GEOTHERMAL RESOURCES AND SYSTEMS IN THE STRUMA (STRYMON) RIFT VALLEY (BULGARIA AND GREECE)

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1. Introduction

The Struma rift valley (graben system) is one of the most interesting and rich in thermal waters regions on the Balkan Peninsula. The geothermal activity is manifested by about 100 natural and borehole thermal sources, and many temperature and hydrogeochemical anomalies provoked by hidden deposits of thermal waters in the basement, boards and sedimentary filling of the grabens.

The Struma geothermal zone is a perfect subject for fundamental studies of the structural, hydrodynamic and geochemical characteristics of non-stratified (fault- and fracture-bounded) hydrogeothermal deposits and circulation systems that have developed in tectonically active granite-metamorphic terrains outside active contemporary volcanic structures and belts. Such studies are needed also for exploration and evaluation of the geothermal resources in view of their utilisation in the tourist industry, urban needs, agriculture (geothermal greenhouses), bottling industry, and other economic activities important for Bulgaria and Greece. Industrial natural CO_2 will be possibly available in the Greek part of the valley.

The present paper is a summary of our estimations and prognoses for the character, spatial distribution, amounts and quality of the geothermal resources emplaced and reproducing themselves in the Struma rift valley. Detailed studies on some particularly important and impressive hydrogeothermal deposits in different parts of the valley will be subject of special publications.

2. Methods and information base

The present study is based on deductive interpretations and summaries of existing evidence about the geological structure, the hydrogeology and geothermal conditions of the Struma rift valley and the surrounding horsts. Methods and ideas already presented in our previous publications and prognoses on the thermal waters and hydrogeothermal systems and provinces (Shterev, 1971, 1984, 1989; Shterev and Penev, 1991) are also used as well as all available data for hydrogeological studies and shallow geothermal drilling (Sidirokastro, Lithotopos, Nigrita, Serres). Precious information has been supplied also by the two deep oil-prospecting boreholes in the Serres graben (Stry-1, Stry-2).

3. Geological setting of the Struma (Strymon) rift valley in view of its geothermal perspectives

The Struma rift valley is a segment of a complex Palaeogene - Neogene fault system in the central parts of the Balkan Peninsula. After the last compressional phase in the Early Miocene, it developed in Neogene and Quaternary time under extensional conditions as a NNW-SSE continental rift (Zagorchev, 1992) extending over more than 200 km in Bulgaria and Greece (Fig. 1).

The basement of the grabens is widely exposed in the surrounding horsts. It consists of amphibolite-facies metamorphic rocks (gneisses, migmatites, schists, amphibolites, marbles) of supposed Precambrian age, intruded by Palaeozoic, Late Cretaceous and Palaeogene granitoids, and partially covered by Palaeogene volcanic and sedimentary formations.

The principal fault sets strike **NNW-SSE** (Struma Lineament), SSW-NNE to SW-NE, and WNW-ESE to W-E. The grabens are usually elongated along the strike of the lineament although some of them follow the strike of oblique or transverse fault sets Thus, the horst-and-graben pattern of the region consists of slightly elongated but almost isometric horsts surrounded by grabens

The neotectonic Serbo-Macedonian Swell formed in the beginning of the Miocene, and has been subject to continuous subsidence since Late Badenian or Sarmatian times. During a first stage (Late Badenian - Sarmatian), a small area along the Struma Lineament has been the site of lacustrine sedimentation. The second stage (Maeotian?) followed to the south of the threshold of the Middle-Mesta fault zone (lineament) with a marine ingression, and to the north, with alluvial to lacustrine sedimentation. New intense vertical block movements began in Pontian time when coarse proluvial and alluvial sediments filled the grabens during the third stage (Pontian - Romanian) A fourth stage (Pleistocene and Holocene) was marked by the most prominent horst uplift The proluvial deposits of this stage form huge fans along the active Quaternary faults. The vertical amplitude (uplift) along the main neotectonic faults reached 3.5 - 4 km. The total thickness of the Neogene and Pleistocene deposits in the grabens varied from 1 to 2 km in the northern (Blagoevgrad, Simitli, Sandanski) grabens, and up to 3 - 3.5 km, in the Serres Graben.

The grabens are usually asymmetric, with steep (60 - 80^{o}) bounding normal faults However, the dip of some faults gradually decreases towards south, and the extension perpendicular to the rift increases considerably In consequence, block rotation and mutual adjustments led to an en-echelon arrangement, and the grabens were tilted against the fault zones with great vertical offset Some of the fault structures and fault intersections control earthquake foci at depths of 2 - 10 km, and in rare cases, down to 45 - *50* km

The fault structures and the movements in the basement and at the sides of the Struma rift valley control a generalised and deep circulation of meteoric waters The result is the formation of non-stratified (fault-and-fracture bounded) hydrogeothermal deposits and systems that contain and reproduce low-mineralised thermal waters with nitrogen gas composition Some of the fault structures in the Serres graben emit intense flows of endogenous CO_2 Carbonated or CO_2-containing thermal waters with increased mineralisation are formed around them

Permeable sedimentary rocks at the deep stratigraphic levels of the Serres and Sandanski grabens represent potential autonomous layered reservoirs of thermal waters as well as possible recipients of hot waters that penetrate from the basement through permeable faults or lithofacies windows. Layered reservoirs of thermal waters possibly exist also in karstified marble bodies in the basement of the Serres graben, and to a lesser extent, of the Sandanski graben

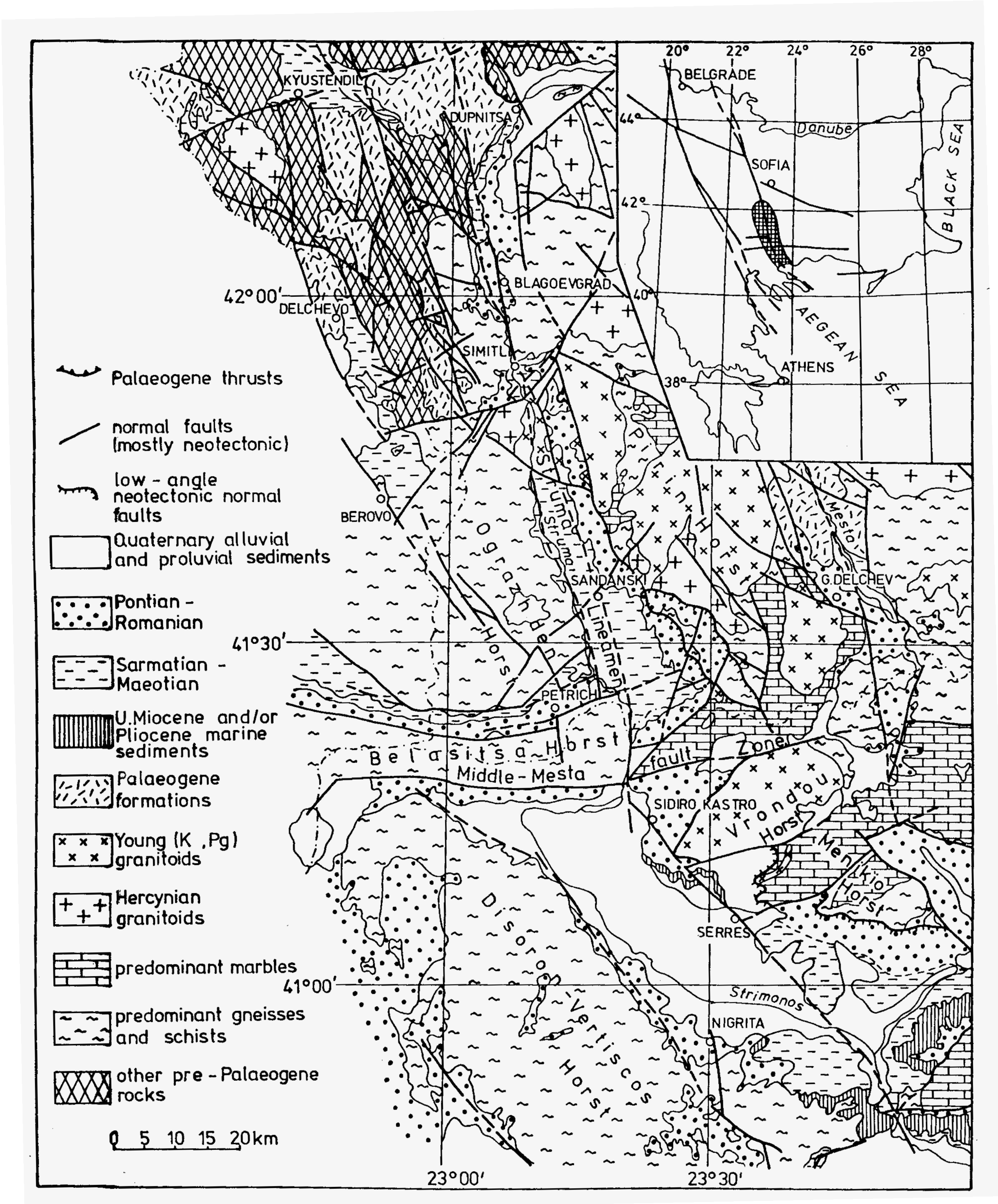

Fig. 1. Simplified geological map of the Strymon valley in Bulgaria and Greece. Inset - position of the area studied in the Struma Lineament and other important lineaments in the Balkan Peninsula

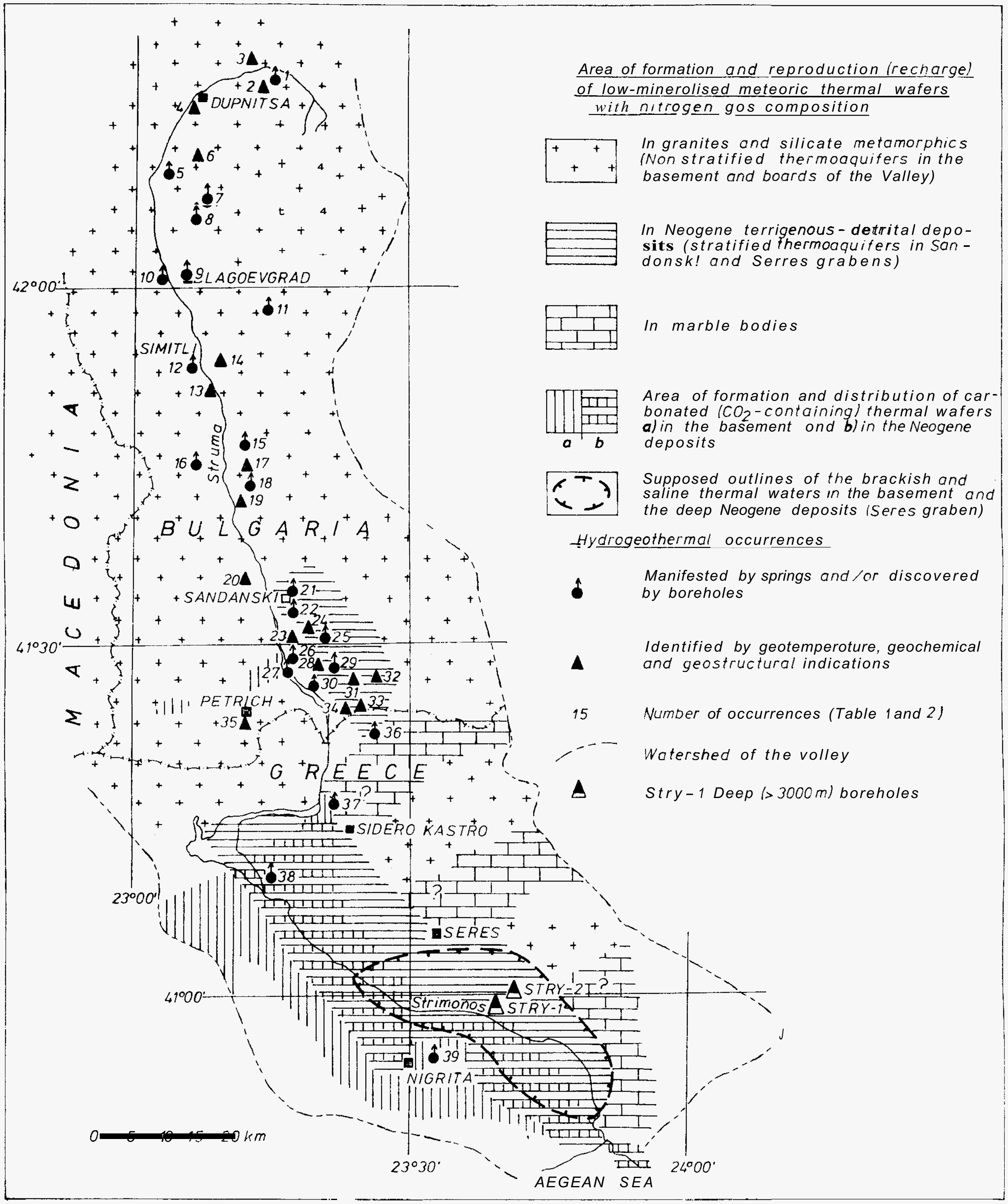

Fig. 2. Hydrogeothermal zoning and activity in the Struma (Strymon) rift valley

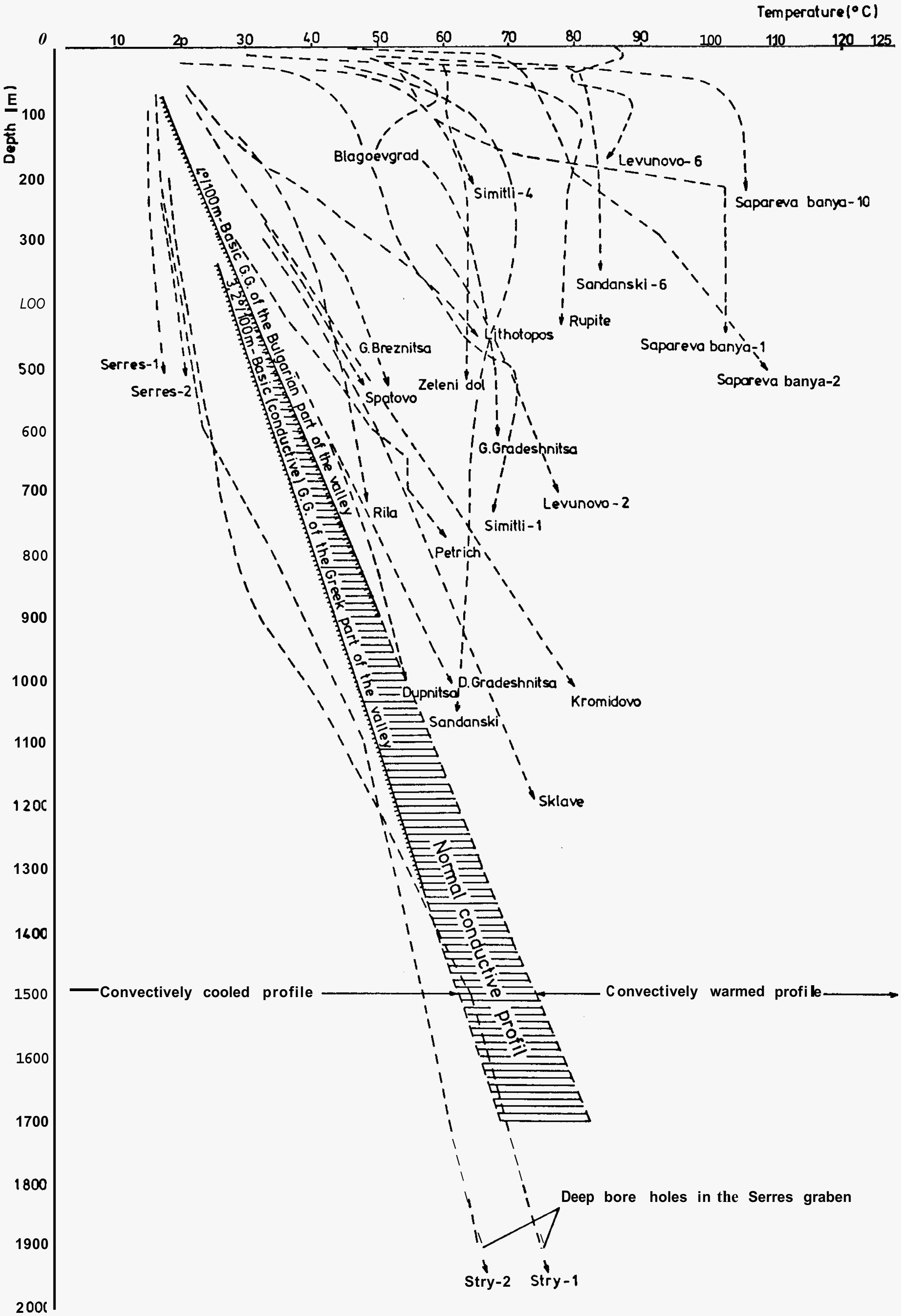

Fig. 3. Geothermal profiles (geothermograms) and regimes in different points of the Strymon valley

Genetic classification: Origin of the solvent	Hydromineral genetic group (after the gas composition)	Hydrogeochemical type	Principal geothermal occurrences (Number correspond to Fig. 2)		Temperature measured / calculated °C	pH	TDS g/l	Cl	SO_4	HCO_3 (CO_3)	K	Na	Ca	Mg	SiO_2 (H_2SiO_3)	F	B (HBO_2)	H_2S (HS)	CO_2	Geological localisation
							Chemical composition	Principal components mg/l								Specific substances mg/l				
ATHMOSPHERIC (METEORIC)	Low mineralized thermal waters containing nitrogen (N_2) (Acratothermae) Ⓐ	A_{si} (in granites and silicate metamorphics)	1	Sapareva banya	101 / 115	9.3	0.650	15	210	82	14.0	170	5.5	-	130	16	4	14	-	Faults and fractures in the granite metamorphic basements and boards of the Blagoevgrad, Simitli and Sandanski grabens
			9	Blagoevgrad	55 / 70	8.0	0.770	31	237	180	11.0	191	9.0	0.5	90	10	3	8	-	
			10	Zeleni dol	61 / 75	9.2	1.06	41	201	410	6.0	290	1.2	-	95	11.5	7	3	-	
			11	D.Osenovo	59 / 75	8.5	0.575	14	171	121	8	119	5.1	2.0	90	10	1	6	-	
			12	Simitli	63 / 80	9.4	0.635	21	223	95	3.0	174	3.1	0.2	98	12	2	8	-	
			15	Oshtava	56 / 75	8.6	0.480	15	117	140	3.5	119	3.5	1.7	60	12	-	3	-	
			16	G.Breznitsa	39 / 55	8.6	0.517	31	108	158	2.4	144	3.0	0.6	54	14	-	1	-	
			18	G.Gra-deshnitsa	67 / 80	8.4	0.520	17	112	159	3.5	126	6.0	0.8	85	10	-	3	-	
			21	Sandanski	83 / 95	7.8	0.653	18	142	220	7.7	153	11.0	0.5	90	6.5	2	2	-	
			25	Hotovo	37 / 80	9.0	0.460	16	134	128	0.6	127	4.6	0.5	40	5.6	-	1	-	
			26	Levounovo	87 / 100	7.5	0.935	28	177	390	12.1	229	18.0	0.2	75	9.0	7	2	10	Secondary reservoirs in the neogene sandstone sequences + marbles
			29	Kromidovo	47 / 80	8.5	0.618	19	201	169	3.2	160	4.0	0.6	47	10.0	3	2	-	
			30	Mari-kostinovo	62 / 75	7.3	1.02	21	223	415	12.0	240	11.0	6.5	65	10.0	6	2	20	
			36	Angistron	40 / 70	7.2	0.398	22	45	173	3.6	60	45.0	4.0	35	5.0	1	2	-	
		A_t in terrigenous detrital deposits	32	Katuntsi	28 / 40	8.9	0.370	14	14	205	1.0	88	3.5	0.2	22	0.3	-	-	-	Neogene sandstone reservoirs
			Unidentified		– / 30 - 60	7.5 - 9.0	< 1.5	<100	<100	<500	<5	<250	<50	<10	<50	<1.5	-	-	-	
		AK_0 in marbles	Subthermal	Unidentified	– / 30 - 40	7.4	0.470	4	17	312	1.2	4	60.0	29.7	35	0.6	-	-	-	Marble basement of the grabens
			Thermal		– / 45 - 70	6.8 - 7.2	< 1.25	<100	<100	<700	<10	<100	<150	<50	<50	<2	<2	<2	<200	
	Carbonated (CO_2 - containing) thermal waters of bicarbonate composition		27	Rupite (Kozhuh)	76 / 90	6.5	2.230	45	133	1360	48	525	31.5	14	60	6.4	10	3	1200	Metamorphics
			37	Sidero-kastro	41 - 54 / 60 - 80	6.3	1.660	54	210	873	40	245	140	24	50	4.0	10	2	1500	Metamorphics and ultrabasites
			38	Lithotopos	37 / 60 - 80	6.5	1.700	76	111	942	24	410	26	20	53	3.9	9	1	>500	
			39	Nigrita	54 - 61 / 70 - 80	6.4	3.500	159	134	2058	82	550	129	122	80	2.2	12	2	>1500	Zones of CO_2 - invasion
Marine sedimentary (relic) or mixed	Carbonated (CO_2) thermal waters of chloride composition	Brackish	Unidentified		– / 40 - 60	~ 6,5	5 - 10	*Cl-HCO₃-Na*, chloride bicarbonate waters									+	+	500	Neogene sand and sandstone reservoirs in the deep (>1000 m) sequences of the Seres graben
		Saline			– / 50 - 70		10 - 35	***Cl-Na***, chloride waters, containing ***I*** and ***Br***									+	+	3000	
		Brine			– / 50 - 80		35 - 50	***Cl-Na***, weak brines, containing ***I*** and ***Br***									+	+	5000	
	Methan (CH_4) containing thermal waters of chloride composition	Brackish	Unidentified		– / 40 - 60	7 - 8	5 - 10	***Cl-Na***, brackish waters									+	+	0-200	
		Saline			– / 50 - 75		10 - 35	***Cl-Na***, saline waters, containing ***I*** and ***Br***									+	+		
		Brine			– / 50 - 80		35 - 50	***Cl-Na***, weak brines, containing ***I*** and ***Br***									+	+		

- Manifested by springs - Discovered by bore holes * Identified indirectly		Measured	Estimated	Water yield - Q		Thermal power - H
(Numbers correspond to Fig. 2)		T_m	T_e	Prognostic Q_p	Manifested (Discovered) Q_m	$H=Q_p(T_e - T_o)$
		^oC		$10^{-3}\ m^3/s$		MW_t
1	Sapareva banya	101	115	20	14,0	8,37
2*	Ovchartsi	-	70	15	-	3,45
3*	Kraynitsi	21	60	10	-	1,88
4*	Dupnitsa	31	60	10	0,8	1,88
5	Slatino	25	50	25	14,0	3,66
6*	Badino	19	50	25	5,0	3,66
7	Rila	37	60	15	1,0	2,82
8	Stob	29	50	10	0,5	1,46
9	Blagoevgrad	55	70	25	16,0	5,75
10	Zeleni dol	61	75	25	14,0	6,27
11	Dolno Osenovo	59	75	15	6,5	3,76
12	Simitli - a	63	80	35	25,0	9,51
13*	Simitli - b	35	70	25	11,0	5,75
14*	Simitli -c	40	70	20	-	4,60
15	Oshtava	56	75	20	5,5	5,00
16	Gorna Breznitsa	40	55	15	6,0	2,51
17*	Vlahi	23	75	15	-	3,76
18	Gorna Gradeshnitsa	67	80	20	8,0	5,43
19*	Dolna Gradeshnitsa	60	80	20	-	5,43
20*	Palat	22	60	15	1,5	2,82
21	Sandanski	83	95	25	18,5	8,37
22	Leshnitsa	35	80	15	2,7	4,08
23*	Delchevo	35	80	15	-	4,08
24*	Sklave - Spatovo	38	80	20	4,0	5,43
25	Hotovo	37	80	20	7,0	5,43
26	Levounovo	87	100	25	15,0	8,90
27	Rupite (Kozhuh)	76	90	45	30,0	14,12
28*	Novo Konomladi	24	70	15	-	3,45
29	Kromidovo	47	80	20	4,5	5,43
30	Marikostinovo	62	75	35	23,0	8,78
31*	Vranya	22	75	20	-	5,02
32*	Katuntsi (under)	40	75	20	0,5	5,02
33*	Novo Hodzhovo	-	70	15	-	3,45
34*	Chuchuligovo	-	60	15	-	2,82
35*	Petrich	30	75	25	1,0	6,27
Unidentified occurrences		-	75	250	-	62,76
Total for Bulgarian part			-	950	235,0	~236,00
GREEK PART						
36	Angistro	40	70	40	20,0	9,20
37	Sidirokastro	54	80	50	25,0	13,60
38	Lithotopos	37	75	50	7,0	12,50
39	Nigrita	61	75	60	~35,0	15,00
Unindentified occurrences including in the marble basement of the SrG			65	300	-	62,70
Total for Greek part				470	87,0	~113,00
TOTAL FOR THE VALLEY				1450	322,0	~349,00

2. IN THE AUTONOMOUS GEOTHERMAL RESERVOIRS OF THE DEEP NEOGENE TERRIGENOUS - DETRITAL

GRABEN	DEPTH	PROGNOSTIC				
	m.	Surface area km^2	Average temperature ^oC	Specific hydrothermal reproduction $l/(s\ km^2)$	Total water reproduction $10^{-3}\ m^3/s$	Total thermal power MWt
Sandanski	300 - 1200	250	45	0,250	75	-9
Seres	500 - 1500	1500	50	0,250	375	-55
Total		1750			450	-64

2.2.2. **Resources:** $H_1 = H_o.R_o$; $R'_o = 0{,}33\frac{T_t - T_r}{T_t - T_o} = 0{,}264$; $R''_o = 0{,}1\frac{T_t - T_r}{T_t - T_o} = 0{,}08$; $T_r = 25^oC$

$H_1 = 1{,}225.10^{18} J$ or $2{,}45 GJ/m^2$

$H'_1 = 0{,}370.10^{18} J$ or $0{,}74 GJ/m^2$

The Neogene marine transgression and sedimentation controlled the formation of brackish and saline thermal waters at deep stratigraphic levels and in the basement in the southern part of the Serres graben.

4. Origin, character and geologic localization of the thermal waters

Our evaluations of the origin, physicochemical characteristics and geologic localization of all exposed and potential thermal waters in the hydrogeological space of the valley are summarized in Table 1 Most of the thermal waters have a meteoric origin and continuous recharge. Only the basement and the deeper Neogene reservoirs of the Serres graben preserved fossil saline thermal waters and brines of sedimentary marine origin.

Most of the meteoric waters possess a nitrogen gas composition, alkali character and very low mineralisation (from 0 3 to 1 - 1 5 g/l) All three natural types of nitrogen hydrotherms (acratothermae) are present They are formed in silicate, carbonate, and terrigenous-clastic geological environment, respectively Carbonated meteoric waters or fossil thermal waters, respectively, with bicarbonate and chloride mineralisation, are formed in zones of endogenous CO_2 invasion

5. Hydrogeothermal activity and zoning of the Struma rift valley

Our ideas about the hydrogeothermal activity and zoning of the Struma (Strymon) rift valley are shown on Figure 2 The geothermal profiles based on boreholes (Fig *3)* illustrate the inductive and convective elements in the geothermal regime of the valley It can be concluded that all hydrogeothermal deposits and systems have originated and acted at normal (or almost normal) geothermal gradients and heat flows (3 - 4^{o}C/100 m and 60 - 100 mW/m^2, respectively)

The hydrogeothermal activity of the Struma valley is expressed in 39 autonomous or conjugate deposits of thermal waters Seventeen of them are still not exposed, although they are identified by temperature and geochemical indicators **A** significant number of unidentified deposits in the granite-metamorphic basement and the boards of the grabens are probable Considerable studies are needed to outline and evaluate the stratified hydrogeothermal reservoirs and recipients in the Neogene sedimentary filling of the Sandanski and Serres grabens

6. Approximate evaluation of the geothermal resources

Table 2 provides a summary of the geothermal resources of the Struma rift valley It covers all manifested, exposed, identified and supposed hydrogeothermal deposits and layer reservoirs in the basement, boards and sedimentary filling of the grabens

The first part of the table contains estimation of the reproducible geothermal resources and powers of the non-stratified (fault- and fracture-bounded) deposits of thermal waters with meteoric origin. Their total reproducible potential is estimated at 1450 l/s thermal waters with temperatures between 50^{o} and 115^{o}C and a total thermal power about 350 MWt. At the present moment, only 322 l/s thermal waters with temperatures from 21^{o} to 101^{o}C and total thermal power about 60 MWt are manifested

The second part of the table presents our prognostic evaluation of the geothermal resources of the open (convective) and closed (conductive) bedded or stratified reservoirs and recipients of thermal waters in the deeper parts of the graben sedimentary filling The reproducible resources of the open reservoirs are estimated at about **450** l/s thermal waters with a mean temperature of 50^{o}C and total thermal power about 64 MWt The thermal potential (heat in place) of the closed (conductive) reservoirs with saline thermal waters in the Serres graben is estimated at 4 64 x 10^{18} J, or 9 28 GJ/m^2 The extractable part of this potential is respectively 1 225 x 10^{18} J (2 45 GJ/m^2) in case of doublet borehole exploitation, and 0 370 x 10^{18} J (0 74 GJ/m^2) in case of singlet borehole exploitation

7. Conclusion

The Struma (Strymon) rift valley is one of the richest and most diverse geothermal zones on the Balkan Peninsula. According to preliminary evaluation, about 1900 l/s thermal waters with a total thermal power above 400 MWt are continuously reproducing themselves in its depth. A considerable geothermal potential (about 4.6 x 10^{18} J) exists also in closed (conductive) bedded reservoirs with salty thermal waters and brines in the Serres graben. Considerable resources of natural C02 are outlined in the Greek part of the valley.

The predominant part of the geothermal resources of the valley are localized and reproduced in the granite-metamorphic basement and the boards of the grabens, i e., in the non-stratified (fault- and fracture-bounded) thermoaquifer systems. According to approximate estimations, each square kilometre of these systems reproduces in depth about 0.2 l/s thermal water, and 50 kWt convective thermal energy.

The studies on the hydrogeothermal resources and systems of the Struma (Strymon) rift valley are of paramount scientific and applied importance The realization of joint scientific and commercisl projects in the Struma geothermal zone would be of considerable interest for the two countries

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