Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Low Enthalpy Geothermal Fields in the Strymon Basin (Northern Greece)

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Key Words: Greece, Strymon basin, exploration, exploitation

ABSTRACT

The basin of Strymon is a typical post-orogenic graben with geothermal interest. It lies in the region of Eastern Macedonia (Northern Greece). The total thickness of the Neogene – Quaternary sediments of the graben is estimated to be 4000 m.

Some important geothermal fields exist in the Strymon basin (fields of Nigrita, Sidirokastro, Lithotopos - Iraklia, Agistro and Ivira – Achinos). The temperature of the waters ranges from 40 to 74^oC and they come from relatively shallow depths (50-650 m). The geothermal anomaly occurs mainly due to deep fault systems, which are normal and strike-slip structures. The majority of the waters are classified as $Na\text{-}HCO_3$ type with TDS 0.3–2.5 g/l (low salinity). Furthermore, the waters of the Nigrita field are rich in CO_2 (about 3.7 kg/m^3 water).

The exploitation of geothermal energy is limited to greenhouses heating (Nigrita and Sidirokastro), balneology and bathing pools (Nigrita, Sidirokastro, Agistro), culture of the microalga Spirulina (Nigrita) and subsurface heating for asparagus cultivation (Nigrita). In the areas of Lithotopos – Iraklia and Ivira – Achinos the geothermal research is still ongoing (some interesting exploration boreholes have been drilled).

In this paper, the geological and geothermal conditions of the various fields in the Strymon basin are reviewed. Furthermore, the corrosion and scaling tendencies of the geothermal waters from the basin were assessed.

1. GEOLOGY, TECTONICS AND GEOTHERMAL CONDITIONS IN THE STRYMON BASIN

The basin of Strymon is a typical post-orogenic graben, which is still active. It has been formed between the Serbomacedonian massif (SRB) on the West and the Rhodope massif on the East (Fig. 1).

The crystalline mass of Rhodope consists of two lithological units: the lower tectonic unit (Pangeon Unit) of lower-grade metamorphism and the upper tectonic unit (Sidironero Unit) of higher-grade metamorphism (Papanikolaou and Panagopoulos, 1981). The eastern margins of the Strymon basin belong to the Pangeon Unit composed of marbles, gneisses and mica schists. The Vrondou granitic complex intrudes the metamorphic rocks of the Pangeon Unit. The ages of this plutonite range between 28 and 32 Ma (Marakis, 1969; Durr et al., 1978; Kolocotroni, 1992).

The Serbomacedonian (SRB) massif (on the W) is divided into two crystalline "series" (Kockel at al., 1971; 1977): (a) the Kerdylia series (at the NW margins of the basin), largely composed of migmatic gneisses, amphibolites and marbles (lower unit) and (b) the Vertiskos series, composed of intercalations of schists, leucocratic and augen gneisses and amphibolites (upper unit). Late Paleozoic, Cretaceous and Paleogene granitoid bodies intruded into the Serbo-macedonian massif (Kilias et al., 1999). On the east the SRB lies structurally above the Pangeo Unit of the Rhodope crystalline rocks (Kockel and Walther, 1965; Koukouzas 1972). The Rhodopian Pangeo / SRB contact is considered by Socoutis et al. (1993) and Dinter and Royden (1993) as a normal Oligo-Miocene detachment fault for more than 150 km along strike and its regional dip is approximately 3^o SW. After the last compressional phase, the Oligocene - Miocene extension and unroofing of the Rhodope massif took place (Kilias and Mountrakis, 1998). During the Eocene-Oligocene NE-SW subhorizontal extension affected the SRB massif with tectonic unroofing of the SRB (Kilias et al., 1999).

The principal faults are oriented in NNW-SSE, NNE-SSW to NE-SW and WNW-ESE to W-E directions. Except of the post-Middle Miocene NE-SW extension, in the wider area of North Aegean the following extensional phases with strike-slip motion are considered (Lyberis, 1984; Mercier et al, 1987, 1989; Pavlides and Mountrakis, 1987; Voidomatis et al., 1990): (a) Late Miocene –Early Pliocene with WNW-ESE direction forming NE-SW faults, (b) Pliocene – Lower Pleistocene with a NE-SW direction of σ_3 creating NW-SE faults and reactivating the older ones, (c) Middle Pleistocene – present with N-S extension reactivating the pre-existing NW-SE or NNE-SSW faults with normal or strike-slip movement and forming a new group of E-W normal faults over the older fault network. Small volcanic edifices (probably alterated rhyolites) outcrop at the margins of the Strymon basin (Strymoniko, Sitsi-Kamen) associated with the above-mentioned extension tectonics.

The total thickness of the Neogene and Quaternary sediments at the center of the basin is estimated to be close to 4000 m. Various depositional palaeoenvironments (continental, fluvial, fluviolacutrine, lacustrine-marshy, marine, brackish, deltaic) were created during the Neogene – Quaternary and their succession (lateral extension and transition as well as the presence of Tethyan and Paratethyan invations) make the stratigraphy very complicated (Syrides, 2000). The typical stratigraphic column of the basin consists of the older Miocene formations (basal conglomerates and breccia, alternations of clays, siltstones, sandstones, dark brown marls, lignite layers, petroliferous limestones), 700-800 m Pliocene sediments (layers of evaporates, conglomerates, travertines, marls, red clays, sandstones, siltstones, limestones, lignites) and 900-1000 m of Pleistocene sediments (alternations of shales, sands, clays, sandstones, marls, conglomerates and limestones) (Lalechos, 1986; P.P.C., 1988).

The Strymon basin is of primary geothermal interest. The thermal manifestations are located at the margins of the basin. The hot springs of Sidiorokastro (water temperatures 40-46^{o}C) and Therma – Nigrita (temperatures up to 52^{o}C) are well known. Most of the thermal waters have a meteoric origin and continuous recharge.

In the central part of the Strymon basin three deep exploration oil boreholes (STR-1, STR-2, STR-3 at depths of 3651, 2678 and 3144 m respectively) were drilled (Fig. 1). In the borehole STR-1 the average geothermal gradient is 31^{o}C/km and the temperatures of 57, 66, 106 and 135^{o}C were measured at depths of 1209, 1475, 2884 and 3651 m correspondingly (P.P.C., 1988). The lithostratigraphy of this well is: 0-870 m Pleistocene sediments, 870-1711 m Pliocene sediments and 1711-3651m Miocene sediments. In the borehole STR-2 the temperatures of 59 and 89^{o}C were registered at 1506 and 2678 m respectively. The boreholes STR-1 and STR-2 suggest the existence of a good reservoir within the Miocene sediments of the basin. For these wells good to very good porosity (18-33%) and permeability have been determined for various horizons up to depths of 1500 m. The borehole STR-3 has a depth of 3144 m and the measured temperatures are 64 and 96^{o}C at 1910 and 3144 m correspondingly (P.P.C., 1988). The basement and the deeper Neogene reservoirs of the basin preserved fossil saline thermal waters and brines of sedimentary marine origin (B.R.G.M. and I.G.M.E., 1982; Shterev et al., 1995).

Two exploration boreholes (SG-1 and SG-2) at depths of 500 m were drilled by I.G.M.E. close to the Serres city (Fig. 1). The temperatures that were measured in these wells are 21^{o}C at 490 m in SG-1 and 17.8 at 470 m in SG-2 (B.R.G.M. and I.G.M.E., 1982). The geothermal gradient is very low (<2^{o}C/Km) because of the presence of aquifers with cold, superficial waters into the alluvial deposits and therefore the real thermal situation and the gradient of the Neogene formations is disguised. In the same area the large faults that affect the basement act as favorable paths for the way down of cold meteoric surface waters.

The geothermal gradient for the Strymon basin has been estimated to fluctuate from 25 to 36^{o}C/km at depths over than 2000 m (P.P.C., 1988). The geothermal conditions in the Strymon basin are favorable as a result of the active extension tectonic and the increased heat flow. Extensional collapse must have taken place in "a back-arc area" setting during the Oligocene – Miocene (Kilias and Mountrakis, 1998) associated with continental crustal thinning [25-28 km in the Strymon basin (Papazachos and Scordilis, 1998)] and influenced upon the dextral moving strike-slip Anatolia fault system. Tertiary granitoids of Vrondou and Pangeon increased the regional heat flow. In addition, the large, deep and "open" faults of the basin are favorable for the uprising of the geothermal fluids at relatively shallow and exploitable depths or at surface. The general geological settings are favorable for the formation of geothermal field, as: (a) the existence of conglomerates and breccia on the top of the basement and as interbedded strata, (b) the presence of an impermeable cap consisting of Neogene clayey and marly sediments, and (c) the water circulation intro the permeable sediments and the fractured crystalline rocks supplying continually the reservoir (Arvanitis, 2003).

2. GEOTHERMAL FIELDS IN THE STRYMON BASIN

The Strymon basin contains several geothermal fields and it is one of the largest geothermal regions in Greece, with almost half the direct use installed capacity country. The geological and geothermal conditions of the various fields are as follows.

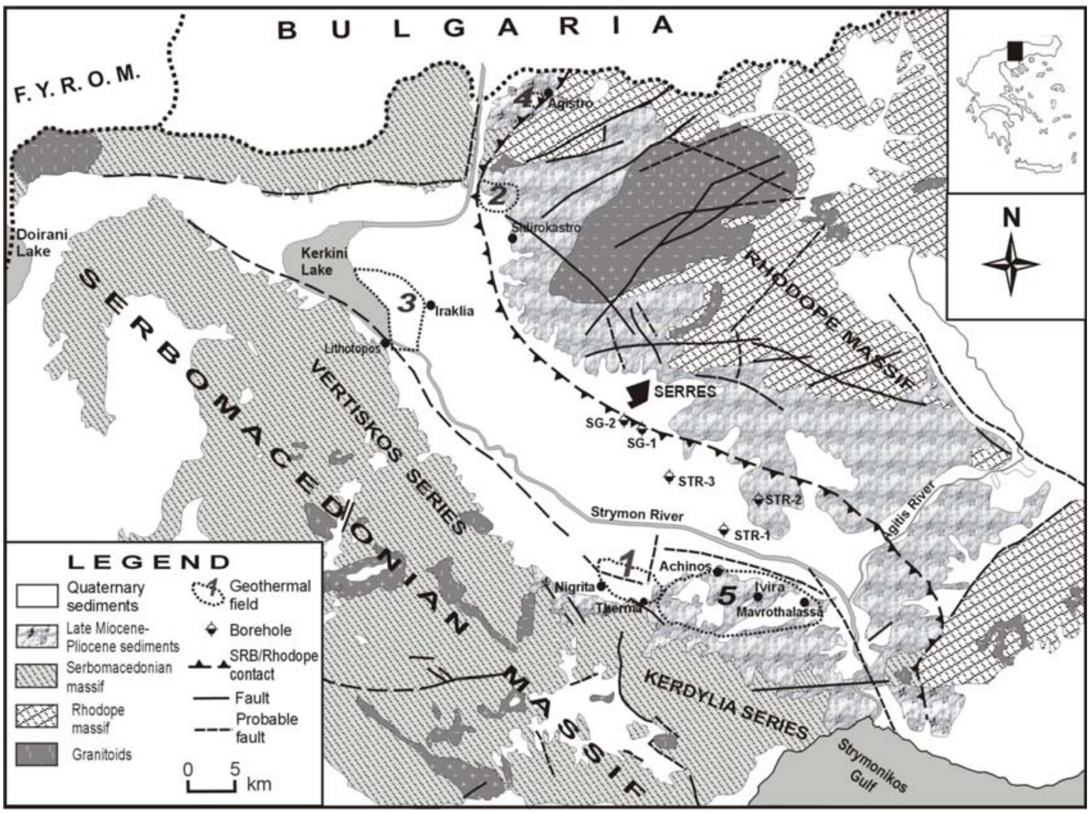

Fig. 1. Simplified geological map of the Strymon basin with some main tectonic structures, the sites of the deep boreholes drilled by P.P.C. and I.G.M.E. and the locations of the known geothermal fields (1: Therma - Nigrita, 2: Sidirokastro, 3: Lithotopos - Iraklia, 4: Agistro, 5: Achinos – Ivira - Mavrothalassa)

2.1 Geothermal field of Therma - Nigrita

The geothermal field of Therma - Nigrita lies in the central-western part of the Strymon basin. Between 1979 and 1992 eight wells were drilled by I.G.M.E. in an area of 16 km^2, while during 1995-1999 an additional drilling exploration project was carried out by the same organization with the construction of seven new wells. The exploration effort resulted in the enlargement of the geothermal area by at least 3 km^2. The maximum temperature recorded was 64°C.

The basement of the area consists of metamorphic rocks of Vertiskos series of the Serbomacedonian massif (gneisses, mica schists, thin layers of marbles) with meta-gabbros, meta-diabases and amphibolites. Very close to the hot springs ophiolites exist (Fig. 2). Above this basement, Neogene and Quaternary sediments were deposited.

In the field of Therma – Nigrita, the geothermal reservoir is located at depths of 100-400 m in basal conglomerates having significant fluctuated thickness (20-65 m) and containing geothermal waters of temperatures 40-64°C. It is a confined aquifer. Above the conglomerates there are other sediments consisting of alternations of marls, sandstones, sands but mainly clays. These sediments form an impervious cap for the geothermal fluids. In these sediments there are some aquifers with waters at a temperature of 25-35°C. The total thickness of the Neogene and Quaternary sediments doesn't exceed 500 m (usually 100-300 m).

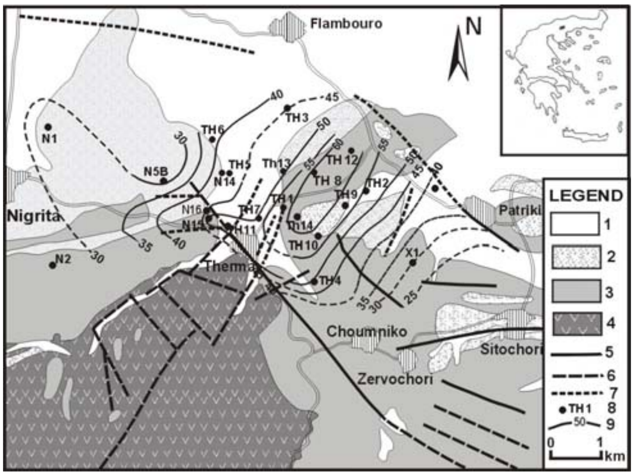

Fig. 2. Simplified geological map of the Therma-Nigrita geothermal field showing the sites of the geothermal wells and the distribution of the isothermal curves [1.Sandy clays, sands, gravels, alluvial fans (Holocene), 2.Sands, gravels, clays, loams (Pleistocene), 3.Fine-layered silts, clays, sandy clays, lacustrine limestones, marls, marly limestones, silts, intercalations of gravel layers, sands, basal conglomerates (Neogene), 4.Ophiolites, 5.Faults, 6.Probable faults on the basis of geophysical, geological and temperature data, 7.Probable faults by geophysical surveys, 8.Boreholes, 9.Isothermal curves]

The geothermal anomaly in the area occurs mainly due to fault systems trending NE-SW and NW-SE. The intersection of these systems north of the Therma village forms probably the main channel raising the geothermal fluids from deeper levels. The geothermal fluids supply the Neogene sediments and especially the basal conglomerates.

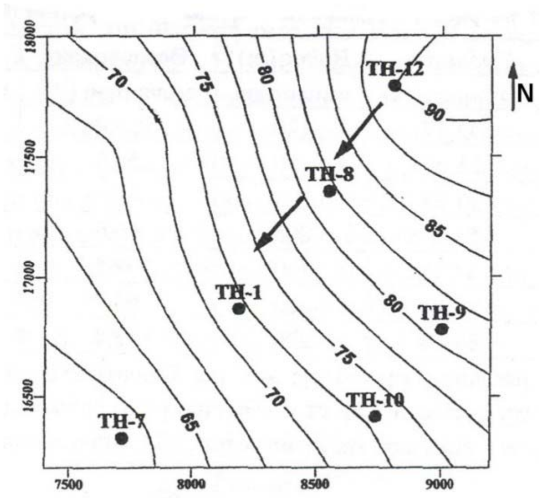

Fig. 3. Piezometric map of the geothermal reservoir in Therma – Nigrita. The contour intervals are 2.5 psi at sea level (0 m). The flow axis of the geothermal fluids is illustrated (TH-12: site of well)

As the horizontal distance from the supply faults increase, the geothermal anomaly and the temperature of the waters decrease because of the longer circulation of the waters and the higher participation of surface waters. The hydraulic contact among the aquifers is affected by block-faults due to the neotectonic activity. The brittle tectonics during the Quaternary probably activates Miocene – Pliocene faults of the basin.

Significant quantities of gases are encountered in this field. Gas samples (after separation of the phases) from several wells from this field were taken using of mobile separation system of segregation of fluid. The characteristic smell of H_2S was not noticed in any gas phase, something verified with the use of a Ecolyzer 100-H_2S detector (Draeger Inc.). The dominant gas from all wells was CO_2 with a content greater than 97% mol/mol. Other gases detected were N_2, O_2, Ar and traces of CH_4. The small quantities of O_2 and Ar can be rather attributed to air intrusion during sampling and analysis. The use of separator enabled the determination of the volume of gases emitted per cubic meter of geothermal water produced (Nm^3 of non-condensible gases/m^3 of water). This ratio for the Nigrita field wells ranges between 2 and 2.6.

The presence of CO_2 in combination with the temperature (thermo-lifting phenomenon) and hydrostatic pressure create a constantly artesian flow of the geothermal aquifer. Therefore, most wells exhibit artesian flow between 80-150 tn/h, their wellhead pressures range from 3 to 7 bar (the highest pressures in low enthalpy geothermal fields in Greece) and two-phase flow (H_2O+CO_2) during pumping.

With the construction of the piezometric map of the geothermal reservoir (Fig. 3), it proves that the recharge area of the reservoir is located in the area of the well TH-12, where a probable NW-SE fault has been considered (Karydakis, 2003). There, the pressure gradient is higher (>5.9 bar). In the same area the water temperatures are high (T>62°C). West and southwest of this area, the pressure gradient is lower (<4.8 bar) and the waters are cooler. Therefore, the fluids rise through the major NW-SE fracture system that affects the basement, northeast of the study area. The type of the geothermal reservoir is determined by

Table 1. Results of chemical analyses from geothermal fields in the Strymon basin

FIELD	Wells (or springs)	Temp. (°C)	T.D.S. (mg/l)	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe	Mn	Li^+	Sr^{2+}	NH_4^+	Cl^-	HCO_3^-	CO_3^{2-}	SO_4^{2-}	F^-	NO_3^-	SiO_2	B
THERMA - NIGRITA	TH-1	59.0	2135	6.80	528.7	82.1	121.8	95.3	0.37	0.100	1.45	1.26	0.44	157.7	1963.4	0.0	104.7	2.20	1.60	71.0	3.50
	TH-2	55.0	1896	7.90	517.3	78.2	52.1	82.7	0.09	—	---	---	0.40	148.9	1662.2	0.0	127.3	0.40	0.00	70.8	2.80
	TH-3	45.0	2479	7.07	533.3	97.8	235.7	105.0	0.16	—	0.75	2.45	0.81	150.7	2362.4	0.0	141.7	0.35	0.00	50.4	2.50
	TH-5	42.0	2201	7.07	524.1	89.9	129.9	109.4	0.07	—	0.77	1.26	0.87	152.4	2025.6	0.0	139.3	0.72	0.00	55.8	3.40
	TH-10	58.0	2227	6.80	537.4	92.2	140.0	90.9	1.10	0.100	0.90	0.80	0.60	156.9	2055.7	0.0	115.9	1.20	0.00	81.3	---
	Th-13	47.0	2466	6.60	620.7	78.2	148.3	116.7	0.03	0.042	0.88	0.79	—	177.2	2252.6	0.0	129.7	0.70	—	85.0	3.42
	Th-14	62.0	2375	7.24	597.7	78.2	140.3	102.1	0.03	0.017	0.87	0.97	—	177.2	2166.0	0.0	128.2	0.70	—	84.0	3.41
	N-14	41.5	2304	6.90	523.0	80.4	131.1	102.0	3.00	0.070	1.00	1.20	0.28	155.8	2209.3	0.0	128.0	--	1.50	90.0	3.40
	N-15	50.0	2337	6.70	574.7	78.2	138.3	113.1	0.21	0.030	0.79	0.69	0.42	170.2	2112.9	0.0	125.8	0.70	1.05	94.0	3.15
	N-16	45.0	2239	6.70	531.0	94.6	137.1	109.4	0.36	0.063	1.07	0.85	0.42	153.6	2074.0	0.0	130.0	1.05	1.50	58.0	3.50
	N-1	32.0	1240	10.9	413.8	9.4	27.3	3.4	1.43	—	0.02	0.09	0.30	109.9	219.0	104.4	456.3	3.00	0.00	—	2.35
SIDIROKASTRO	Sd-2a	41.0	1137	6.78	225.3	36.0	137.9	23.1	---	—	0.44	0.08	0.10	70.9	795.8	0.0	208.5	3.55	3.10	34.0	3.40
	Sd-3a	55.0	1197	6.60	238.4	37.2	151.5	22.6	0.40	—	0.50	1.15	0.10	53.2	906.7	0.0	204.1	2.00	0.00	38.9	2.30
	Sd-5	42.0	1276	6.70	294.3	35.2	142.3	25.5	2.00	—	0.33	1.40	—	51.4	1018.9	0.0	192.1	1.40	<6.2	27.0	3.00
	Sd-8	48.0	1328	6.60	267.8	43.0	169.3	26.1	3.00	—	0.35	1.50	0.00	53.2	1098.2	0.0	192.1	1.70	<6.2	28.0	3.00
	Sd-8a	42.0	1300	6.40	256.1	50.3	182.1	25.2	1.30	0.100	0.50	1.30	0.00	55.1	1095.0	0.0	148.8	3.60	0.80	36.1	---
	Sd-14a	43.0	1231	6.76	244.1	37.2	148.3	24.6	0.40	—	0.50	1.17	0.00	51.4	937.2	0.0	200.8	2.00	0.00	58.9	2.30
	SD-11s	42.5	1258	6.40	250.6	44.6	135.5	21.3	0.07	—	0.50	1.20	—	52.4	869.4	0.0	194.0	5.10	43.4	76.0	6.50
	SD-15	50.0	1278	6.90	257.5	46.9	132.3	25.8	0.20	—	0.50	1.20	—	51.4	933.5	0.0	215.2	6.00	6.20	75.0	2.30
	SD-18	34.0	1232	7.50	252.9	6.3	139.5	22.9	0.10	—	0.50	1.20	—	51.8	932.3	0.0	204.6	5.00	12.4	75.0	2.30
AGISTRO	AG-1s	42.5	405	8.07	81.6	3.9	36.5	3.9	---	—	0.12	0.10	—	16.0	174.5	0.0	120.1	5.00	0.00	52.2	0.18
	AG-1as	42.5	442	7.80	94.3	4.3	32.1	4.9	---	—	0.02	0.04	—	14.2	170.9	0.0	142.8	5.30	0.00	60.0	0.23
	AG-6	25.5	250	7.85	29.9	2.3	50.9	3.6	---	—	0.03	0.30	—	8.9	185.5	0.0	50.4	1.10	0.00	11.7	0.04
	AG-7	29.3	516	8.00	109.2	4.7	40.1	5.4	---	—	0.15	0.60	—	17.7	159.9	0.0	201.7	1.70	1.20	55.0	0.32
	AG-4P	40.0	263	7.55	36.2	2.8	46.6	5.1	0.30	0.040	0.07	0.15	0.00	9.9	189.1	0.0	32.6	---	2.60	33.7	---
IRAKLIA	Li-2	31.8 *(308 m)*	1915	8.17	712.6	45.0	16.0	29.2	0.14	—	0.52	0.66	0.11	159.5	1800.0	0.0	48.0	0.65	0.00	16.5	4.00
	Li-4	62.0 *(438 m)*	1189	9.81	487.4	15.6	0.4	0.7	0.04	—	0.14	0.09	0.13	93.9	490.5	295.2	48.0	0.30	0.00	3.8	2.82
	Li-7	40.8 *(398 m)*	1368	7.74	505.0	14.0	16.0	9.0	0.09	—	0.17	0.30	0.51	85.0	1043.0	0.0	160.0	0.62	0.00	62.0	3.60
	LI-19	29.0	268	7.08	65.0	2.7	18.6	2.2	---	—	---	---	—	6.7	191.0	0.0	52.0	0.27	—	26.0	---
	LI-21	31.0	887	7.40	292.1	7.8	18.4	8.3	0.00	—	---	---	0.30	56.7	607.6	0.0	144.6	---	0.00	60.0	1.20
IVIRA-ACHINOS	TRG-1	40.3	2540	7.30	1017.0	15.3	18.4	6.2	0.65	0.06	0.42	1.75	1.50	101.2	2513.0	0.0	102.2	1.00	1.50	34.5	1.80
	A-7	26.9	587	8.05	160.0	3.7	32.6	19.7	0.03	—	0.07	0.86	1.16	51.0	427.0	0.0	84.0	0.36	3.08	20.9	0.40
	A-10	33.5	756	7.92	289.8	4.1	11.3	7.1	0.01	—	0.14	0.71	1.17	28.2	744.2	0.0	20.0	2.37	1.76	24.0	0.30
	S-17	31.8	582	7.40	234.5	3.9	3.2	0.5	<0.01	—	<0.02	0.56	0.10	23.0	490.6	0.0	45.6	0.60	3.10	26.0	<0.1
	I-7	28.2	987	8.80	408.0	2.3	2.1	1.4	0.01	—	0.08	0.07	2.52	34.5	944.0	40.0	10.0	1.30	6.20	14.1	0.8
	AD-9	28.7	1120	7.72	418.2	4.7	14.0	9.8	0.04	—	0.21	0.53	1.64	33.5	915.0	0.0	166.0	2.0	2.20	17.5	0.7

s : spring

a constant pressure gradient of 1.1 bar/km. It is characterized as "plane" confined (under pressure) reservoir with linear profile and likely is supplied by faults with constant potential (Karydakis, 2003).

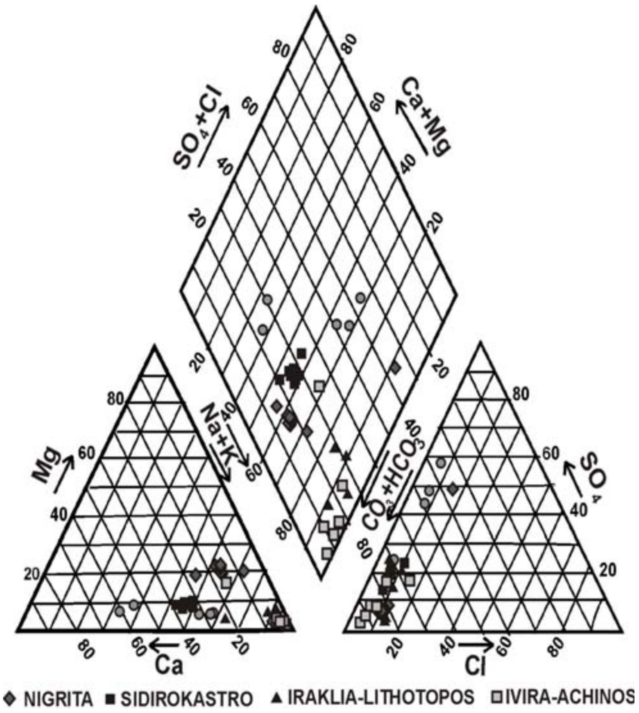

Fig. 4. Presentation of the values of chemical analyses of the geothermal waters from the Strymon basin on a trilinear diagram according to Piper (1944)

The geochemical study proved that the geothermal waters with TDS values between 1.9 and 2.5 g/l are of the Na-HCO_3 type according to Davis & De Wiest classification (1966). They are rich in Na^+, K^+, Mg^{2+}, Cl^- and SiO_2 contents. The geothermal waters from the wells have similar chemical composition with the thermal springs of the area. There is a linear relationship between the ionic Na^+ and Cl^- contents and the temperatures. Mg/Ca ratio is high indicating the circulation of the geothermal waters into the silicate rocks of the basement and especially into the ophiolites. Na^+ is the main cation (413-621 mg/l). Mg^{2+} concentrations in the waters come from the hydrolysis of the Mg-minerals, as the serpentines. The Ca^{2+} content ranges from 27 to 236 mg/l as a result of the dissolution of Ca-minerals. The high values of pCO_2 (7.91×10^{-1} – 1.61×10^{-1} atm) calculated by the use of the thermodynamic model Wateq-f (Truesdell and Jones, 1974) favors this dissolution. The geothermal waters are saturated with calcite, aragonite and dolomite and supersaturated with quartz and talc.

With the aid of the chemical geothermometers of SiO_2 (Fournier, 1981), Na/K (Arnorrson et al., 1983), Na-K-Ca (Fournier and Truesdell, 1973), Na-Li (Fouillac and Michard, 1981), K/M (Giggenbach et al., 1983) and Mg/Li (Kharaka and Mariner, 1989), the deep temperature is estimated in 130 – 140°C (Arvanitis, 1998). This value is similar to the measured temperature at the bottom of the deep oil borehole STR-1 (135°C at 3651 m) and close to the temperature of 150°C estimated by the use of the isotopic O^{18} (SO_4^{2-}-H_2O) geothermometer (Dotsika, 1991).

2.2 Geothermal field of Sidirokastro

The geothermal field of Thermopigi-Sidirokastro lies at a distance of about 30 km NNW of Serres at the NE margins of the Strymon basin covering an area of 14 km^2. Geologically the area belongs to the Rhodope massif close to the tectonic contact line with the Serbomacedonian one. The geological basement of the field consists of marbles, mica gneisses and schists. Primary sulfide concentrations and sulfates are hosted by the metamorphosed and plutonic rocks of the Agistro-Vrondou mountain chain (Katirtzoglou et al., 1994).

The Neogene sediments of the area consist of the basal breccia and the clay-gritty series. The basal breccia of 50-100 m thickness consists of gravels, pebbles and cobbles from gneisses and marbles. It is often fractured with sulfate deposits. The lacustrine – fluvioterrestrial clay-gritty series composed of alternated bends of sands, clays and micro-conglomerates. The thickness of this series ranges from a few meters (westwards) to >350 m (eastwards). Lignitic zones and volcano-sedimentary deposits outcrop in some locations.

The Quaternary formations include the post-Pliocene volcanic rocks (rhyolites) of Sitsi-Kamen, the breccia with gravels from marbles and the travertines on the top. The rhyolites of Sitsi-Kamen are associated with E-W fault. The travertines occur to the north and west of the Thermopigi village and cover an area of 3 km^2. Their thickness varies between some meters and 35-50 m. They have been deposited over the Pleistocene sediments and they are associated with the thermal springs of the area.

The main faults are oriented in NW-SE, NNW-SSE, NE-SW and E-W directions. The observed E-W faults are the youngest and they are formed because of the active extensional regime with N-S tensional direction (Fig. 5).

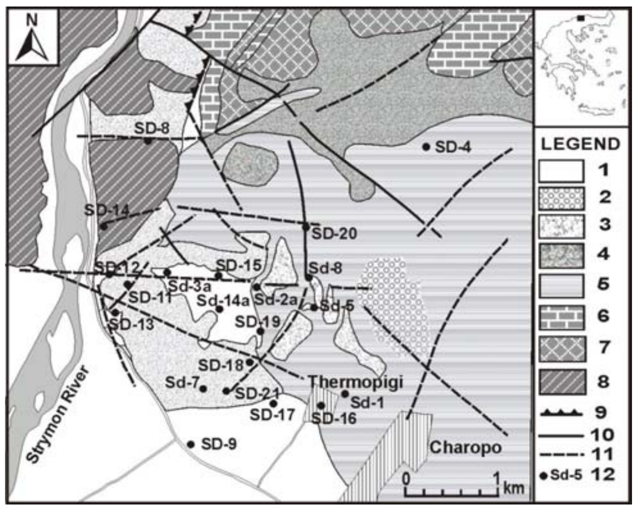

Fig. 5. Geological map of the Thermopigi - Sidirokastro area with the sampling sites (wells and springs) [1: Modern deposits (Quaternary), 2: Calcareous breccia (Quaternary), 3: Travertines (Quaternary), 4: Rhyolites (Quaternary), 5: Clayey-gritty series (Plio-Pleistocene), 6: Marbles (Rhodope massif), 7: Alternations of schists and gneisses (Rhodope massif), 8: Gneisses (Serbomacedonian massif), 9: Thrust, 10: Fault, 11: Probable fault, 12: Borehole]

The area of Thermopigi-Sidirokastro manifests geothermal interest because of the presence of the thermal springs with water temperature 35-55^{o}C. Eleven exploration boreholes were drilled by I.G.M.E. during the period 1979-1986. During 1995-1999 an additional exploration geothermal project carried out towards north of the existing geothermal field with the construction of two boreholes (one exploration at depth of 300 m and one production at 150 m).

The geothermal investigation in the area has proved the existence of two important aquifers: (a) the first aquifer is shallow (at depths of 10-50 m) into the travertines with water temperatures 40-65^{o}C. This aquifer is unconfined, partly saturated with water and it belongs to the reservoirs with single-phase flow of fluids. The hydrostatic pressure is equal to the atmospheric one. (b) The second reservoir is deeper and it is located at the top of the metamorphic basement (100-450 m) into the breccia with geothermal waters temperatures ranging from 40 to 75^{o}C. Some boreholes that have drilled this deep reservoir produce artesian waters. Pumping tests in the wells yielded 22 kg/s flow rate.

Systematic pumping tests were performed in the well Sd-3a with constant flow rate at 13.5 kg/s in order to define the hydraulic parameters of the shallow geothermal reservoir into the travertines (Karydakis, 2003). The depth of this well is 48 m and the water temperature is 56^{o}C. The hydraulic parameters of the shallow reservoir in the area of the well Sd-3a have the following values: thickness of the reservoir H = 23 m, permeability k = $4.2x10^{-12}$ m^2 (4.2 darcy), k.H = $9.7x10^{-11}$ m^3, transmissivity T=$1.9x10^{-3}$ m^2/s, storativity S=3% and storage coefficient s′=$1.3x10^{-4}$ Kg/m^3.Pa. The exploitable flow rate is Q_c = 16 Kg/s. The recharge area of the reservoir is located north of the well Sd-3a where E-W faults have been observed and the hydraulic gradient is higher. In this area the water temperatures are higher (60-65^{o}C). South of this area the hydraulic gradient is lower and the waters are cooler (T<40^{o}C). The aquifer has variable hydraulic gradient (8% and 4% in some parts) because of the change of dip of the underlying sedimentary series (Karydakis, 2003).

The geothermal waters in the Thermopigi-Sidirokastro area are classified in Na,Ca-HCO_3 type according to Davis & De Wiest (1966) classification (Fig. 4). They have low salinity with TDS of 1.1-1.4 g/l and the pH values range from 6.4 to 7.5. The main cation is Na^+ (200-326 mg/l) probably derived from the hydrolysis of Na-plagioclase (e.g. albite), which is one of the major minerals of the gneisses and granites. The presence of Ca^{2+} (129-170 mg/l) seems to be related with the marbles and the travertines. The Mg/Ca ratio (0.23-0.35) indicates the circulation of the geothermal waters into the calcareous rocks of the area (Arvanitis, 1998). The Na/CI ratio is high (4.9-12.2) suggesting waters from aquifers into the metamorphosed rocks. The SO_4^{2-} contents vary between 155 and 215 mg/l indicating probable dissolution of the sulfides and sulfates hosted by the metamorphosed and plutonic rocks of the Vrondou-Agistro mountain chain (Katirtzoglou et al., 1994). The geothermal waters are rich in F^- (1.4 – 6.0 mg/l) because of their probable circulation through large faults into the gneisses and the granites of the wider area and the hydrolysis of the fluoride minerals hosted by these rocks. The SiO_2 contents range from 28 to 75 mg/l. The thermodynamic model Wateq-f (Truesdell and Jones, 1974) that was applied has shown for the thermal waters pCO_2 pressures between $10^{-0.384}$ and $10^{-1.053}$ atm because of the presence of the dissolved CO_2 in the waters in small amounts and as a result of probable dissolution of the carbonate rocks occurring in the area. These solutions are also supersaturated with silica indicating that the SiO_2 concentrations are related more with the hydrolysis of siliceous minerals than the temperature. With the aid of the chemical SiO_2, Na/K, Na-K-Ca, Na-Li, K/M and Mg/Li geothermometers, the deep temperature is estimated in 100^{o}C. The occurrence of the travertines in the area indicates no high temperatures of the geothermal fluids unless bicarbonate waters, after their cooling, come in touch with limestones.

2.3 Geothermal field of Lithotopos - Iraklia

The geothermal field of Lithotopos - Iraklia is located at the NW edge of the Strymon basin. It lies between the Kerkini Lake and the small city of Iraklia. Geologically belongs to the Serbomacedonian massif (Vestiskos series). The crystalline basement consists of amphibolites, mica gneisses, schists, quartzites, leucocratic and augen gneisses and migmatites and it is intensively fractured.

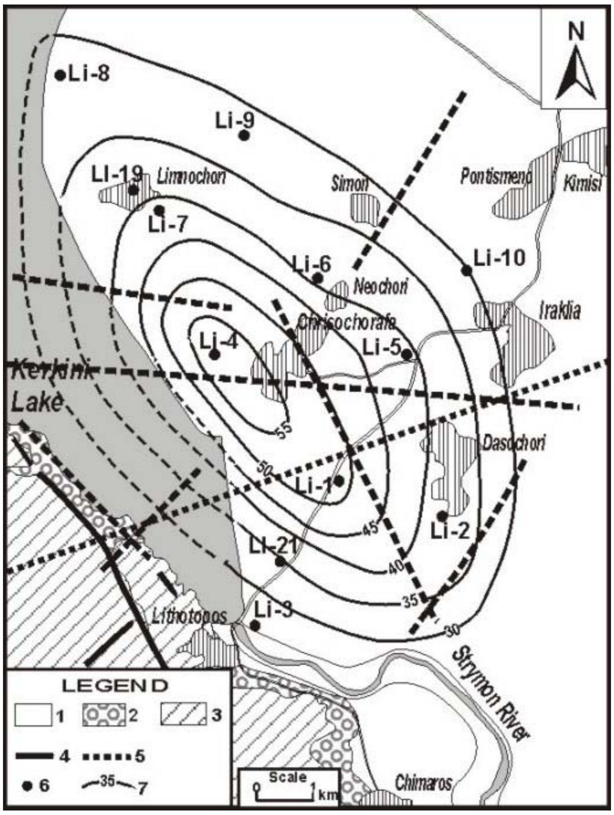

Fig. 6. The geothermal field of Lithotopos - Iraklia with the sites of the geothermal exploration (Li-1 to Li-10) and common (Li-19, Li-21) wells and the distribution of the isothermal curves at depth of 400 m [1: Alluvial deposits, 2: Plio-Pleistocene sediments, 3: Metamorphic rocks, 4: Faults, 5: Probable faults by geophysical surveys, 6: Boreholes, 7: Isothermal curve].

The Neogene and Quaternary sediments of the area are divided into two groups: (a) a lower group (fluctuant thickness about 200 m) of Plio-Pleistocene age consisting of clays and sandstones and (b) an upper group having fluctuant thickness about 200 and composed of alternations of sands, clays and gravels coming from gneisses.

The main fault systems of Neogene and Quaternary age are orientated in NW-SE and ENE-WSW directions. During the Quaternary, the new active extensional regime with N-S tensional direction formed a new group of normal E-W faults and reactivated the pre-existing faults.

Ten exploration boreholes (Li-1 to Li-10) were drilled by I.G.M.E. during the period 1982-83. The results of this drilling project have revealed an area of 15 km^2 with geothermal interest. The temperatures of 40-62^oC were measured at depths of 300-450 m within the sandstones and conglomerates close to the basement. The crystalline and highly fractured basement has been revealed by the gravity and magnetic investigations and coincides with the area of high temperatures and specific anomalies on the SP contour map (Thanassoulas and Lazou, 1993). It was drilled only in three boreholes (Li-1, Li-3, Li-7) at a maximum depth of 400 m. The values of the average geothermal gradient in the exploration boreholes range from 23^oC/km (Li-3) to 107^oC/km (Li-4). This important geothermal anomaly, as illustrated in Fig. 6, is elongated along NW-SE direction and coincides with the large normal fault trending NW-SE that affects the basement in the area of the Kerkini Lake at the margins of the basin. This NE–dipping tension fault maybe has been reactivated during Quaternary time and it could act as preferential path for the circulating fluids. Some other normal faults are parallel to the above-mentioned large fault. One tectonic line in the E-W direction is also evidenced by geophysical surveys and seems to contribute to the geothermal anomaly.

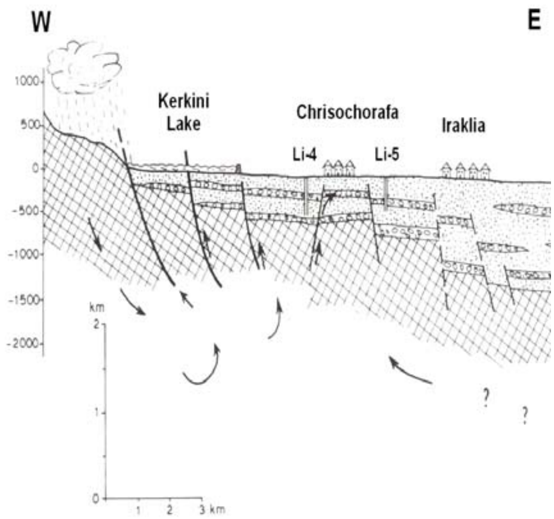

Fig. 7. Hydrothermal model for the Lithotopos – Iraklia geothermal field

The geothermal waters belong to the Na-HCO_3 type (Fig. 4) according to Davis & DeWiest (1966) classification with TDS of 0.9-1.9 g/l. The cold, superficial waters are rich in Ca^{2+} and Mg^{2+} contents and are characterized as Ca(Mg,Na)-HCO_3 ones. The main cation in geothermal waters is Na^+ (300-500 mg/l) probably due to the circulation of the waters into the fractured metamorphosed basement and water-rock interaction. Generally the Na^+, K^+, B, HCO_3^-, SO_4^{2-} and Cl^- concentrations in the thermal waters are increased. The calculated values of pCO_2 range from $10^{-1.383}$ to $10^{-1.743}$ atm (similar to the cold waters). All waters (thermal and cold) are supersaturated with silica indicating that the SiO_2 concentration probably is governed by siliceous rock dissolution rather than temperature influence. Generally mixing of hot with cold waters is quite possible. With the aid of the chemical SiO_2, Na/K, Na-K-Ca, K/M and Mg/Li geothermometers the deep temperature is estimated in 80^oC.

Unfortunately, there are no production geothermal wells in the area. The hydrothermal model for the Lithotopos - Iraklia geothermal field is illustrated in Fig. 7.

2.4 Geothermal field of Agistro

The geothermal field of Agistro is located at the northwestern margins of the Strymon basin, close to the Greek-Bulgarian borders, in the area of the tectonic line between the Serbomacedonian and Rhodope massifs. It extends to an area of 3-4 km^2. The geothermal reservoir is located at the fractured basement of the metamorphosed rocks of the Rhodope massif (marbles, gneisses, sipolines and schists). Above the basement there is a sedimentary sequence beginning with Neogene lacustrine, fluvio-lacustrine and fluvial-terrestrial deposits. These sediments consist of sands, argillaceous sands with intercalations of conglomerates, micro-breccia, gravels, pebbles and cobbles. The Quaternary sediments have been deposited over the Neogene ones and consist of diluvial deposits (red beds, red clays, gravels, pebbles), conglomerates and breccia. Alluvial fans and talus cones are formed at the margins of Mt Agistro. The Neogene and Quaternary sediments constitute a weakly permeable cap, which hardly prevents the heat diffusion and the mixing with cold shallow groundwater.

Because of the presence of the Agistro thermal springs an exploration geothermal project was launched. The thermal springs (AG-1s and AG-1as) have a temperature of about 40^oC and they are formed due to normal fault trending W-E. I.G.M.E. constructed 6 wells (5 exploration and 1 production) reaching depths of 100-300 m, where temperatures of 40-47^oC were recorded (Fig. 8) The production well (AG-4P) 120 m deep has been constructed at a distance of 128 m south of the thermal springs and very close (only 38 m) to the exploration well AG-4.

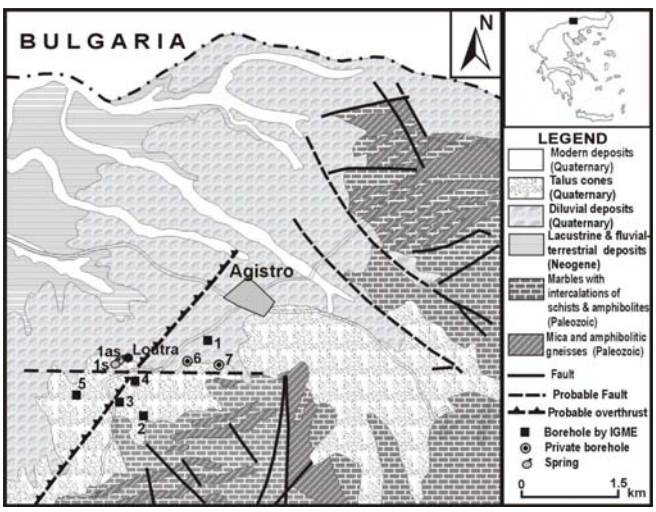

Fig. 8. Simplified geological map of the Agistro geothermal field with the sites of the boreholes and springs

The existence of two aquifers has been identified: the first aquifer is shallow (up to 50 m) and the second one is deeper (70-130 m). These aquifers have hydraulic communication through fractures and joints of the intermediate zone.

During the pumping test at the production well the hydraulic parameters were measured, while the exploitable flow rate was of the order of 30 kg/s. On the basis of the results from pumping tests and using the Hantush method (Hantush and Jacob, 1955) the hydraulic parameters T and S were calculated for the boreholes AG-4 and AG-4P. The values are $T=2.9x10^{-2}$ m^2/s and $S=1.1x10^{-5}$ for the well AG-4 and $T=1.3x10^{-2}$ m^2/s for the well AG-4P.

The hydraulic model of the system in the Agistro area is shown in Fig. 9. During the steady state there is simultaneous flow from the cold and hot aquifer. The system is "open" and the rainfall (precipitation) influences the temperature and the discharge of the springs. The chemical composition of the thermal springs shows mixing between cold and hot waters of the area. With the beginning of pumping tests an intense drawdown and inversion of the hydraulic potential of the cold–hot aquifer are caused creating a vertical flow from the cold to the hot aquifer (leaky aquifers). This results in decrease of the pumping water temperature. The vertical flow is more intense close to the borehole. At the same time the drawdown of the water table of the phreatic (unconfined) aquifer causes the "cold component" decrease of the total discharge. When the hydraulic potential of the unconfined, cold aquifer is reduced the flow from the cold to hot aquifer increases and so the total discharge remains nearly constant and the water temperature of the springs increases.

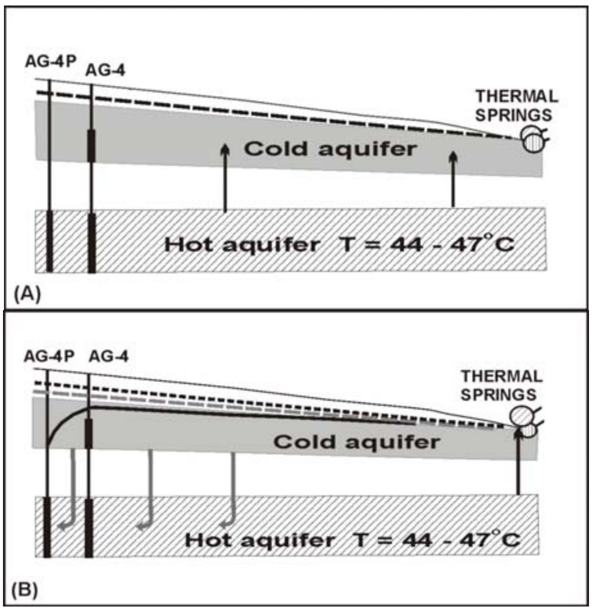

Fig. 9. The hydraulic model of the system in the Agistro area (A) Piezometric surfaces of the cold and hot aquifers before pumping test, (B) Piezometric surfaces during pumping test

The geothermal waters of the thermal springs belong to the group of $Na-HCO_3SO_4$ waters according to Davis & DeWiest (1966) classification (Fig. 4) in contrast with the superficial, cold waters that belong to the $Ca-HCO_3$ type. The thermal waters have a low salinity with TDS of 0.25-0.5 g/l and the main ions are Na^+, HCO_3^- and SO_4^{2-}. The Mg/Ca ratio is low (~0.2) indicating the circulation of the thermal waters into the marbles and other calcareous rocks of the area. The contents of SO_4^{2-} could be related to the primary mixed-sulfide concentrations and the sulfates hosted by the metamorphosed and plutonic rocks of the Vrondou-Agistro Mounts (Katirtzoglou et al., 1994; Arvanitis, 1998).

The thermodynamic equilibrium model Wateq-f (Truesdell and Jones, 1974) among solution and solids that was applied for the thermal waters has shown that the values of pCO_2 range from $8.71x10^{-3}$ to $1.61x10^{-3}$ atm, similar to cold waters of the same area. It has also shown that the thermal waters are saturated with quartz and supersaturated with talc. With the aid of the chemical SiO_2, Na/K, Na-K-Ca, K/M, Na-Li and Li-Mg geothermometers the deep temperature is estimated in 60-100°C (Arvanitis, 1998). No corrosion or scaling problems were encountered. The chemical composition of gas discharges from thermal springs water has shown the high percentage of N_2 (889.1 $m.mol.mol^{-1}$) together with absence of H_2S, H_2 and CH_4. This suggests that the gas sample is likely to differ considerably from those in any deep equilibration condition. At the same time an extremely long rising time from the deep under low-temperature condition and mixing with descending air-saturated cold groundwaters are very likely. The estimated temperature on the gas composition using the D' Amore and Panichi's (1980) geothermometer is 121°C (Minissale et al., 1989).

2.5 Geothermal field of Ivira – Achinos - Mavrothalassa

This is a new area in the southwestern part of the Strymon basin explored in common by I.G.M.E. and Aristotle University of Thessaloniki during 1993-2002. It extends to an area of about 25 km^2. Geologically the area belongs to the Serbomacedonian massif. The crystalline basement consists of mica-schists, biotite gneisses, amphibolitic gneisses, marbles, plagioclase gneisses, pegmatites, quartzites etc. The Neogene and Quaternary sediments have been deposited over the basement (Fig. 10). These sediments consist of the basal conglomerates, limestones, sandy limestones, sandstones, sands, marls, sandy marls, marly limestones, silts, clays, silty sands, sandy clays with interbedded strata of gravels and cobbles. The main characteristic of these deposits is their clayey-marly composition and therefore they can form an impervious cap for the geothermal fluids. In these sediments there are aquifers with shallow waters at a temperature of 25-35°C and higher ones (50-60°C) at deeper layers (Arvanitis, 2003). The total thickness of the Neogene and Quaternary sediments ranges from a few meters (close to the basement) to 1000 m (north of the villages Achinos and Ivira) or more (up to 4 km in the central part of the Strymon basin).

The tectonic setting in the area is very complicated. The faults are oriented in NE-SW, NW-SE and E-W directions affecting the crystalline basement and the sediments (Arvanitis, 2003). The gradual tectonic subsidence of the substratum from South to North is characteristic. Fig. 10 is a simplified geological map showing the faults of this area. The interpretation of the geophysical (geoelectrical, seismic, gravimetric) surveys has revealed the presence of large faults covered by the deposits (Arvanitis, 2003).

A detailed thermometrical survey took place along with water sampling. All existing wells (about 230) for water supply and irrigation purposes within the study area were measured. In 80 boreholes up to 300 m deep thermal gradient measurements were possible (Arvanitis, 2003). In most boreholes temperatures measured are consistently higher than normal ones. The higher recorded temperatures were: 36.8°C close to the known geothermal field of Therma-Nigrita, 34.6°C NNW of the Ivira village and 33.5°C south of the Achinos village. An isogradient map was drawn based on the measurements of the irrigation and water supply wells (Fig. 11).

The study area is characterized by an elevated thermal gradient, 2-3 times higher than the normal one (>30°C/km). The isogradient curve corresponding to 30°C/km delineates the area at the margins of the basin close to the crystalline basement. The thermal gradient is higher, with values as high as 100-150°C/km in the western part of the study area near the geothermal field of Therma-Nigrita. Other important thermal anomalies (geothermal gradient >60°C/km) occur in the Patriki area, north of the Ivira village and in the area between the Patriki and Achinos villages. Geothermal interest manifests itself in the areas: north of Mavrothalassa (>40°C/km), southwest of Ivira (Ivira-Dafni-Leftotopos) and east of Agios Dimitrios. The isogradient map (Fig. 11) illustrates the correspondence between the thermal data and the tectonic structure of the field. It appears furthermore that the main thermal anomaly is associated with two NW-SE fault systems that affect the basement in the areas of Patriki and north of Achinos-Ivira correspondingly. The presence of NE-SW faults extends the anomaly southwestwards (Arvanitis, 2003).

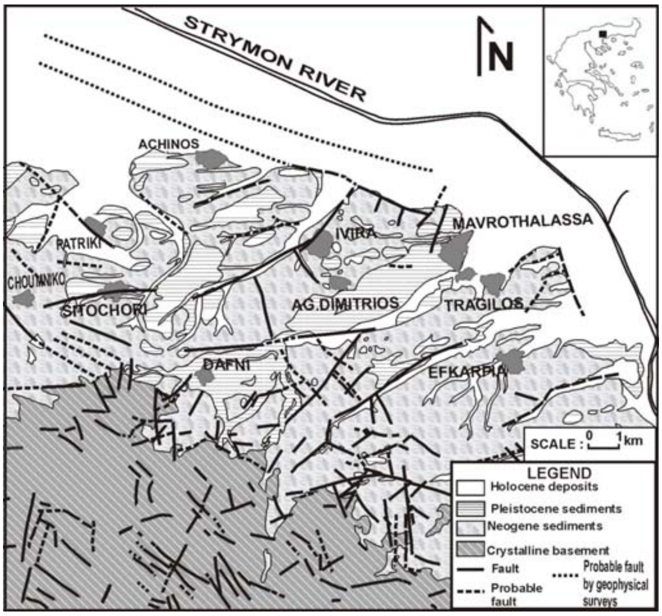

Fig. 10. Simplified geological map of the Ivira-Achinos-Mavrothalassa area (Arvanitis, 2003)

The results of the preliminary geothermal investigation helped in sitting (Fig. 11) two exploration (ACH-1, TRG-1E) boreholes and one production (TRG-1) well. The borehole ACH-1, drilled to depth of 473 m, showed a sedimentary sequence of grey-greenish clays and marls with intercalations of sands, sandstones and gravels. The temperature of 42.4°C has been recorded at 460 m and the average thermal gradient has been estimated in 57°C/km. The borehole TRG-1E drilled NNW of the Ivira village (Fig.11). Its depth is 566 m and the aquifers consist of sands, sandstones, quartzy gravels and micro-conglomerates alternating with impermeable layers of grey-greenish or greenish clays and marls. The temperature of 51°C has been recorded at 560 m and the average thermal gradient is 61°C/km. The production well TRG-1, at depth of 650 m, was drilled at a distance of 210 m NNE of the borehole TRG-1E. It produces thermal waters at a temperature of 41°C (at wellhead)

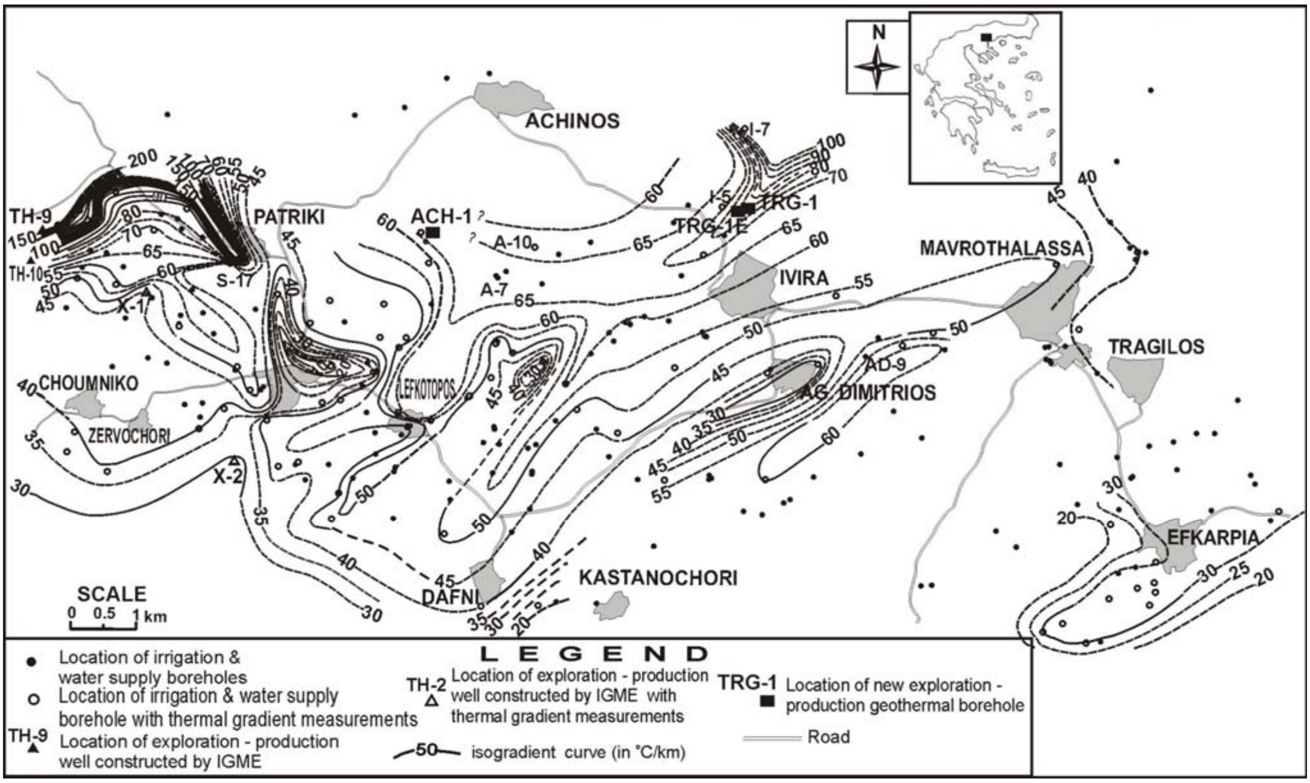

Fig. 11. Isogradient map (in °C/km) in the Ivira-Achinos-Mavrothalassa geothermal field based on the thermal gradient measurements into the irrigation and water supply boreholes (Arvanitis, 2003)

yielding >100 m^3/h (Arvanitis, 2003).

The geothermal water TRG-1 with TDS of 2.54 g/l belongs to the group of Na-HCO_3 waters according to Davis & DeWiest (1966) classification (Fig. 4). Na^+ concentration is very high (1017 mg/l) because of probable Na-Ca ionic exchange in clays and marls. Ca^{2+}, Mg^{2+} and SiO_2 contents are low. This thermal water is differentiated chemically from the geothermal ones in the neighboring geothermal field of Therma-Nigrita. Some other waters from irrigation and water supply wells of the area with increased temperatures (26.9-33.5°C) are of the Na-HCO_3 type (Arvanitis, 2003).

2.6 Analysis of Gas Phase

Significant quantities of gases are encountered only in the field of Nigrita. Gas samples (after separation of the phases) from several wells from this field were taken using of mobile separation system of segregation of fluid. The characteristic smell of H_2S was not noticed in any gas phase, something verified with the use of a Ecolyzer 100-H_2S detector (Draeger Inc.). The dominant gas from all wells was CO_2 with a content greater than 97% mol/mol. Other gases detected were N_2, O_2, Ar and traces of CH_4. The small quantities of O_2 and Ar can be rather attributed to air intrusion during sampling and analysis. The use of separator enabled the determination of the volume of gases emitted per cubic meter of geothermal water produced (Nm^3 of non-condensible gases/m^3 of water). This ratio for the Nigrita field wells ranges between 2 and 2.6.

2.7 Problems of scaling and corrosion

The tendency of the geothermal waters for $CaCO_3$ scaling in the Strymon basin can be estimated using the supersaturation ratio, the Langelier Index and the Ryznar Index. The former quantity is defined as $S=\left[(Ca^{2+})(CO_3^{2-})/K_{sp}\right]^{1/2}$, where K_{sp} is the thermodynamic solubility product of calcite (the predominant scale-forming phase) and the quantities in parentheses denote activities of the corresponding ions. For scale formation to occur, S must exceed unity. The values of the supersaturation ratio of waters from several wells are presented in Table 2. These values correspond to water pH after the CO_2 separation and were estimated using the HYDRAQL code. In the same table, the Langelier Index and the Ryznar Index of the waters are also presented.

All geothermal waters may theoretically form scales. However, since for most cases the supersaturation ratios are low, it is not expected to encounter severe scaling problems. The largest ratios are calculated for the Nigrita waters, which have the highest temperature. Indeed, in this area scaling problems have been observed mainly in the plate heat exchangers of the 60ºC waters. Scaling of the transportation pipes was also observed, but the scaling rate was rather small and scales did not cause any real operating problem. A picture of a scaled 0.1-m i.d. PVC pipe from the return water line (well TH-1) is shown in Fig. 12. The solution to the scaling problems is either keeping CO_2 in water by maintaining a pressure higher than the bubble point of the system, an approach that can be not applied to the existing systems, or using scale inhibitors.

The corrosive nature of the geothermal waters in the Nigrita field can be seen in Table 2, with the presence of significant quantities of Cl^-, CO_2, HCO_3^-, $SO_4^=$ and smaller quantities of NH_4^+, which make impossible the use of copper or copper alloys. In addition, it is almost impossible to avoid oxygen presence in the surface installations. General comments on the corrosivity of geothermal waters can be made with regards to the classification system of geothermal water corrosivity suggested by Ellis (1981). The Total Key Solids of several geothermal wells are presented in Table 2. In these cases, the pH of the water ranged between 6.4 and 7.6, while the concentration of chlorides for most waters corresponds to about 5% of the TKS. Because all the transportation pipes are polymeric, corrosion is limited mainly to the well casing, heat exchangers and metallic valves. General and galvanic corrosion are the two types of corrosion found in the field of Therma - Nigrita. Corrosion of the outer surface of the well casing and of the metallic pipes is also evident in most installations, and the situation is sometimes deteriorated by the leaking of geothermal water from unsuitable flanges.

3. GEOTHERMAL EXPLOITATION IN THE STRYMON BASIN

Current geothermal applications in the Strymon basin include greenhouse heating, soil heating for asparagus cultivation and culture of the microalga Spirulina. Almost half of the geothermal greenhouses in Greece are located in the Strymon basin, while intense interest has been expressed from local institutions for new applications in the geothermal sector. The total covered greenhouse area is 9 ha, producing vegetables (6 ha) and flowers or flowerpots. For several years soil heating was applied in a 3-ha area in Nigrita, but the co-operative running the field decided to cease production for reasons irrelevant to geothermal energy. Another application involves the cultivation of spirulina (a green-blue algae) in temperature controlled ponds in Therma-Nigrita utilizing both geothermal heat and CO_2.

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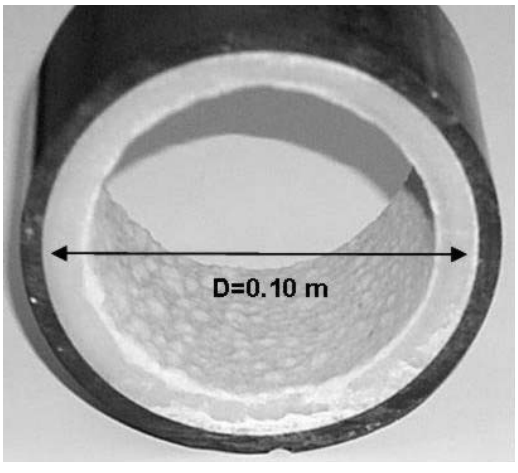

Fig. 12. Picture of a scaled PVC pipe carrying geothermal water from the TH-1 well

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Table 2. Characteristics of geothermal waters in the Strymon basin regarding their tendency for scaling and corrosion

	AG-4P	**Sd-8a**	**Sd-2a**	**N-15**	**TH-10**
Fluid characteristics					
Temperature (°C)	40	42	41	50	58
pH (at 25°C)	7.55	6.40	6.78	6.70	6.80
TDS (mg/L)	263	1300	1137	2337	2227
Saturation indices					
Saturation ratio (S) *	1.27	1.14	1.18	3.0	2.1
Langelier Index (LI)	0.20	0.08	0.13	0.6	0.4
Ryznar Index (RI)	7.17	6.24	6.42	5.6	5.9
Corrosivity characteristics					
Total Key Species, TKS (mg/L)	232	1300	1033	2500	2334
% Cl/ TKS	4.3	4.3	6.7	6.6	6.9

* with respect to calcite