrov et al. (1998) estimate, but still in the same order of magnitude, which is considered as a reasonable estimate for the Pleven area thermal power potential.

Gerginov et al. (2022) also assessed the chemical characteristics of the thermal waters reserves of the Malm-Valanginian aquifer in the Pleven area. Figure 13 shows the breakdown of thermal water reserves considering their temperature and water salinity (TDS). Most of the reserves belong to 3 main classes, namely  $T < 50^{\circ}\text{C}$  and  $\text{TDS} < 10\text{ g/L}$ ,  $T = 50\text{-}80^{\circ}\text{C}$  and  $\text{TDS} < 10\text{ g/L}$ , and  $T = 50\text{-}80\text{ g/L}$  and  $\text{TDS} = 10\text{-}30\text{ g/l}$  (Figure 13). This indicates that a significant portion of the thermal water reserves are brines with salinity exceeding  $10\text{ g/l}$ , whose utilization in heating processes shall be duly considered by estimating their scaling and corrosion potential.

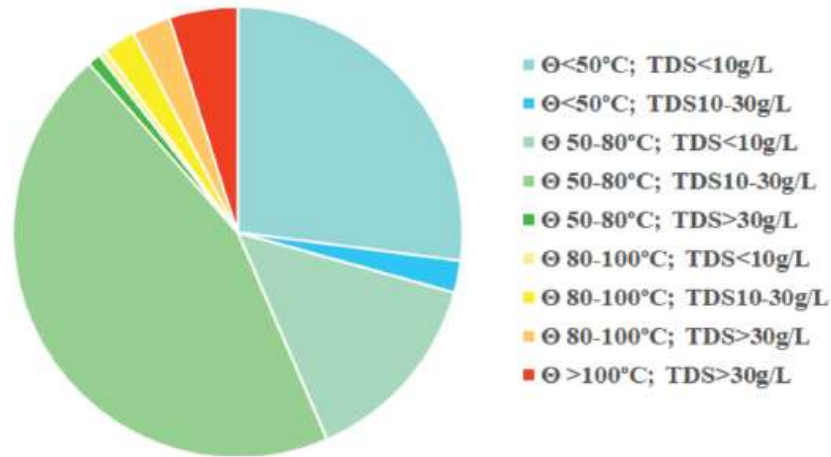


Figure 13- Breakdown (%) of thermal water reserves by temperature and total dissolved solids (TDS) in the Malm-Valanginian aquifer (Gerginov et al., 2022).

Some additional data about the Malm-Valanginian aquifer in the Plevna area are provided by Trayanova et al. (2020) who published a temperature distribution map and depth to the top of the aquifer (Figure 14) and the distribution of salinity (TDS) at the aquifer top (Figure 15).

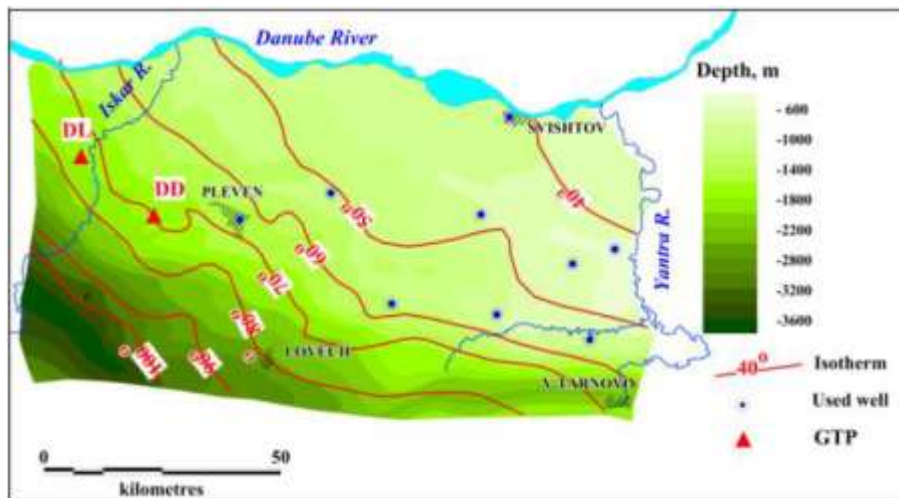


Figure 14 - Map of temperatures at, and depth of the top of the Malm-Valanginian aquifer with locations of boreholes used in the past and geothermal plants (GTP: DD = Dolni Dabnik, DL = Dolni Lukovit) (Trayanova et al., 2020).

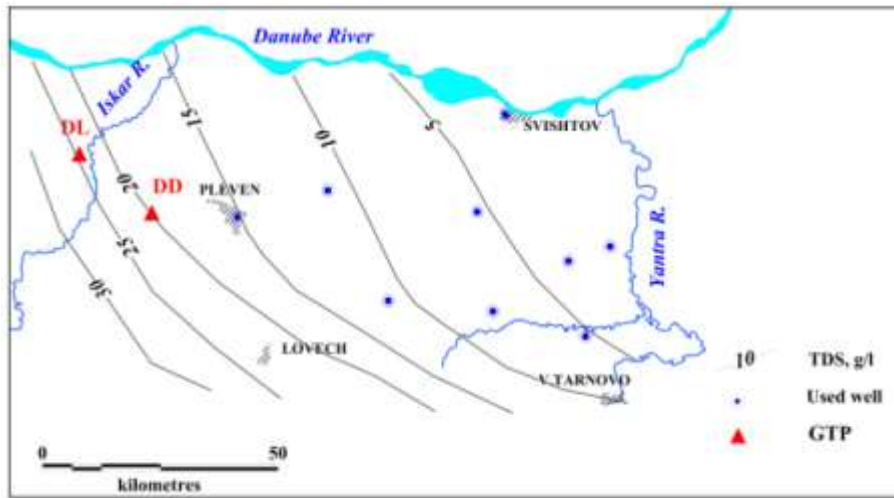


Figure 15- Map of TDS distribution of the Malm-Valanginian aquifer and locations of boreholes used in the past and of geothermal plants (GTP: DD = Dolni Dabnik, DL = Dolni Lukovit) (Trayanova et al., 2020).

### Malm-Valanginian aquifer - Black Sea (Varna) zone

The Black Sea portion of the Malm-Valanginian aquifer is located around Varna, along the Black Sea coast, and on the southwestern slope of the North-Bulgarian Arch (See Figure 4). This is part of an artesian basin containing a dynamic aquifer with low-salinity water of meteoric origin, and temperatures varying between 25°C and 65°C. The hydraulic transmissivity of the aquifer increases from S to N from 0.02 to 0.14 m<sup>2</sup>/s. Nitrogen is the predominant dissolved gas, except for the Northern Black Sea region, where the waters contain dissolved methane. The total natural flow in the thermal and coastal part of the basin was estimated at 3.45 m<sup>3</sup>/s, with 1.2 m<sup>3</sup>/s that was captured in flowing boreholes at depths of 800- 1,800 m (Figures 16 and 17) (European Commission, 2002).

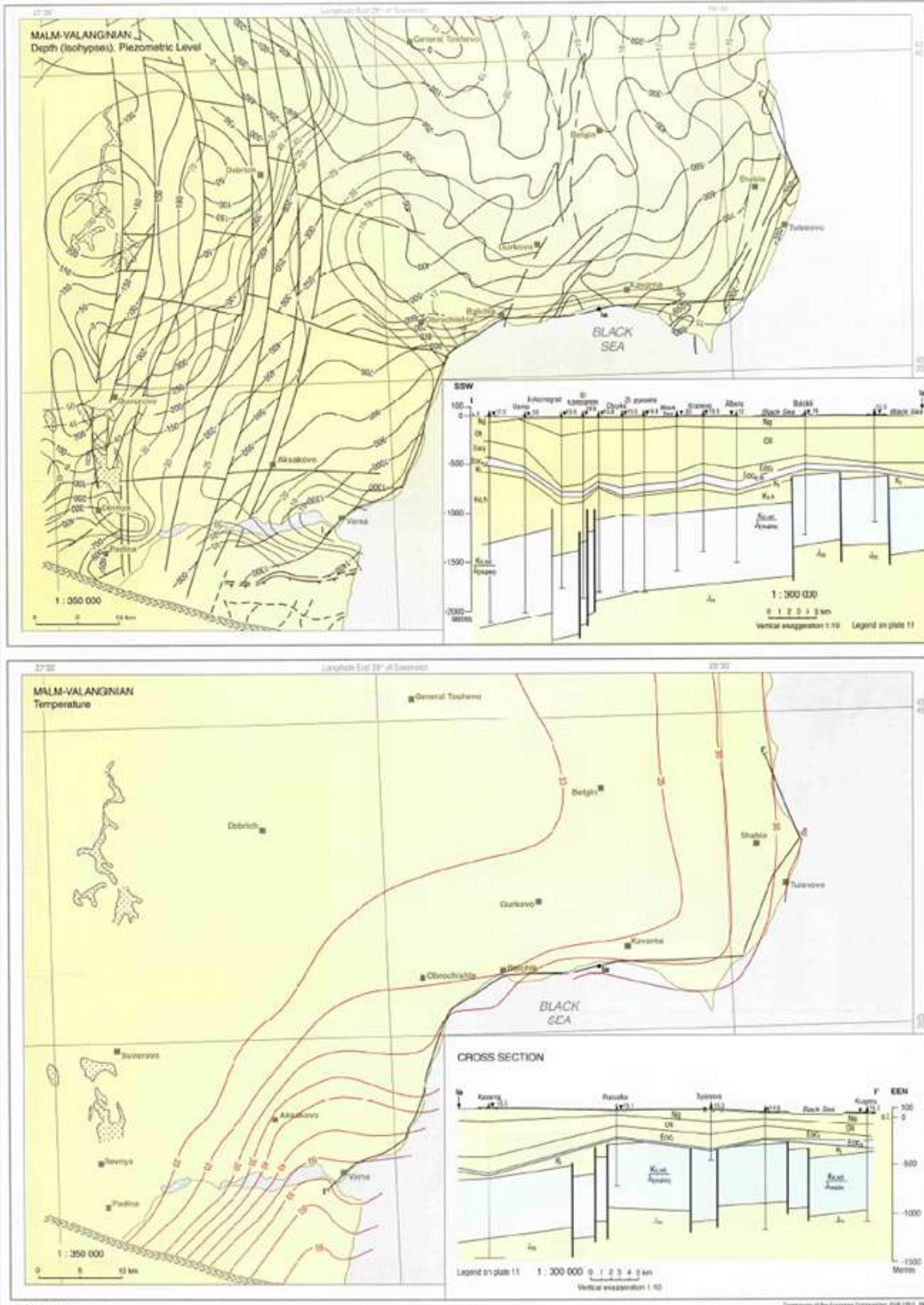


Figure 16- Malm-Valanginian (Black Sea) aquifer. Maps of depth to the reservoir top, piezometric level and temperature, and cross sections drawn along the Black Sea coast (European Commission, 2002).



Despite the considerable depth of the reservoir (> 800-1000 m), the aquifer temperature does not exceed 65°C. Its hottest part (50-65°C) comprises Varna and the area immediately to the south. This is reportedly due to convective cooling and heat transport towards natural discharge areas into the Black Sea. Therefore, the geothermal resource estimation reported in the Atlas of Geothermal Resources in Europe for this zone of the Malm-Valanginian aquifer is limited to approximately  $2.9 \times 10^{18}$ J (European Commission, 2002).

In addition to assessing the geothermal resource through the doublet heat extraction model, the Atlas of Geothermal Resources in Europe also evaluated the extractable thermal energy using the natural regional flow rate. This evaluation was made assuming that the natural flow of the aquifer is captured by wells located along the litoral section of the Black Sea, where the highest temperatures are inferred (area around Varna – see Figure 16) (European Commission, 2002). The obtained thermal potential estimate is 289 MWt. Similar results (217 MWt) were previously reported by Petrov et al. (1998) and subsequently validated and reported by COWI (2005).

### 3. Geothermal resources of Central and South Bulgaria

As previously mentioned (Section 1.2), the geothermal resources in Central and Southern Bulgaria occur in a geological and hydrogeological context, which is different from Northern Bulgaria where extensive sedimentary formations host large and thick, mostly static, geothermal aquifers. Geothermal systems in Central and South Bulgaria are instead more localized, along major fault zones and associated tectonic depressions filled by recent clastic sediments. These are dynamic hydrothermal systems, with deep convective circulation of meteoric waters along faulted/fractured rocks, and karstified limestone and marble formations. Fault-controlled localized up-flows of geothermal waters heated at depth may reach the surface to form hot springs or accumulate to form relatively shallow aquifers in adjacent graben depressions.

The geothermal systems in Central and South Bulgaria commonly shows the following characteristics:

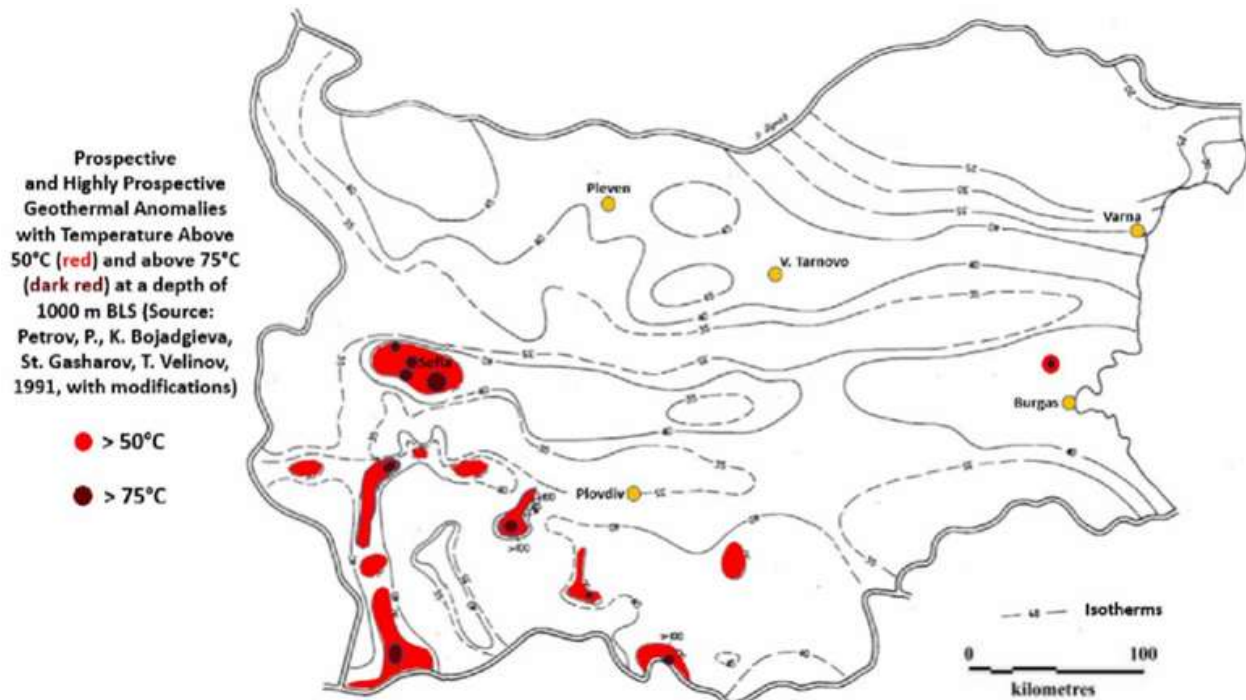
- The geological environment is predominantly composed of igneous (old volcanics and intrusives) and metamorphic rocks characterized by sharp lateral variations, that tend to constrain the distribution of secondary permeability, and prevent to a large degree the lateral extrapolation of the available information.
- The main targets of exploration, rely on the identification of favorable structural setting (i.e. fault intersections, extensional tectonic features, etc.) that may create adequate permeability by fracturing (secondary permeability).
- Though drilled wells exists in some geothermal areas in South Bulgaria, these are relatively shallow and provide limited underground data for comprehensive assessments of thermal and hydraulic conditions of potential geothermal prospects.

Given this situation, the criteria used in this report to identify and characterize geothermal zones in Central and South Bulgaria are mostly based on the identification of promising structural features, surface evidence of hydrothermal activity (hot springs), and geothermal data provided by dispersed shallow wells drilled in the region, often in proximity of surface manifestations to increase the thermal water extraction. This information was collected from existing literature sources and reviewed to assess their soundness and reliability.

The main sources of information used for this assessment are the studies conducted by Petrov et al. (1998) on hydrogeological resources in Bulgaria, the catalog of geothermal data by Bojadgieva and Gasharov (2001), the Atlas of Geothermal Resources in Europe published by the European Commission (2002), and

the reports on geothermal areas in Central and South Bulgaria produced by the Ministry of Energy's project for Sustainable Use of Geothermal Resources in Bulgaria (COWI, 2005). These last documents include a data base on geothermal resources, with a list of priority areas, a list of available wells and well flow rates, as well as detailed case studies for development projects in different geothermal sites.

Figure 18 illustrates the scattered distribution of geothermally anomalous areas, based on a temperature map at 1000 m depth. It is worth observing that the major geothermal anomalies are located in the SW region of Bulgaria, within the Morva-Rhodope tectonic zone (see Figure 4).



**Figure 18- Identification of macro-areas considered to be of geothermal interest in Central and South Bulgaria (modified from Hristov, 2023, modified from Petrov et al., 1991).**

Petrov et al. (1998) report a quantitative (or semi-quantitative) capacity estimate of the extractable resource for the known geothermal areas in South Bulgaria (Rhila-Rhodopes region, Table 2). These data were successively reviewed and validated by COWI (2005). No further assessments and updates were conducted after 2005.

Petrov et al. (1998) calculated the thermal power ( $P$ ) for each geothermal area considering two cases, one with cooling of the thermal water down to 40°C and the other to 15°C, reporting the corresponding thermal energy ( $Q_0$ ) extracted in one year, and the equivalent avoided fuel consumption (assuming oil is used) (Table 5). The thermal power was estimated from the known flow rate and temperature of thermal water discharged from springs and existing boreholes. This is referred to by Petrov et al. (1998) as “available” or “operational” resources and shall be considered as minimum values of the actual thermal potential. The authors considered the available information unsuitable to define the extension and boundary conditions of the geothermal reservoirs to allow an estimate of the total thermal water resources. Larger resources could be available by drilling more, and deeper, wells.

Table 2 – Available geothermal resources in the Rhila-Rodopes Massif (from Petrov et al., 1998).

Hydrothermal areas	Total flow rate	Water temperature	Thermal power and Thermal Energy produced in 1 year				Equivalent fuel	
			P		Q <sub>d</sub>		θ'40°C	θ''15°C
			θ'40°C	θ''15°C	θ'40°C	θ''15°C		
			L/s	°C	kW (kJ/s)		TJ/365d	
<b>Osogovo</b>								
Kyustendil basin	62	19-75	4,621	9,331	145.6	293.7	3,478	7,016
<b>Rhodope massif</b>								
Struma graben	180	18-98	16,990	69,032	536	1,072	12,908	25,488
<b>Local Grabens</b>								
Razlog basin	105	25-55	3,389	15,073	139	475	3,313	11,334
Gotsedelchevsky basin	161	17.6-44	-	9,259	-	291.7	-	6,969
<b>Western and Eastern Rhodopes</b>								
Northern Rhodope slopes and the southern parts of G. Thrace	190	18-47	544	8,610	17.1	270.8	409	2,258
Chepinska valley	159	27-95	12,532	27,106	395	908	9,437	21,703
Bratsigov basin	3.3	18-24	-	55	-	1.7	-	42
The valley of the Vacha river	113	20-72	1,469	7,689	46.3	286.2	1,106	9,641
The Chepelarska river valley	2.6	22-29	-	122	-	3.8	-	92
Gorna and Malka Arda and Erma river	25	22-89	4,102	5,201	97.8	164	2,337	3,918
Ex. Rhodope structural depressions	58	18-57	2,009	6,222	63.4	195.8	1,514	4,686
<b>Total:</b>	<b>1059</b>	<b>18-95</b>	<b>45,656</b>	<b>157,700</b>	<b>1,440.2</b>	<b>3,962.7</b>	<b>34,502</b>	<b>93,147</b>

Note: The equivalent fuel is computed assuming that the combustion of 1 t of oil releases  $4.186 \times 10^2$  TJ of heat.

Figure 19 shows the major geothermal sites of Central and South Bulgaria where temperatures above 75°C (up to 98°C) is reported from surface hot springs and/or wells drilled at relatively shallow depths (100-700 m). As already observed in Figure 18, most of these sites are located in SW Bulgaria, excluding the sites of Kazaniak (4) and Straldzha (3), and also certain thermal anomalies reported in the Plovdiv area that are located in the Central East region of Bulgaria. However, the information available for these sites in Central East Bulgaria is scarce and does not allow for a comparison and classification with the areas in SW Bulgaria.

Considering all the above and after assessing, based on the review of literature sources, the geothermal resources perspectives and the corresponding advancement in knowledge and characterization of the geothermal systems, the following four areas are proposed as the most interesting for further exploration and development in the Central and Southern region of Bulgaria (Figure 20):

- Sofia Basin
- Struma Valley Region (including Kyustendil and Sapareva Banya)
- Chepinska Valley (Velingrad area)
- Erma Reka (Zlatograd)

The main characteristics of these areas are described further below.

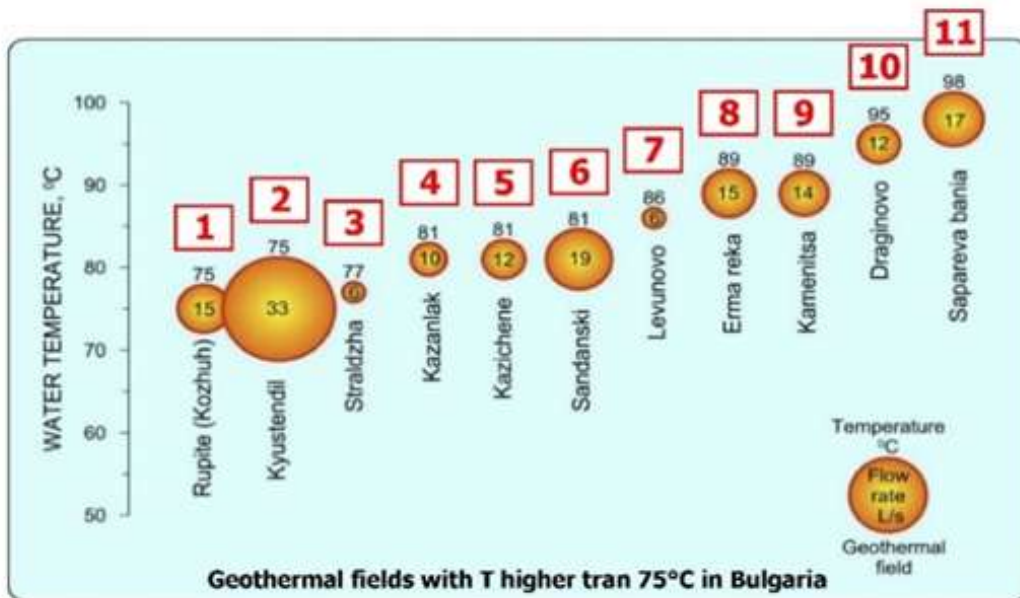
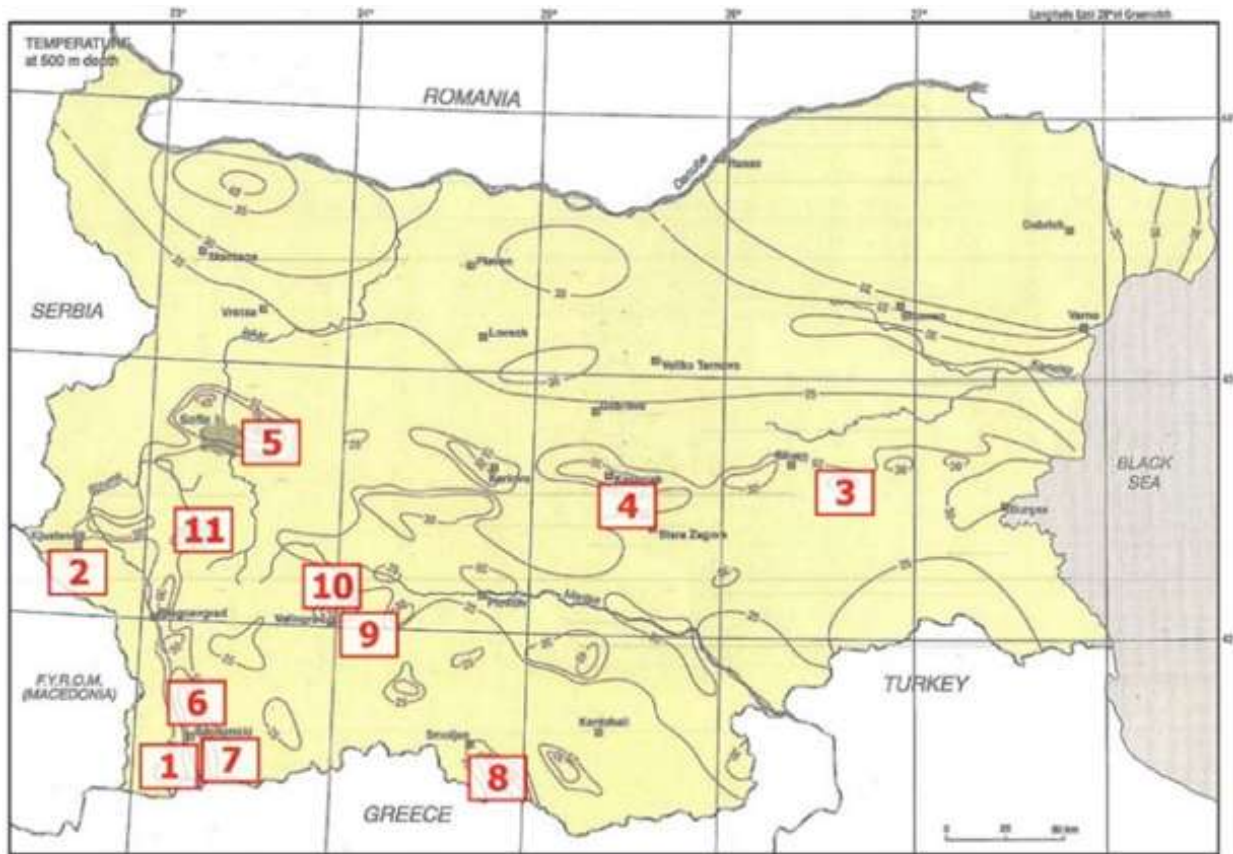


Figure 19- Temperature map at 500 m depth and location of geothermal sites with measured temperature above 75°C (from Hristov, 2021).

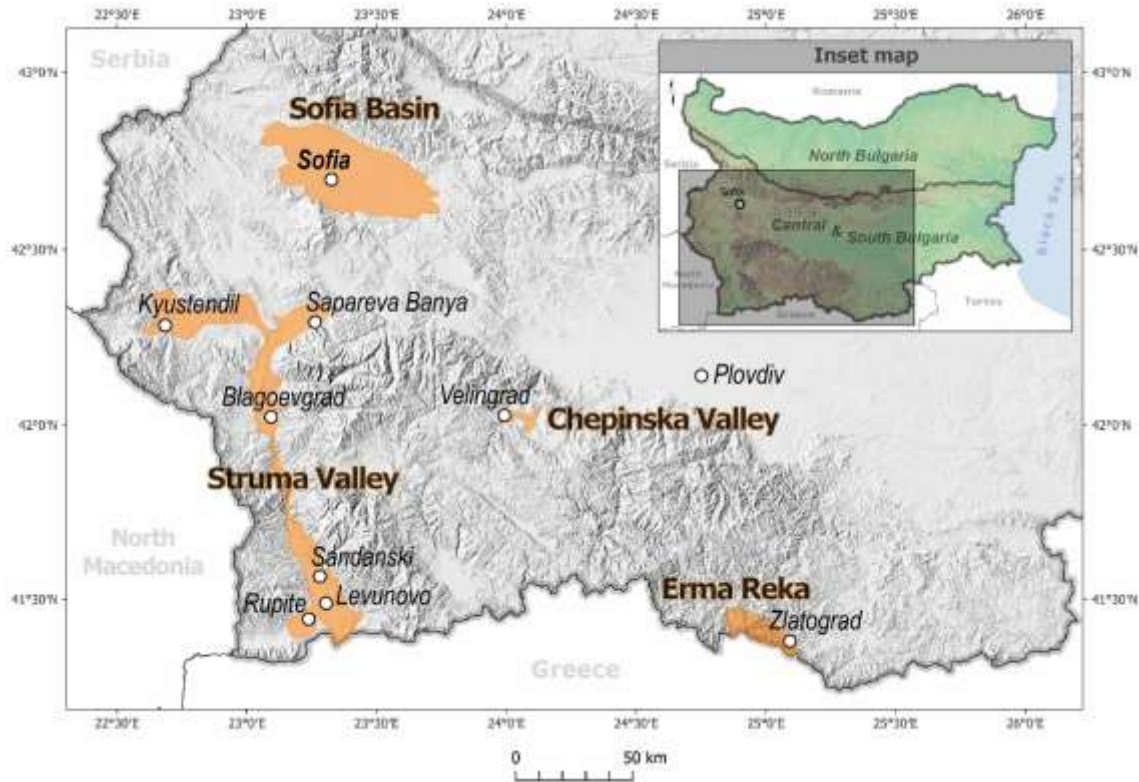


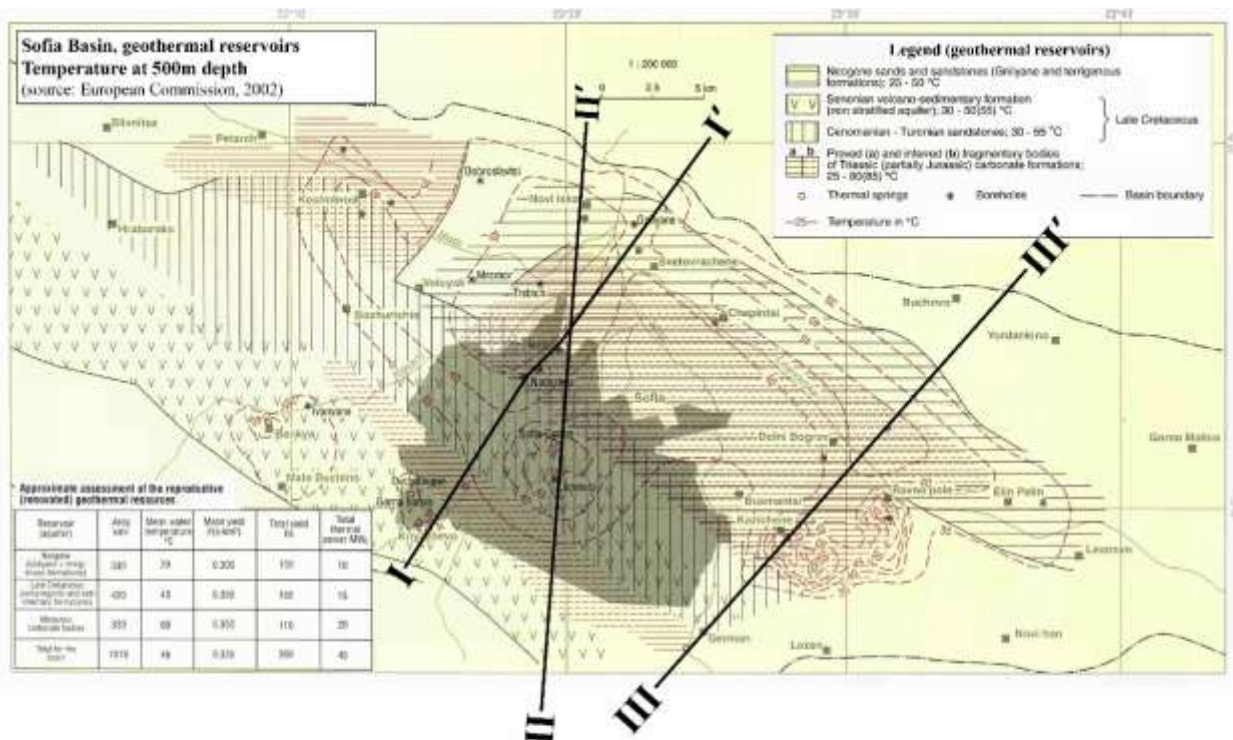
Figure 20 – Proposed most interesting geothermal areas in Central & Southern Bulgaria (orange areas).

## Sofia Basin

The city of Sofia and nearby areas lie on a wide structural basin (graben structure) filled by Neogene and Quaternary sediments deposited over a basement of Mesozoic and pre-Mesozoic rocks. The Sofia area is known as a geothermal resource area for many natural hot springs used since the Roman age for thermal bathing and water supply. Several wells were also drilled in more recent times to tap geothermal aquifers at depths mostly in the range of 300 – 750 m both within the basal sandstone and gravel formation of the Neogene graben filling and the underlying basement composed of Late Cretaceous volcanogenic-sedimentary rocks and isolated bodies of Triassic and Late Jurassic limestones and dolomites. The thermal water upflows within the basin across different stratigraphic levels and reservoirs, controlled by active (neotectonic) fault structures, lithofacies windows, volcanic and intrusive igneous bodies. This up-flowing/convective effect can be observed in the geometry of the temperature distribution in cross sections (European Commission, 2002; Shterev, 2004 - see Figure 20).

Most thermal waters in the Sofia Basin are of meteoric origin with very low salinity (TDS), though a considerable area in the northern part of the basin contains thermal water with greater  $\text{HCO}_3$  and  $\text{SO}_4$  mineralization (2-5 g/l).

The geothermal water temperature ranges between 30-40 °C up to 60- 80 °C, depending on the depth of circulation in the geothermal system and the location of the tapping points with respect to major upflow zones (Figure 20). The hottest temperature so far measured in the Sofia basin is 81°C recorded in the 686 m deep well R-1, located in Kazichene, in the eastern outskirts of Sofia (SE portion of the basin).



**Simplified cross sections through the Sofia hydrogeothermal basin**  
 (source: Shterev, 2004)

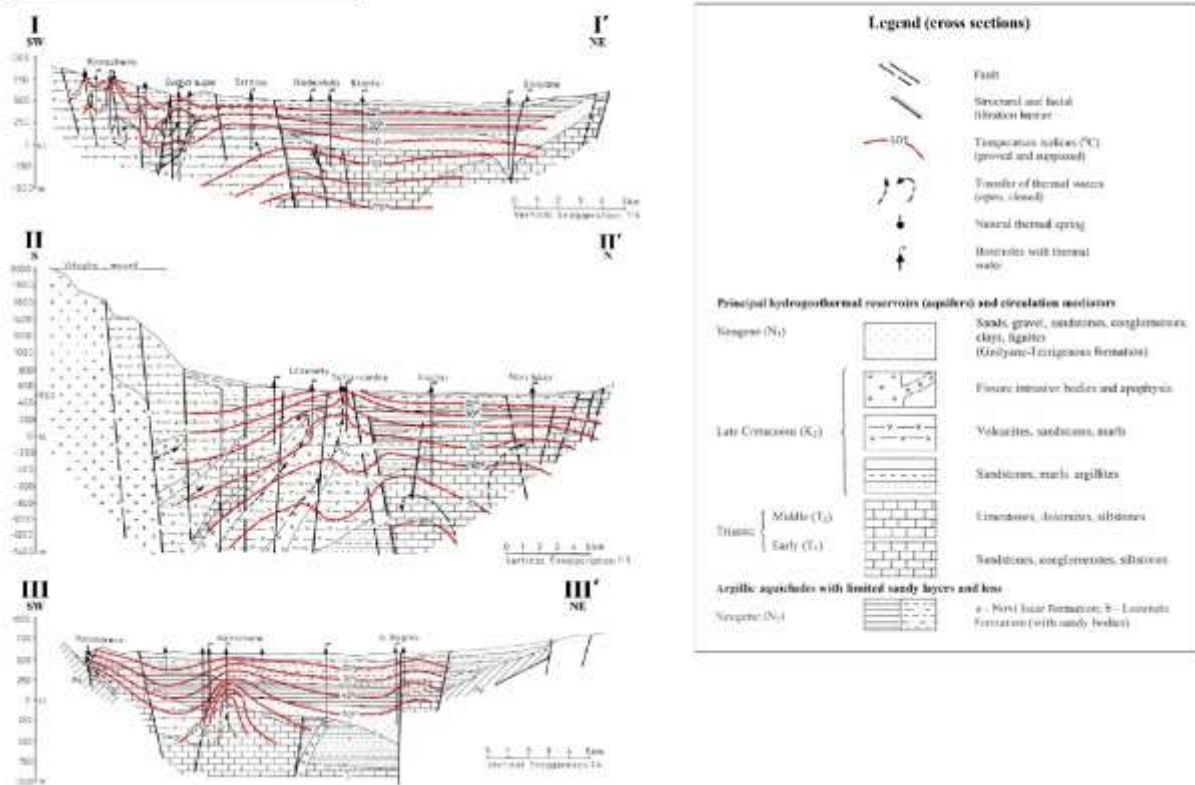


Figure 21 - Sofia Basin geothermal reservoirs map (European Commission, 2002) and geological cross sections from Shterev (2004).

An estimation of the geothermal potential for the Sofia Basin area was reported in the Atlas of Geothermal Resources in Europe (European Commission, 2002) and other authors, as a lower range value since it is essentially based on the sum of the thermal water flow rates used/measured in hot springs and existing wells. According to Petrov et al. (1998), the used/measured hot water flow rate yields 360 l/s. Shterev (2004) and Shterev and Georgiev (2011) reported the currently available/discovered thermal power capacity of the Sofia basin at 48 MWt, while the European Commission (2002) had previously indicated a capacity of 45 MWt.

## **Struma Valley**

For this study, the Struma Valley geothermal area embraces different geothermal sites located within and nearby the Struma tectonic depression, including those of Kyustendil and Sapareva Banya, that although geographically not inside the Struma Valley are adjacent to it to the north and are similarly associated with large faults and graben structures.

The Struma geothermal system is hosted in granitic-metamorphic basement rocks and in the Neogene filling of a NW-SE trending rift valley that initiates in southwest Bulgaria (Struma rift valley or Struma graben complex) and continues further south into Greece (Shterev et al., 1995). Extensive deformation in Neogene and Quaternary times, with large vertical displacements (up to 3.5 km), stimulated deep infiltration and circulation of meteoric water to charge at depth with geothermal energy in several sectors of the Struma valley. Most of the geothermal reservoirs in this area are constrained along fault systems; however, porous reservoirs of thermal waters were also discovered within Neogene sediments in the southernmost part of the Struma graben (i.e. at Sandanski – Figure 22). Some of these porous reservoirs are fed by geothermal waters ascending from the basement in correspondence of main faults.

According to Petrov et al. (1998) some 40 sites with thermal manifestations occur in the Bulgarian part of the Struma valley, but only half of them are characterized by geochemical analysis of thermal waters and geological information. The major thermal areas within the Struma Valley, from south to north, occur in proximity to the towns of Rupite, Levunovo, Sandansky, Sapareva Banya, and Kyustendil (Figure 22). Their key characteristics are summarized as follows:

- Rupite: (Kozhuh) scattered hot springs and wells BH-1961 (177 m deep); BH (500 m deep); and BH-1980 (246 m); higher measured temperature 75°C and total available flow rate 15 l/s.
- Levunovo: scattered hot springs and wells BH-1, BH-3 (152 m deep); higher measured temperature 86°C and total available flow rate 6 l/s.
- Sandansky: hot spring “Periloto” and well BH-1 (700 m deep); higher measured temperature 81°C and available flow rate 19 l/s.
- Sapareva Banya: two springs and well Nr. 1 (460 m deep); higher measured temperature 98°C and total available flow rate 17 l/s.
- Kyustendil: scattered hot springs and the wells BU and MC-5, with maximum temperature of 75°C and 33 l/s of available total flow rate.

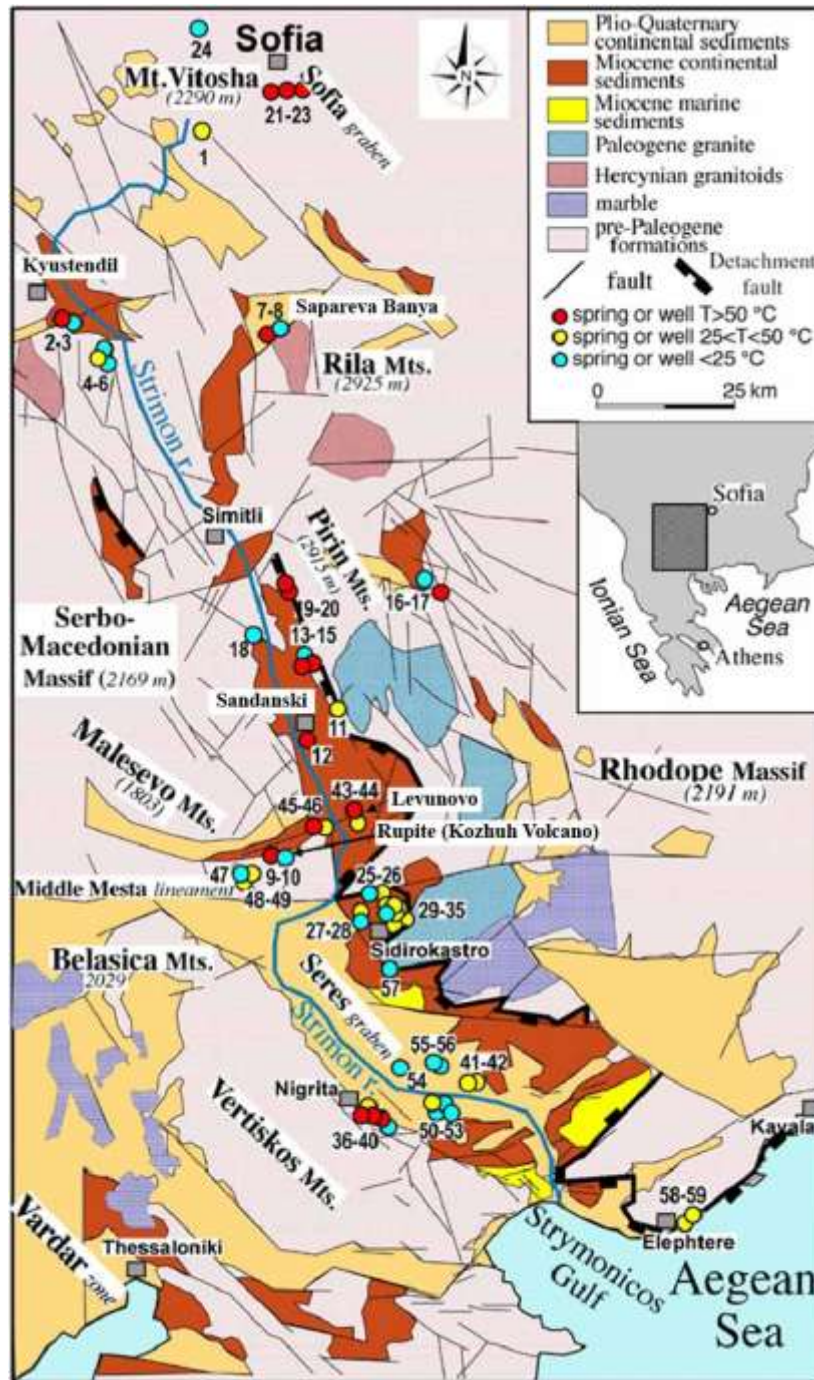


Figure 22- Geological schematic map of the Struma River Valley with main spring/wells and relevant temperatures (from Minissale et al. 2023 - modified from Shterev et al., 1995).

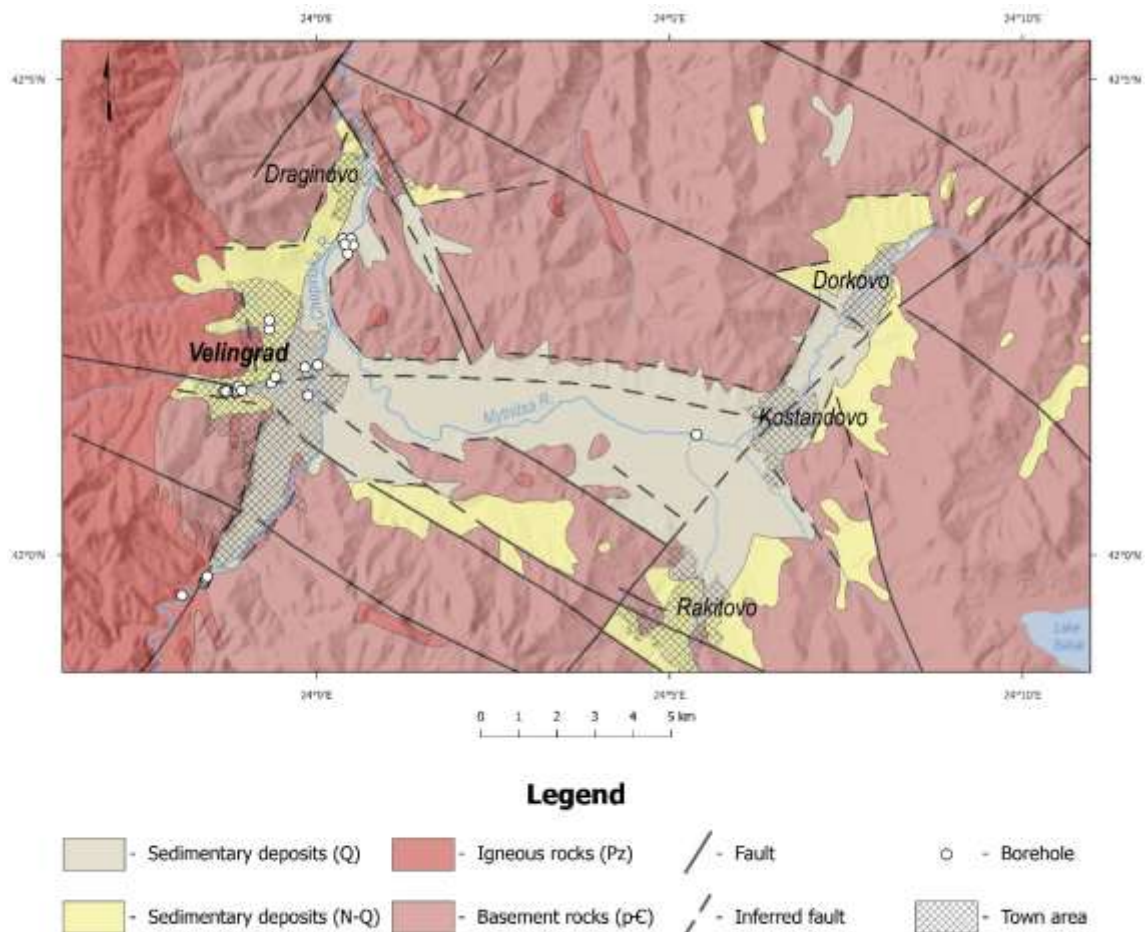
The total flow rate of thermal springs and wells in the Struma Valley area was estimated by the European Commission (2002) at 950 l/s, corresponding to 236 MW of thermal power (which would imply an average temperature drop of about 60°C). Substantially different figures for the Struma Valley and Kjustendil were given by Petrov et al. (1998), that reported 242 l/s and 78.4 MWt (at a final T of 15°C) (see Table 2). These same data were successively reviewed and reported by COWI (2005).

## Chepinska Valley

This geothermal area encompasses the town of Velingrad and the nearby minor centers of Draginovo and Rakitovo. It is hosted at the intersection of two main graben structures (one NNE trending and the other E-W trending) which form the Chepinska Valley depression where the river with the same name flows (

Figure 23). The exposed geological formations in this area are basement rocks (metamorphosed mylonite gneiss, liptinite, and marbles, intruded by Palaeozoic granite and Upper Cretaceous pegmatite granite), and Neogene sediments (sandstone, siltstone, mudstone, and conglomerate intercalations) deposited in the main graben structures. The permeability of the basement rocks is quite high due to extensive brittle deformation.

The main geothermal manifestations occur within (or nearby) the towns of Velingrad, Draginovo and Rakitovo. More than 30 wells have been drilled at various depths (50-600 m) and many scattered hot springs occur in this area. The temperature ranges between 37 and 94°C with a total flow rate of about 150 l/s. The corresponding thermal power is 27.1 MWt (Petrov et al., 1998; COWI, 2005).



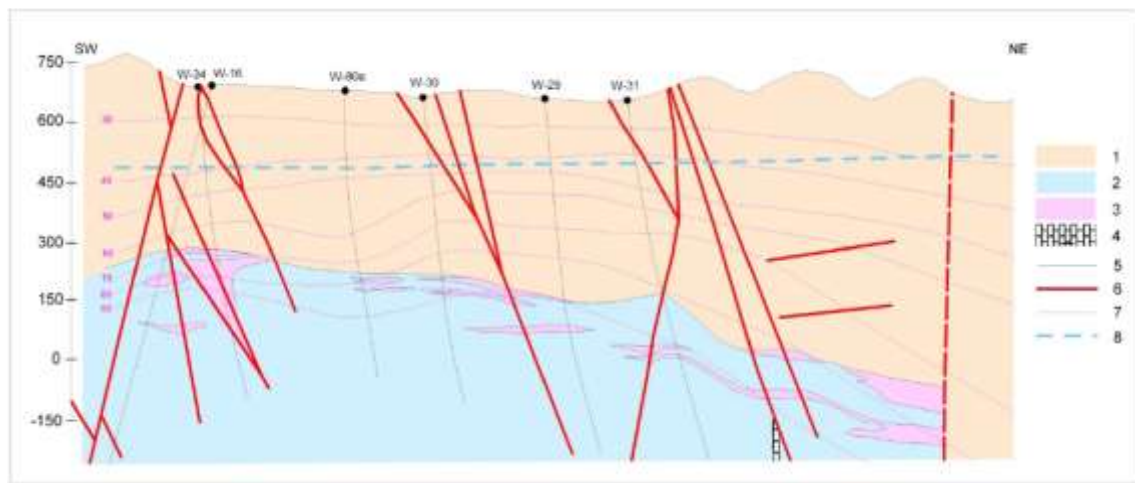
Sources: Geological map of Bulgaria 1:100000 (K-34-072 Velingrad, K-35-061 Pazardzhik, K-34-084 Bellitsa, K-35-073 Rakitovo), GEOFUND database, MoEW database, Catalogue of Geothermal Data of Bulgaria, Copernicus DEM, OpenStreetMap

*Figure 23 – Simplified geological map of the Velingrad graben. Drawn from Katskov and Dimitrova (1988), Katskov and Marinova (1988), Kozhukharov et al. (1988), and Kozhukharov et al. (1989).*

## Erma Reka

The Erma Reka geothermal area is located in the southern part of Bulgaria, close to the Greek border, some 12 km north-west of the town of Zlatograd and in correspondence of a Pb-Zn ore deposit, discovered in 1955 and which is still under exploitation, although with reduced production (Benderev et al., 2015).

Waters with temperatures as high as 90 °C were encountered during the mining works in a strongly karstified marble body embedded within a gneissic complex (consisting mostly of amphibolites and gneisses) at a depth of 450 m b.g.l. (see Figure 24). The marble body is reported to extend over a surface of about 25-30 km<sup>2</sup>, being delimited to the west and north by major faults and intersected by numerous fault systems (Benderev et al., 2015). About 60 wells with depths up to 1,500 m were drilled in the ore deposit, intersecting huge caverns. Figure 25 shows the temperature contour at +450 m a.s.l. (Teneva-Georgieva et al., 2005).



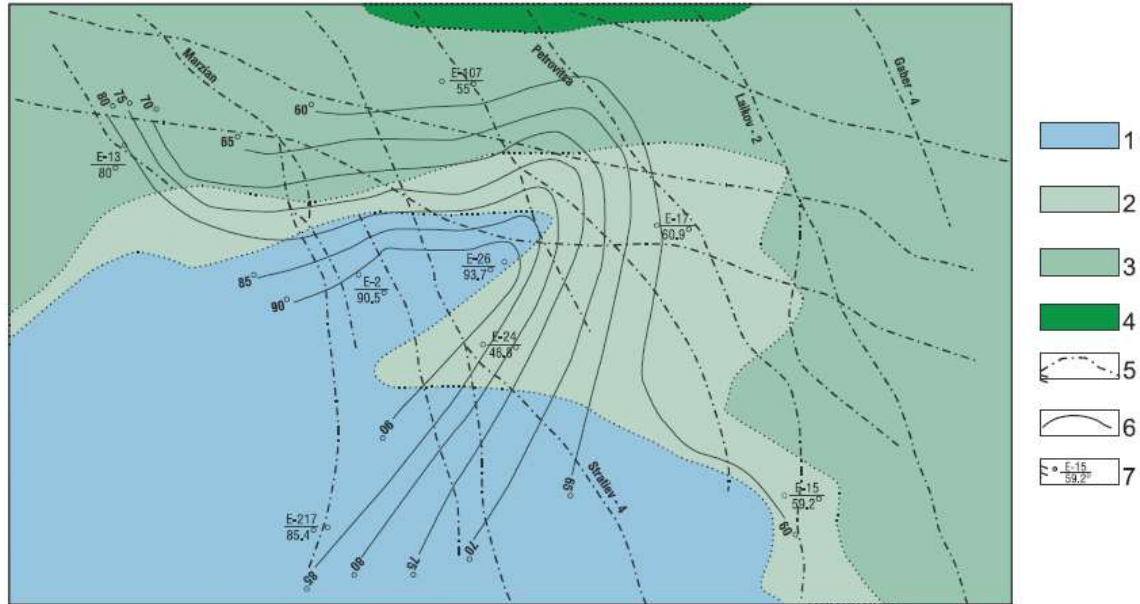
**Figure 24 – Geological section along the Erma Reka hydrothermal reservoir, including isotherms (from Benderev et al., 2015 – no location of the cross-section is provided in the literature source)**

Legend: 1. amphibolites, gneisses; 2. marbles; 3. quartz zones and ore zones; 4. caverns; 5. geological boundaries; 6. faults; 7. temperature isolines, °C; 8. piezometric water level (m); W-# wells.

It is worth observing that academics of the University of Mining and Geology met during the country visit conducted in December 2023 mentioned that temperatures of 130 °C have been measured in a 1,000 m deep well in the Erma Reka area. The location of the well was not informed. Such temperature value would be consistent with the silica geothermometer calculated in this study (see Annex C)

The Erma Reka thermal fluids have a relatively low salinity, with TDS between 0.6 and 1.6 g/l, and Na(Ca)-HCO<sub>3</sub>(SO<sub>4</sub>) composition (Benderev et al., 2015). The water volume contained within the marble body is in the order of 200 x 10<sup>6</sup> m<sup>3</sup>. Pumping tests conducted in several wells revealed a transitivity of 60 to over 2,000 m<sup>2</sup>/d and a hydraulic conductivity of 5 to over 100 m/d. These data indicate a geothermal reservoir with highly favorable hydrogeological conditions and potentially interesting temperatures.

A thermal energy of about 15 MW was estimated by Petrov et al. (1998) and subsequently reported by COWI (2005).



**Figure 25 – Temperature map of the Erma Reka geothermal system at an elevation of +450 m a.s.l. (from Teneva-Georgieva et al., 2005 – geographical reference for the map is not available in the literature source)**

Legend: 1. Granite-gneisses; 2. Biotitic gneisses; 3. Muscovite gneisses; 4. Marbles; 5. Faults; 6. Isotherms; 7. Well – number and measured temperature

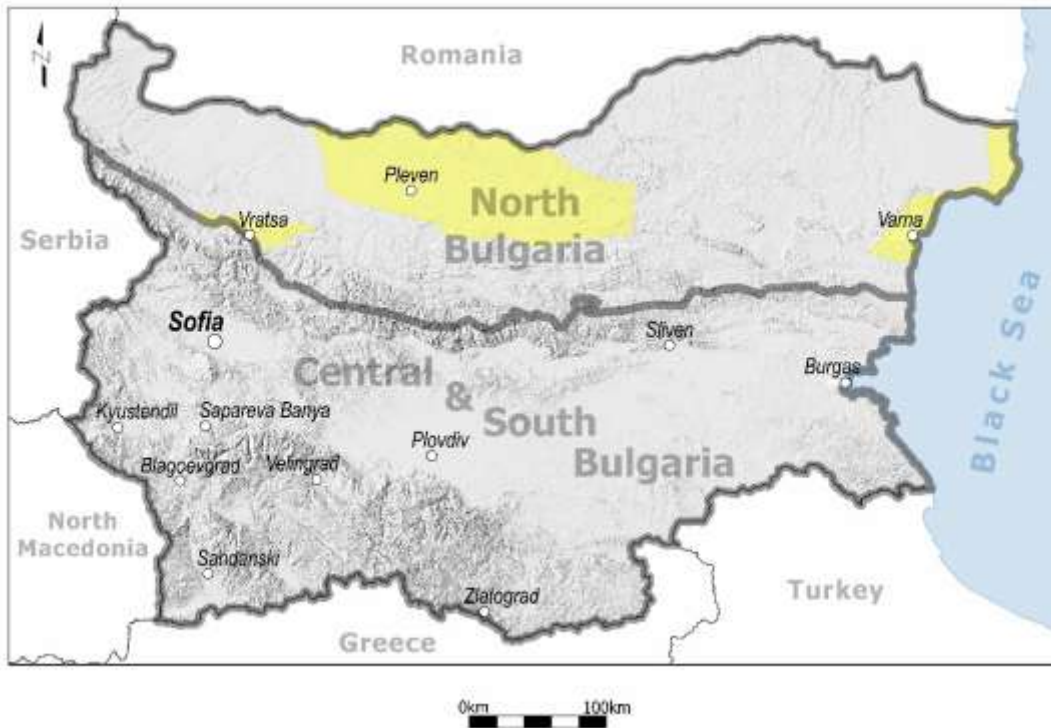
## 4. Summary of proposed priority geothermal areas in Bulgaria

### 4.1 Priority geothermal areas in the Moesian platform and Fore-Balkan zone

Among the 3 aquifers identified in North Bulgaria, the deepest ones of Devonian-Carboniferous and Middle-Late Jurassic ages are poorly known, as they were reached by a small amount of the wells drilled for oil and gas exploration. In addition, despite these aquifers may reach higher temperatures, of about 150°C, its utilization is likely hindered by the high costs of drilling deep geothermal wells, at depths of 4,000-6000 m, and by the high inferred salinity of the deep geothermal brines implying potential scaling and corrosion issues. For this reason, it is worth concentrating initial geothermal development efforts on the better-known and lower-risk Malm-Valanginian aquifer.

The more promising areas of the Malm-Valanginian aquifers in the Moesian platform and Fore-Balkan zone were selected in this study considering the temperature data and estimations of extractable thermal energy per unit surface reported by the Atlas of Geothermal Resources in Europe (European Commission, 2002). The resulting most promising areas, suggested to be considered for short-term resource development in North Bulgaria, are as follows (Figure 26):

- **Pleven** (central portion of the Malm-Valanginian aquifer in the Moesian Platform).
- **Varna** (portion of Malm-Valanginian aquifer adjacent to the northern Black Sea coast).
- **Vratsa** (small portion of the Malm-Valanginian aquifer located within the western Fore-Balkan zone).



*Figure 26 – Proposed most promising geothermal areas in northern Bulgaria (highlighted in yellow).'*

#### 4.2 Priority geothermal areas in Central and South Bulgaria

In central and southern Bulgaria, the more promising geothermal areas were selected considering the major structural features, temperature anomalies in surface springs and drilled wells, and the available data on thermal power from existing wells and natural hot springs.

Based on the review of available data, the following geothermal areas are suggested as the most promising in Central and South Bulgaria (Figure 27):

- **Sofia Basin** (Sofia city area and surrounding region, Kazichene in particular)
- **Chepinska Valley** (towns of Velingrad, Draginovo, Rakitovo, and nearby areas in the Chepinska Valley)
- **Struma Valley** (towns of Sandansky, Rupite, Sapareva Banya, Kyustendil, and Blagoevgrad and nearby areas within the Struma River tectonic rift).
- **Erma Reka** (town of Zlatograd and nearby areas including the Erma Reka mine).

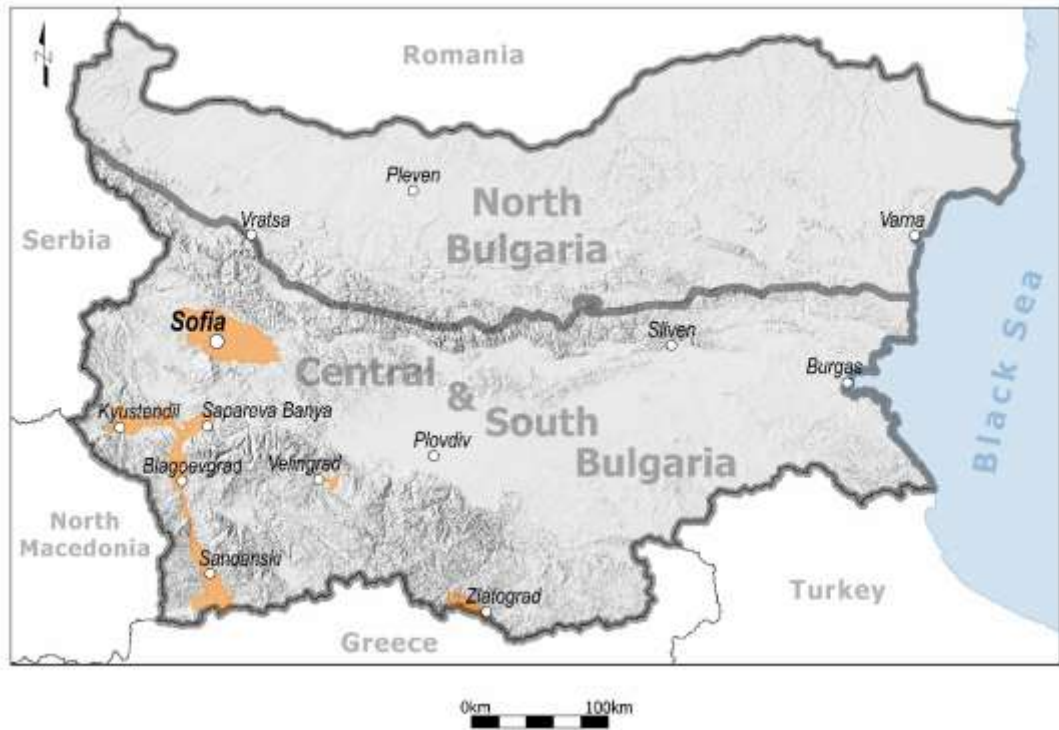


Figure 27 – Proposed most promising geothermal areas in central and southern Bulgaria (highlighted in orange).

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