GEOTHERMAL EXPLORATION IN THE SANI - AFYTOS AREA OF THE KASSANDRA PENINSULA (CHALKIDIKI PENINSULA, NORTHERN GREECE)

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Abstract

The Sani-Afytos area in the Kassandra Peninsula (Chalkidiki) was the area of systematic geothermal exploration. Based on deep oil borehole data, the Paleogene, Neogene and Quaternary sediments show significant thickness reaching 3600 m and cover the metamorphosed Mesozoic, mainly carbonate, basement. The detailed water temperature investigation proved the presence of sub-thermal waters (20-28°C) at depths up to 300 m and the spatial distribution of the isothermal curves at depths of 150 and 200 m according to the main NW-SE and SE-NW tectonic structures of the area. Through the construction of geothermal exploration and production wells at depths of 422-583 m, thermal waters of 31.7-36°C were detected within the Upper Miocene sediments. The average value of the geothermal gradient was calculated to be 3-4°C/100 m. One production well of 520 m depth provides waters of 34°C while its potential flow rate is approximately 50 m^3/h. The geothermal waters were classified in Na-HCO_3 and Na-Cl types of waters with T.D.S 0.89-2.03 g/l. With the aid of chemical geothermometers the deep temperature was estimated to be 80-100°C. In one exploration well, the presence of gas phase (77% v/v CH_4, 21.8% v/v N_2) was detected. The geothermal exploration resulted in the characterization of the area as the "geothermal field of Sani-Afytos" and in the prospective development using the geothermal fluids in the tourism and other activities.

Key words: *wells, field, low enthalpy system, thermal waters, resources.*

Περίληψη

Η περιοχή Σάνης – Αφύτου της Χερσονήσου Κασσάνδρας (Χαλκιδική) απετέλεσε περιοχή συστηματικής γεωθερμικής έρευνας. Από την αξιολόγηση των δεδομένων βαθιών γεωτρήσεων έρευνας υδρογονανθράκων διαπιστώθηκε το σημαντικό πάχος (μέχρι περίπου 3600 m) των Παλαιογενών, Νεογενών και Τεταρτογενών ιζημάτων που καλύπτουν το μεταμορφωμένο Μεσοζωικό (κυρίως ανθρακικό) υπόβαθρο της περιοχής. Η συστηματική θερμομετρική έρευνα κατέδειξε την παρουσία υπόθερμων

νερών (20-28°C) σε βάθη μέχρι 300 m και την χωρική κατανομή της θερμοκρασίας σε βάθη 150 και 200 m σύμφωνα με τις κύριες τεκτονικές δομές ΒΔ-ΝΑ και ΒΑ-ΝΔ διεύθυνσης της περιοχής. Με την ανόρυξη γεωθερμικών γεωτρήσεων (ερευνητικών και παραγωγής) βάθους 422-583 m εντοπίσθηκαν νερά 31,7-36°C στα Ανω-Μειοκαινικά ιζήματα. Η μέση τιμή της γεωθερμικής βαθμίδας υπολογίστηκε σε 3-4°C/100 m. Παραγωγική γεώτρηση βάθους 520 m δίνει νερά 34°C με δυνατότητα παροχής περίπου 50 m^3/h. Τα γεωθερμικά νερά είναι Na-HCO_3 και Na-Cl με Σ.Δ.Α. 0,89-2,03 g/l. Με τη βοήθεια χημικών γεωθερμομέτρων εκτιμάται ότι η θερμοκρασία του βαθιού γεωθερμικού ρευστού είναι της τάξης των 80-100°C. Η παρουσία αέριας φάσης (77% κ.ό. CH_4, 21,8% κ.ό. N_2) διαπιστώθηκε σε μία από τις ερευνητικές γεωτρήσεις. Αποτέλεσμα της γεωθερμικής έρευνας ήταν ο χαρακτηρισμός της περιοχής ως «γεωθερμικό πεδίο Σάνης – Αφύτου» (Φ.Ε.Κ. 1012/τ.Β/19-7-2005) και οι προοπτικές ανάπτυξης με χρήση των γεωθερμικών ρευστών στον τουρισμό και σε άλλες δραστηριότητες.
Λέξεις κλειδιά: *γεωτρήσεις, πεδίο, σύστημα χαμηλής ενθαλπίας, θερμά νερά, πόροι.*

1. Introduction

This paper presents the results of the geothermal investigation in the Sani-Afytos-Kassandria area performed by the Institute of Geology and Mineral Exploration (I.G.M.E.). This area constitutes the northern part of the Kassandra Peninsula, which is located at the western part of the wider Chalkidiki Peninsnla, in Northern Greece (Macedonia). The interest of systematic geothermal exploration was drawn due to the known thermal springs of Agios Nikolaos -Agia Paraskevi in the southern part of the Kassandra Peninsula with water temperature of 39°C. This project was supported by the 2nd E.U. Framework Programme (Programme "Energy").

2. Geological and tectonic settings in the area

The western part of the Chalkidiki Peninsula belongs to the tectonic zone of Axios. Between Thessaloniki and Toronaeos Gulf, the Axios Zone is built up of Mesozoic metamorphic rocks (epigneisses, schists, phyllites, metadiabases, quartzites, marbles), ophiolites, granitoids, limestones, sandstones and conglomerates (Mountrakis 1985). These rocks are covered with Paleogene, Neogene and Quaternary deposits of a total thickness reaching the 3500 m or even more. The Paleogene (Oligocene-Eocene) molassic sediments are exposed to the southern part of the Kassandra Peninsula but their thickness is important [700-1000 m or more (up to 2600 m)] according to the data derived from deep oil boreholes (P.P.C. 1988).

The Neogene-Quaternary sediments of Western Chalkidiki are composed of clastic sediments from various depositional palaeoenviroments (continental, fluviodeltaic, lacustrine, lacustrine-deltaic). These sediments can be separated (Syrides 1990) in the following formations (Fig. 1): (a) Antonios Formation [Lower (?)-Middle Miocene and Upper Miocene] consisting of alternating lens-shaped beds and lenses of sands and unconsolidated conglomerates (fluvial sediments), (b) Triglia Formation [Upper Miocene (Vallesian-Lowermost Turolian)] composed of continental sediments and red-beds, (c) Trilophos Formation [Uppermost Miocene (Pontian Turolian)] composed of sands, silts, sandstones and limestones (well stratified and bedded brackish-lacustrine fossiliferous sediments), (d) Gonia Formation [Pliocene (Ruscinian)] consisting of lenses and beds of sands, clays, sandstones, marls and massive marly limestones (fluvio-lacustrine sediments) and (e) Moudania Formation [Villafranchian and later] composed of red-beds (continental sediments). In the Kassandra Peninsula the sediments are inclined up to 5° NNW (Mountrakis *et al.* 1993). In general, the Neogene formations are dominated by clayey sediments with low permeability and capacity.

The Western Chalkidiki constitutes a weak deformed block bounded by great structures i.e. the North Aegean Trough (ENE-WSW trending dextral strike-slip faults), the NW-SE Thermaikos

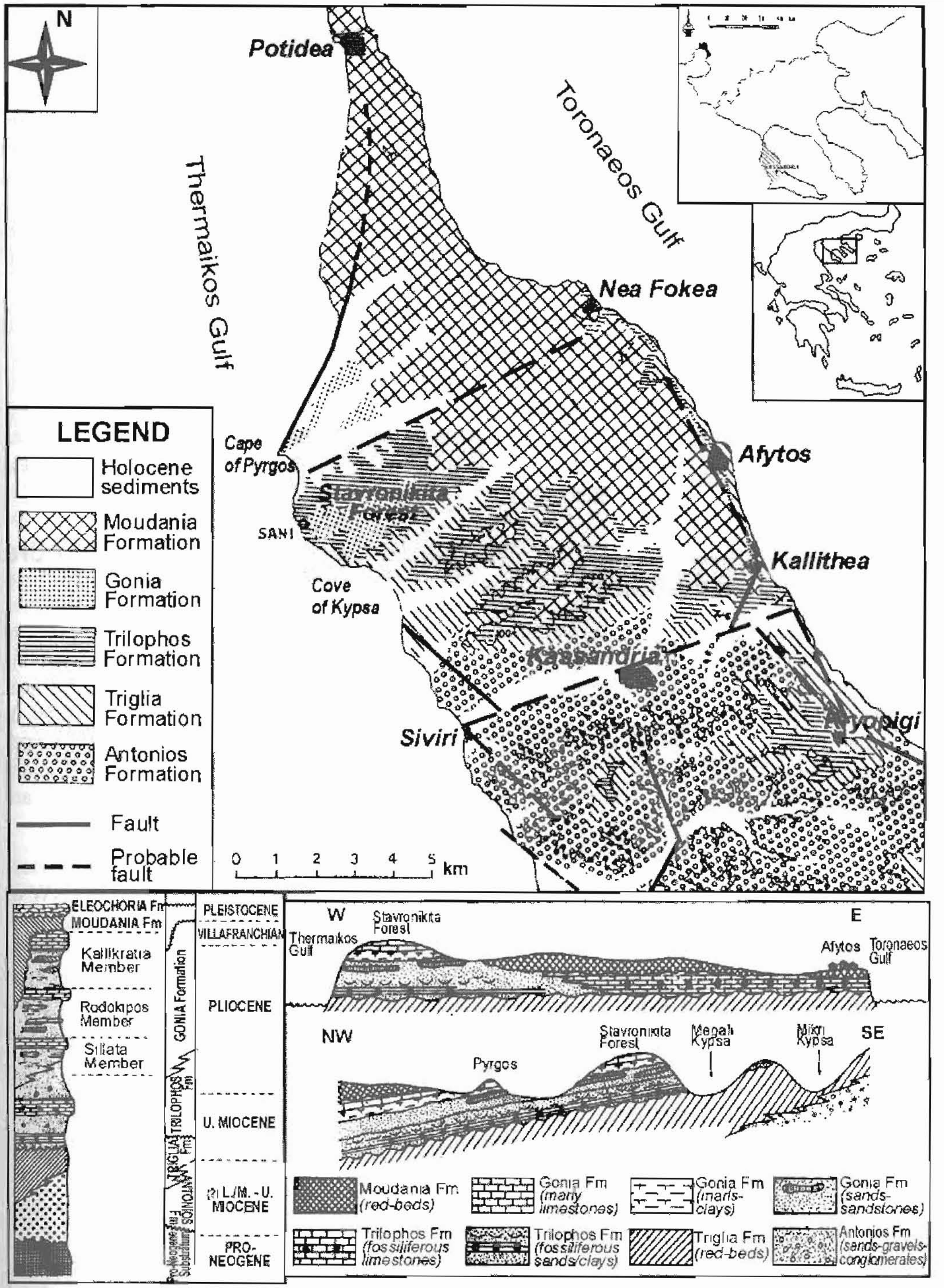

Figure 1 - Above: Geological map of the Sani-Afytos-Kassandria area (Syrides 1990) with the addition of some main and probable faults by Mountrakis *et al.* (1993). Below: Lithostratigraphic column and two geological cross-sections through the Kassandra Peninsula in the research area (Syrides 1990)

major faults, the important active fault of Anthemountas (N of the Kassandra Peninsula), the Olynthos dextral strike-slip fault (NNE-SSW) and the smaller fault zone in the Toronaeos Gulf. A NE-SW extension affecting pro-Neogene and late Miocene-Pliocene sediments (post-Oligocene? - Pliocene) has been weakly detected using fault slip and joints data. The middle Pleistocene (?) - active extension trending N-S affects the morphology, while this phase is accompanied by significant strike-slip movements (Mountrakis *et al.* 1993). Between Potidea and Kassandria, the area has a gentle relief inclining about 5° SSW. The northern coast shows a steep dip to N. The main and the probable faults that control the topography of this area are illustrated in the geological map of Fig. 1. Two main fault systems trending NW-SE and NE-SW dominate in the Sani-Afytos-Kassandria area affecting its morphology. A fault trending NNE-SSW, between Sani and Potidea, constitutes the probable continuation of the Olynthos dextral strike-slip fault southwards.

According to Pavlides *et al.* (1990) the geometry of the studied faults in the wider area of Central Macedonia and Chalkidi is as followed: (a) The NW-SE trending megastructures acted as oblique-slip faults, with a sinistral compouent, while E-W striking faults activated as pure dip-slip faults. (b) The few and small NE-SW faults showed dextral strike-slip displacements. (c) The N-S trending faults (N10°-20°) are old inherited structures, which show some recent reactivations (mainly dextral strike-slip movements) not influencing the morphology. (e) Many older reverse faults were reactivated as normal faults.

3. Geothermal conditions in the wider area of the Kassandra Peninsula based on deep oil boreholes data

Western Chalkidiki and the Kassandra Peninsula, constituting the eastern margin of the Paleogene post-orogenic Thessaloniki-Thermaikos basin, show a geothermal interest. At the margins of this basin and along the main tectonic structures, where the crystalline basement is uplifted, the heat flow increases resulting to the presence of low enthalpy geothermal waters at depth <1000 m (Kolios and Kavouridis 1988). Some of the geothermal manifestations like the coastal thermal springs of Agios Nikolaos-Agia Paraskevi (T=39 °C) in the southern part of the Kassandra Peninsula and the known geothermal fields of Eleochoria (T=33-42 °C) and Anthemountas, are present in the wider area of Western Chalkidiki.

Four deep oil boreholes (KAS-1, KAS-2, KAS-3, KAS-4) were drilled in the Sani-Afytos-Kassandria area by the Power Petroleum Corporation (P.P.C.). Well KAS-2 drilled on the NW of the Afytos village (Fig.2) has a depth of 1785 m. The stratigraphic column of this borehole is: 350-1025 m Miocene sediments, 1025-1092 m Upper Eocene sediments and 1092-1720 m Middle Eocene formations. The Miocene sediments consist of sands, sandstones, micro-conglomerates, clays, conglomerates and siltstones. The Eocene formations are composed of siltstones, micro-conglomerates, clays and conglomerates. In KAS-2 the porosity within the upper 1000 m was estimated to vary from 14 to 27 % with good permeability. In addition, the temperatures of 56 and 70 °C were measured at depths of 1282 and 1785 m respectively in this borehole. Up to the depth of 1500 m strata with geothermal interest were detected at 385-433 and 840-1025 m in sands and micro-conglomerates [porosity: 24 and 15 %, permeability: very good and good] with temperatures of 31 and 46 °C correspondingly (P.P.C. 1988).

In borehole KAS-3 (Fig. 2), the temperatures of 68 and 75 °C were measured at depths of 1653 and 1975 m respectively. East of the Kassandria village (Fig. 2), the temperatures of 40.5, 68 and 75 °C were recorded at 352, 1509 and 1904 m correspondingly in well KAS-1 (P.P.C. 1988). The average values of the geothermal gradient for boreholes KAS-2, KAS-3 and KAS-1 (for the total depth) are calculated to be 3.0, 2.97 and 3.08 °C/100 m respectively based on the Kassandria's meteorological station data and the mean annual air-surface temperature of 16.3°C. These values are equal to the normal geothermal gradient.

Another deep oil borehole (POS-1) of 4120 m depth was drilled close to the Kalandra on the south of the research area. Miocene (0-1010 m) and Oligocene-Eocene (1010-3610 m) formations were drilled. No permeable strata were detected below 1010 m. The temperatures of 55, 103, 136 and 156°C were measured at depths of 1197, 2394, 3468 and 4120 m respectively (P.P.C. 1988) and the average geothermal gradient is calculated to be 3.39°C/100 m for the total borehole depth.

Based on the stratigraphic data derived from the deep oil boreholes, a tectonic uplift of the basement by 160 m was recognized between Afytos and Kryopigi. In the area between Kryopigi and Posidi the basement is plunged from 2560 to 3160 m while the thickness of the Paleogene formations increases. Furthermore, the basement is plunged at greater depths in the center of the Thermaikos Gulf. The uplift of the basement and the main tectonic structures are associated with the rise of the isothermal curves.

The basement in the Kassandra Peninsula and in the wider area of Western Chalkidiki is made up mainly of Upper Jurassic carbonate formation (limestone), which is karstified and fractured. The thermoaquifer system of this formation seems to be continuous in most of the area but with considerable displacements along normal faults. Breaks are due to the ophiolites and granitoids (Shterev and Meladiotis 1993).

In the western part of the Chalkidiki Peninsula the estimated heat flow density fluctuates between 50 and 70 mW/m^2 (Shterev and Meladiotis 1993). The geothermal interest in the Kassandra Peninsula is focalized into the Miocene formations at depths >500 m and up to 1000 m (the Plio-Miocene sediments of the area have a thickness of about 1000 m). In borehole KAS-2 the average geothermal gradient was calculated to be 2.97 °C/100 m for the upper 1000 m (Miocene sediments). Convective transport of heat is occurring into the Paleogene molassic sediments. Such

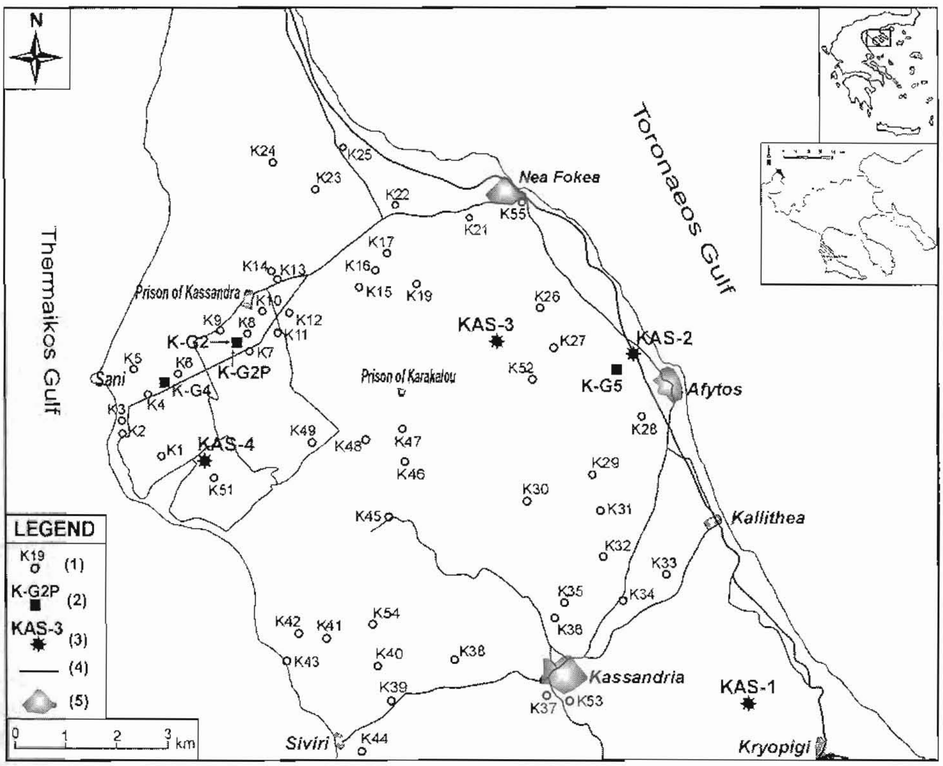

Figure 2 - Location map showing the sites of (a) the measured irrigation and water supply wells, (b) the deep oil boreholes and (c) the geothermal wells
[Legend: (1) irrigation and water supply wells, (2) geothermal (exploration and production) wells drilled by IGME, (3) deep oil boreholes, (4) road, (5) village]

hydrothermal systems are developed within the lower Eocene formations at depths >2000 m with temperatures of about 100 °C. Into the Neogene sediments, thermal aquifers (with temperature up to 50 °C) were detected within conglomerates at 400-1000 m of total thickness >200 m.

Table 1 – The results of thermometric survey in irrigation and water supply wells

Well	Depth of the well (m)	Temperature (°C)		Well / Spring	Depth of the well (m)	Temperature (°C)	
		At the wellhead	At the bottom			At the wellhead	At the bottom
K-1	150	---	20.2	K-30	170	21.1	---
K-2	190	---	22.9	K-31	160	19.0	---
K-3	200	24.4	---	K-32	170	20.5	---
K-4	170	24.7	---	K-33	128	20.7	---
K-5	204	22.8	---	K-34	190	---	18.8
K-6	174	21.7	---	K-35	160	18.4	---
K-7	197.5	25.7	---	K-36	156	18.5	---
K-8	170	21.2	---	K-37	210	19.2	21.8
K-9	200	21.5	---	K-38	260	---	25.5
K-10	200	20.5	---	K-39	50	18.2	
K-11	165	---	21.2	K-40	200	19.8	---
K-12	144	18.4	---	K-41	200	19.5	---
K-13	150	19.9	---	K-42	114	18.3	---
K-14	220	24.2	25.1	K-43	120	17.9	---
K-15	160	18.4	---	K-44	110	---	17.5
K-16	181	24.5	---	K-45	200	19.8	---
K-17	100	19.1	---	K-46	140	19.9	---
K-19	230	---	24.5	K-47	180	20.3	---
K-21	194	19.9	---	K-48	Spring	16.7	---
K-22	230	---	24.9	K-49	220	21.9	---
K-23	160	21.0	---	K-51	220	22.9	---
K-24	220	---	24.6	K-52	270	---	19.7
K-25	□80	---	23.7	K-53	190	---	22.4
K-26	200	25.3	---	K-54	170	---	20.0
K-27	308	---	28.2	K-55	256	25.7	24.1 (150 m)
K-28	190-200	20.6	---				
K-29	170	20.3	---				

Some information on the screens placed in the following wells:

K-4: at depths of 39-45.7, 49.7-56.3, 91.9-103.5, 138.8-158, 164-170 m

K-6: at depths of 25.5-31.6, 37.8-45, 73.6-78.3, 109.6-116.4, 119.4-122.5, 137.2-144.4 m

K-7: at depths of 27.5-33.5, 42.5-57.3, 153-156, 159-163.2, 165.2-174.2, 176.7-182.7, 186.7-195.5 m

K-8: at depths of 26-32.8, 39.4-45.1, 85-91.5 m -- K-9: at depths of 47-53.5, 121-129 m

K-24: at depths of 90-114, 132-150, 168-180, 186-204, 210-220 m

K-27: at 72-84, 108-114, 120-127, 132-136, 144-156, 168-180, 198-222, 240-276, 248-300 m

4. Water temperature measurements in the Sani - Afytos area

A systematic and detailed thermometric survey was undertaken in the Sani-Afytos-Kassandria area. The water temperatures were measured either at the head (during their pumping) or at the bottom (lowering a temperature sensor) in irrigation and water supply wells. The results of this thermometric investigation are presented in Table 1 and the location map with the sites of these wells is shown in Fig. 2, where are also marked the positions of the deep oil boreholes and the geothermal wells drilled by I.G.M.E

The depths of the irrigation and water supply wells range from 50 to 308 m. All these boreholes are in the Quaternary and Neogene sediments of the area. Between Sani and Nea Fokea, the existing wells having depths of 100-256 m produce waters with temperatures of 18.4-25.7 °C. South and southeast of the Nea Fokea village the waters at the boreholes heads have temperatures up to 25.3 °C (well K-26). Moreover, around the Siviri village the provided waters out of the existing wells have temperatures of 17.9-19.8 °C.

Fig. 3 shows temperature-depth curves for various irrigation and water supply wells. The maximum temperature of 28.2 °C was measured at the depth of 308 m in borehole K-27. Considering that the mean annual surface temperature of the area is 16.3 °C, the average geothermal gradient is calculated to be 3.86 °C/100 m (for the entire depth of well K-27). The values of the average geothermal gradient for wells in the Sani-Afytos-Kassandria area were estimated to fluctuate between 1.09 and 4.11 °C/100 m. Low values of the geothermal gradient (1.09 and 2.18 °C/100 m) were determined for boreholes around the Siviri village. Other wells with average geothermal gradient less than the normal one (i.e. <3 °C/100 m) are the followings: K-1 [(2.6 °C/100 m) SSE of Sani], K-34 [(1.32 °C/100 m) between Kassandria and Kallithea], K-52 [(1.26 °C/100 m) W of Afytos] and K-37 [(2.62 °C/100 m) S of Kassandria]. High values of geothermal gradient were estimated for wells K-25 [(4.11 °C/100 m), NW of Nea Fokea] and K-14 [(4.0 °C/100 m), NE of the Kassandra Prison]. For

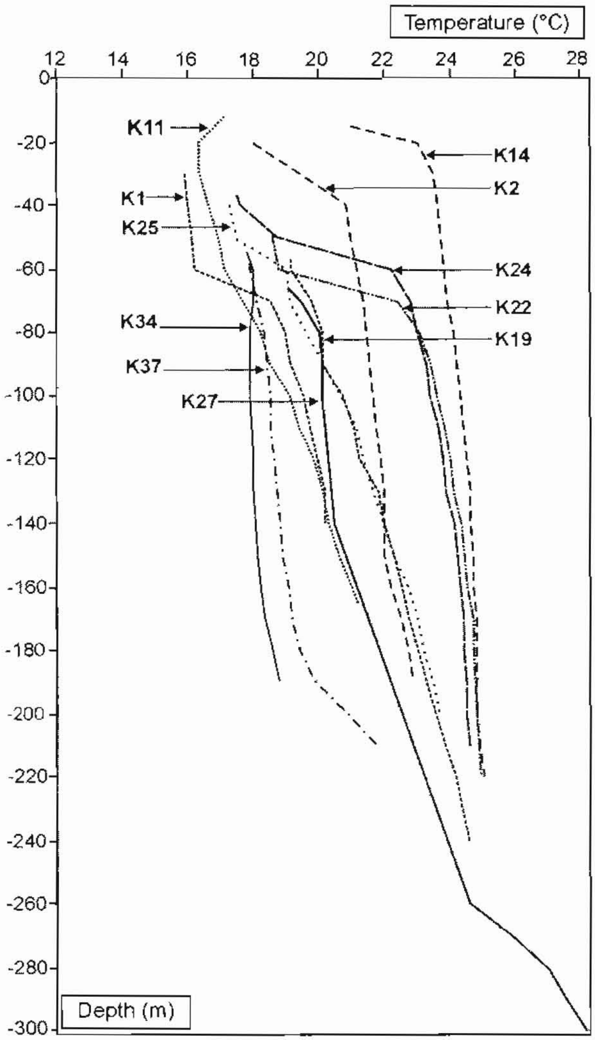

Figure 3 - Temperature vs. depth curves for the irrigation and water supply wells in the Sani-Afytos-Kassandria area

well K-55 (in Nea Fokea), the geothermal gradient was calculated for depth up to 150 m to be 5.2 °C/100 m. For the rest of the boreholes, the values of the average geothermal gradient range from 3 to 3.77 °C/100 m, that is slightly higher than normal.

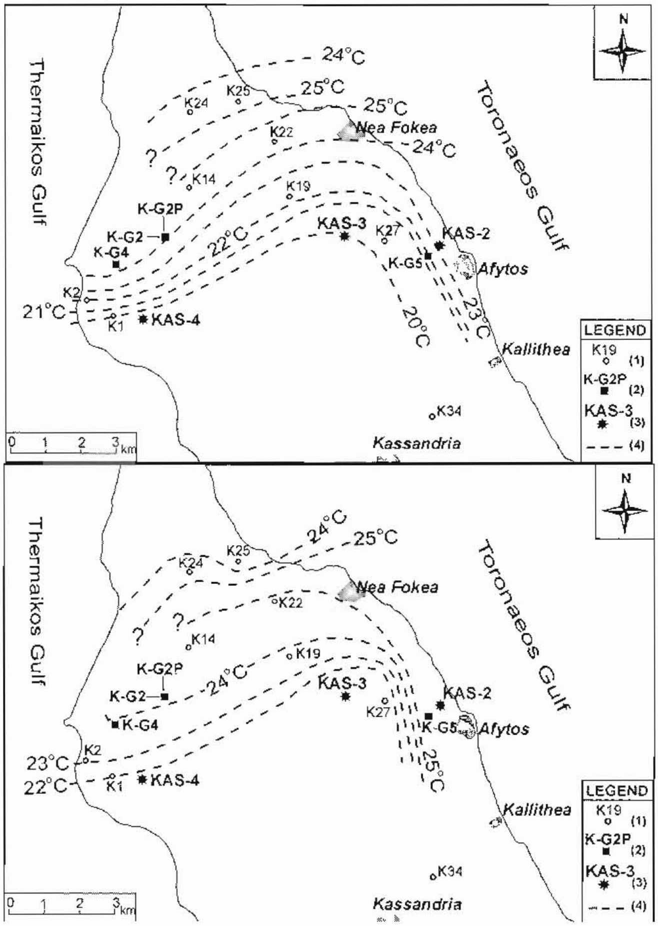

Figure 4 - Map of the isothermal curves at the depths of 150 m (above) and 200 m (below) [Legend: (1) irrigation and water supply wells, (2) geothermal wells drilled by IGME, (3) deep oil boreholes, (4) probable isothermal curve]

Fig. 4 shows the distribution of the isothermal curves with T>20 °C at depths of 150 and 200 m in the investigated area. The shape of these isothermal curves shows SW-NE and NW-SE distinct directions and coincides with the main tectonic structures (Fig. 1) trending SW-NE (between Sani and Fokea) and NW-SE (along the coast, between Nea Fokea and Kallithea).

5. Drilling exploration – Construction of geothermal exploration and production wells in the Sani - Afytos area

Based on the results of the preliminary thermal - thermometric investigation, 4 new geothermal wells were constructed by I.G.M.E in the exploration area during the period June 1998 - September 2000. Three of them (KG-2, KG-4 and KG-5) are exploratory and only one (KG-2P) is productive. The sites of these wells are shown in the location map of Fig. 2.

Exploration well KG-2, with a depth of 542 m, has drilled sediments of the Upper Miocene. Clays in various colors (reddish, light-colored, whitish, greenish) alternating with sands and gravels dominate in the upper part of the sedimentary sequence and up to 316 m. At greater depths the material is enriched with sands, sandstones, gravels, conglomerates with a few clays and alternations of clays. The first shallow aquifers are located into the sandy intercalations at depths of 73, 109-116 and 119-122 m and the deeper ones at 316, 398-444 and 480-520 m. The casing of the well has a diameter of 4´´ at 0-120 m and 2´´at 120-542 m. The well has an artesian flow with water temperature of 34°C.

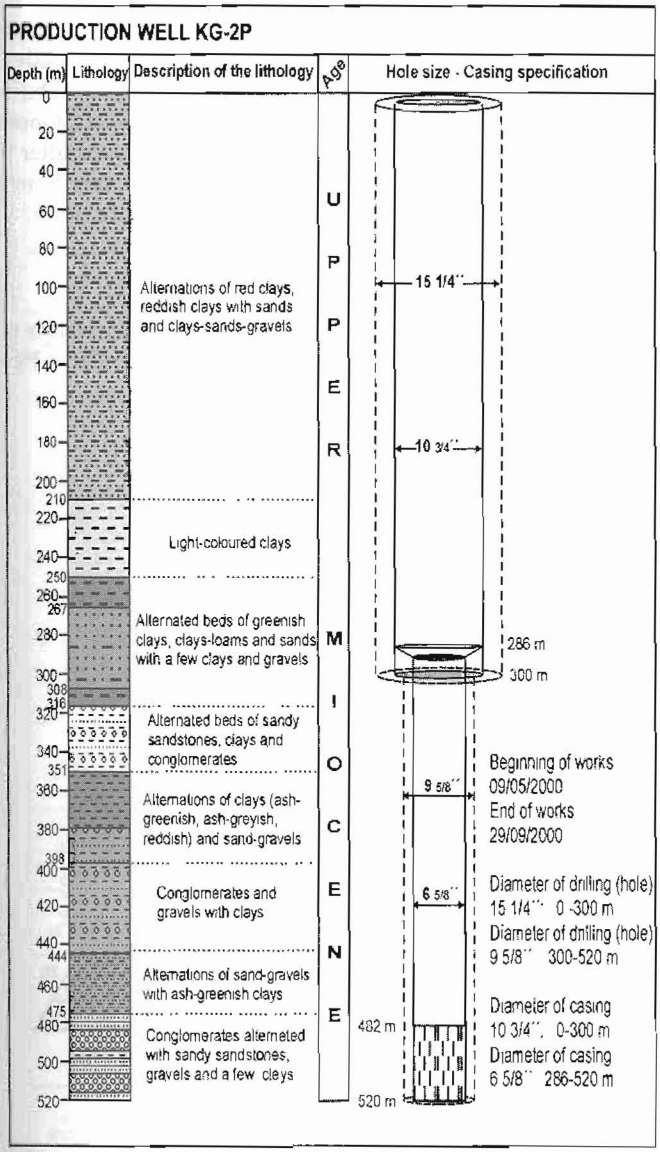

Figure 5 - Geothermal production well KG-2P

Exploration well KG-4 was constructed at a distance of 1.6 km SE from KG-2. Its depth is 583 m. Sediments of the Upper Miocene were drilled. Clayey-sandy sediments alternating with sands, gravels and sandstones dominate. Deep aquifers are located at depths of 300-318 m and 392-498 m. The casing of this well has a diameter of 5´´ at 0-195 m and 2 ½´´at 195-583 m. The well has an artesian flow with pressure of 1.5-2 atm. The water temperature into the reservoir is 36 °C.

Exploration well KG-5, placed close to the Afytos village, has a depth of 422 m. Pleistocene and Miocene sediments were drilled. The Pleistocene sediments have a thickness of about 350 m composed mainly of marly limestones, sandstones and marls alternated with clays, sands and conglomerates. The Miocene sediments consist of clays with sands and gravels. Aquifers are located below 375 m and into the base of the Pleistocene formations. The water temperature was measured 31.7 °C at depth of 422 m. The water level was found at 42.9 m. The casing of the well has a diameter of 5´´ at 0-200 m and 2 ½´´at 200-422 m.

Considering that the mean annual surface temperature of the area is 16.3°C, the values of the average geothermal gradient for boreholes KG-2, KG-4 and KG-5 are calculated to be 3.27, 3.38 and 3.65°C/100 m respectively (for the entire depth). These values are slightly higher than the normal geothermal gradient (3 °C/100 m) value.

Exploration - production well KG-2P (Fig. 5) was constructed next to borehole KG-2. Its depth is 520 m. It has drilled Miocene sediments similar to the ones in KG-2. The casing of the well is 10 ¾'' up to 300 m and 6 5/8'' from 286 to 520 m depth. Screens were placed at 482-520 m. The well has an artesian flow (15 m^3/h) with water temperature 33.7-34 °C.

Constant-rate and step-drawdown pumping tests were performed in well KG-2P. The constant-rate pumping test was conducted for 24 hours with Q=70 m^3/h. The final (after 24 h of pumping) drawdown was measured at 51.4 m. On the basis of this pumping test data and assuming that the aquifer thickness is 50 m, the following hydraulic parameters were calculated: transmissivity $T=6.52 \times 10^{-4}$ m^2/s, hydraulic conductivity $K=1.30 \times 10^{-5}$ m/s and storativity $S=4.40 \times 10^{-8}$. During this pumping test the water temperature was increased by 0.3 °C. When pumping stopped, recovery measurements of the water level were made. Complete recovery was observed after 65 min. During its production and exploitation phase, well KG-2P may discharge 50-55 m^3/h geothermal waters with a constant temperature of 34 °C and prospective drawdown at 22-25 m.

6. Geochemical investigation in the Sani - Afytos area

The results of the chemical analyses of thermal and non-thermal (cold, sub-thermal) waters are given in Table 2. All the samples were plotted on a trilinear diagram (Fig. 6) according to Piper (1944).

The geochemical study proved that the geothermal waters KG-2, KG-2P and KG-5 with T.D.S. 0.89-1.4 g/l are according to the Davis and DeWiest classification (1966) of the Na-HCO_3 type. On the other hand, the water sample from borehole KG-4 with T.D.S. 2.03 g/l is ordered to the Na-Cl type. The non-thermal (cold or sub-thermal) water samples with temperatures of 16.7-28.2 °C and T.D.S. 0.46-1.57 g/l are classified in various types: Na-HCO_3, Ca,Mg,Na-HCO_3, Ca,Mg-HCO_3, Ca,Mg-HCO_3Cl, Ca,Mg,Na-HCO_3Cl, Ca-HCO_3Cl, Ca,Na-HCO_3Cl, Ca,Na-HCO_3, Ca-HCO_3 and Na-Cl. Samples K-27 and K-38, with temperatures of 28.2 and 25.5 °C respectively and higher values of salinity than the other sub-thermal waters, belong to the Na-Cl type. Cold water samples K-48 and K-43 with temperatures of 16.7 and 17.9 °C correspondingly are classified in Ca,Mg-HCO_3 and Ca-HCO_3Cl (on the boundary line separating Ca-HCO_3Cl waters from Ca-HCO_3 ones) types.

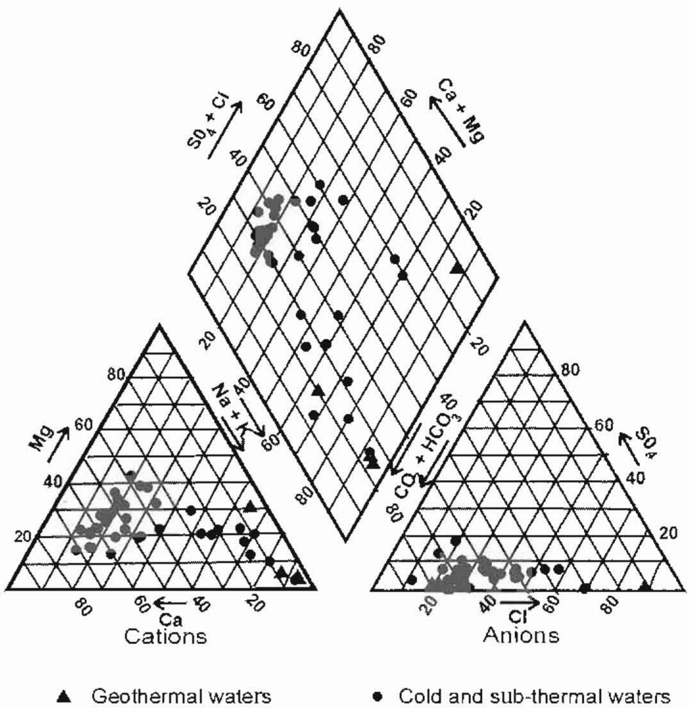

Figure 6 - Presentation of the values of chemical analyses of the waters (cold, sub-thermal and geothermal) from the Afytos – Sani area on a trilinear diagram according to Piper (1944)

Table 2 - The results of chemical analyses of waters (cold, sub-thermal and geothermal) from the Sani-Afytos area (in mg/l)

Wells	T (°C)	T.D.S. (mg/l)	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe	Mn^{2+}	Li^+	Sr^{2+}	NH_4^+	Cl^-	HCO_3^-	CO_3^{2-}	SO_4^{2-}	F^-	NO_3^-	Br	SiO_2	B
K-2	22.9	474.5	7.69	92.2	2.4	46.5	31.9	—	0.500	—	—	0.000	92.2	388.1	0.0	1.9	—	1.86	—	15.0	–
K-3	24.4	545.7	7.83	116.6	2.4	51.3	24.8	0.465	0.000	< 0.01	0.60	0.000	76.2	423.4	0.0	12.0	0.08	2.48	0.05	25.8	25.6
K-4	24.7	530.5	8.10	161.2	2.0	17.2	10.7	0.415	0.000	< 0.01	0.40	0.000	85.1	444.2	0.0	0.0	<0.01	0.62	0.85	22.4	12.0
K-6	21.7	562.1	7.70	158.2	1.6	27.3	14.8	0.023	0.000	0.00	0.32	0.000	106.4	435.0	0.0	12.0	0.26	3.10	0.19	22.5	2.0
K-7	25.7	659.7	8.06	238.9	1.6	9.6	3.4	0.046	0.000	< 0.01	0.20	0.000	113.4	544.3	0.0	0.0	<0.01	1.24	0.76	19.1	4.7
K-8	21.2	741.6	7.35	52.0	1.2	151.1	48.1	<0.001	0.000	0.00	1.05	0.000	187.9	446.0	0.0	32.2	0.23	21.70	0.22	25.8	1.5
K-9	21.5	811.8	7.72	75.6	0.8	138.7	58.6	0.022	0.150	0.00	1.10	0.000	226.9	455.2	0.0	41.8	0.61	18.60	0.25	24.1	1.5
K-10	20.5	671.0	7.13	49.4	0.8	143.5	34.3	—	0.000	—	—	0.000	141.8	442.4	0.0	34.1	—	17.38	—	33.0	–
K-12	18.4	748.2	7.39	51.0	1.0	156.3	36.5	0.016	0.023	< 0.10	0.77	0.001	177.3	455.1	0.0	42.9	0.33	32.12	0.18	26.6	0.1
K-13	19.9	626.7	7.37	43.0	1.0	148.3	30.6	0.008	0.023	< 0.10	0.51	0.000	124.1	373.3	0.0	43.8	0.17	24.20	0.14	27.9	0.0
K-14	24.2	664.1	7.69	160.0	2.0	47.3	30.1	0.019	0.032	< 0.10	0.74	0.000	138.3	506.3	0.0	0.6	0.26	4.40	0.12	29.8	2.2
K-15	18.4	796.2	7.16	103.2	0.8	136.3	32.1	0.008	0.163	0.00	0.53	0.000	209.2	421.0	0.0	49.0	0.10	22.30	0.19	32.3	3.7
K-17	19.1	748.4	7.59	79.0	2.0	157.1	19.4	0.011	0.027	< 0.10	0.65	0.000	237.6	305.0	0.0	46.4	0.36	28.16	0.19	27.8	0.1
K-21	19.9	753.7	7.91	75.2	1.2	148.3	31.6	—	0.000	—	—	0.000	223.3	424.7	0.0	25.0	—	6.20	—	34.7	–
K-22	24.9	890.2	7.79	100.0	2.0	166.0	43.3	0.018	0.016	< 0.10	0.85	0.029	273.0	427.0	0.0	47.7	0.64	19.36	0.10	27.9	0.1
K-23	21.0	1005.5	7.30	160.0	2.0	141.9	49.1	0.064	0.061	< 0.10	1.00	0.020	361.7	379.4	0.0	63.1	0.87	12.76	0.15	26.6	0.2
K-26	25.3	608.0	7.64	138.9	2.4	51.7	25.5	0.032	0.000	0.00	0.32	0.000	148.9	391.1	0.0	21.1	0.23	1.24	0.21	24.3	1.5
K-27	28.2	1324.3	7.66	340.0	3.0	60.1	62.2	0.052	0.131	< 0.10	1.40	0.068	609.9	457.5	0.0	0.0	0.47	0.44	0.19	19.1	3.0
K-28	20.6	543.4	7.11	43.0	1.6	113.8	31.6	—	0.100	—	—	0.100	85.1	445.4	0.0	12.0	—	4.30	—	32.5	–
K-29	20.3	507.2	7.17	37.2	0.8	118.6	18.0	—	0.250	—	—	0.140	46.1	360.0	0.0	51.9	—	31.00	—	26.8	–
K-30	21.1	566.6	7.11	43.7	2.0	101.0	44.3	—	0.000	—	—	0.100	95.7	457.0	0.0	14.9	—	8.10	—	33.0	–
K-31	19.0	459.3	7.29	33.6	1.2	105.8	15.3	—	0.000	—	—	0.100	55.0	334.4	0.0	27.9	—	24.20	—	32.5	–
K-32	20.5	529.3	7.10	34.7	1.2	111.4	33.6	—	0.000	—	—	0.110	93.9	402.6	0.0	12.9	—	13.00	—	31.3	–
K-35	18.4	621.7	7.22	40.0	2.0	138.7	27.7	0.005	0.004	< 0.10	0.35	0.053	99.3	457.5	0.0	36.4	0.40	27.72	0.11	24.5	0.3
K-36	18.5	664.1	7.15	32.0	3.0	161.9	33.5	0.029	<0.001	< 0.10	0.39	0.012	92.2	408.7	0.0	49.8	0.38	65.56	0.14	24.6	0.3
K-38	25.5	1569.7	7.90	450.0	4.0	56.1	68.0	0.056	0.007	< 0.10	1.90	0.160	695.1	502.6	0.0	14.5	0.34	2.20	0.12	24.6	5.8
K-39	18.2	743.5	7.33	59.0	2.0	130.7	50.5	0.050	0.106	< 0.10	0.44	0.102	92.2	540.5	0.0	118.5	0.58	6.60	0.10	17.6	0.2
K-41	19.5	528.6	7.54	38.0	2.0	92.2	43.3	0.030	0.001	< 0.10	0.48	0.022	92.2	386.7	0.0	27.5	0.16	19.80	0.12	23.1	0.2
K-42	18.3	522.4	7.29	40.0	2.0	99.4	33.5	<0.001	0.013	< 0.10	0.39	0.062	92.2	378.2	0.0	27.5	0.44	19.36	0.12	21.9	0.2
K-43	17.9	572.0	7.38	42.0	1.0	113.8	33.5	0.012	<0.001	< 0.10	0.46	0.047	102.8	416.0	0.0	32.8	0.48	16.72	0.12	24.0	0.3
K-45	19.8	577.6	7.64	46.0	3.0	83.4	56.9	0.020	0.025	< 0.10	0.78	0.000	102.8	457.5	0.0	28.2	0.64	7.04	0.09	24.3	0.2
K-46	19.9	582.1	7.75	69.0	5.0	84.2	56.4	0.011	<0.001	< 0.10	0.99	0.083	92.3	441.6	0.0	24.6	0.39	3.08	0.13	29.4	0.2
K-47	20.3	600.8	7.33	61.0	3.0	89.0	55.4	0.026	0.022	< 0.10	0.88	0.048	102.8	473.4	0.0	26.3	0.37	2.20	0.11	27.5	0.1
K-48	16.7	684.2	7.16	36.0	2.0	166.7	20.4	0.017	0.051	< 0.10	0.36	0.000	117.0	378.2	0.0	48.5	0.48	81.84	0.09	25.4	0.0
K-49	21.9	583.7	7.25	63.7	2.4	110.6	37.0	—	0.100	—	—	0.650	101.0	455.2	0.0	15.9	—	1.86	—	27.5	–
K-51	22.9	652.0	7.47	87.4	3.1	86.6	49.1	—	0.000	—	—	0.200	195.0	366.7	0.0	25.9	—	0.00	—	25.0	–
K-52	19.7	626.4	7.01	80.0	3.0	102.2	25.8	2.300	0.030	—	—	0.129	120.6	384.3	0.0	36.5	0.58	35.20	0.06	30.0	0.9
K-55	25.7	627.3	7.41	180.0	4.0	31.6	24.6	0.002	0.018	< 0.01	<0.01	0.042	46.1	600.2	0.0	17.6	0.16	2.20	0.05	26.4	0.4
KG-2	34.0	912.9	7.40	360.0	3.0	11.2	7.8	0.085	0.008	—	—	0.064	127.7	763.7	0.0	0.2	0.95	0.44	0.00	20.3	6.2
KG-4	36.0	2028.4	7.76	720.0	5.0	56.1	21.9	0.022	0.030	—	—	0.146	1081.5	248.9	0.0	0.5	0.16	1.32	0.03	19.7	–
KG-5	31.7	1396.5	8.26	400.0	6.0	21.6	97.7	1.384	0.028	< 0.10	1.70	<0.001	184.4	1303.0	7.2	0.0	0.20	0.00	0.06	34.8	3.0
KG-2P	34.0	888.7	7.85	337.0	3.0	11.1	8.6	0.035	0.015	—	—	0.109	134.8	736.9	0.0	1.7	1.01	0.00	—	23.5	6.8

Thus, the geothermal waters (T≥30 °C) in the Sani-Afytos-Kassandria area are classified in two groups, which are characterized by a different degree of mineralisation (T.D.S.) and chemical composition. The first one of the carbonated waters ($Na-HCO_3$) with temperatures of 31.7-34 °C and mineralization ranging from 0.89 to 1.4 g/l is rich in Na^+ (337-400 mg/l) and HCO_3^- (736.9-1303 mg/l). The Cl^- concentrations are not very high (127.7-148.4 mg/l). The relatively high Na^+ concentration with no Cl^- correspondence is probably due to the effective cationic exchange between the rich in Na^+ clayey intercalations and the rich in Ca^{2+} and Mg^{2+} waters (Na-Ca ionic exchange) at deeper levels. The low Ca^{2+} content (11.1-21.6 mg/) of samples KG-2, KG-5 and KG-2P supports tbis thesis.

The second geothermal waters group is the saline mineral (Na-Cl) waters, like sample from borehole KG-4, having much higher salinity than the waters of the first group. The Neogene marine transgression and sedimentation are considered (Shterev and Meladiotis 1993) as the primary source of salty sea water which fill a big part of the Upper Jurassic carbonate reservoir, the terrigeneous reservoirs in the Miocene formations as well as in the non-compacted marine Neogene clayey sediments. These are transformed connate waters with a Na-Cl composition and high degree of mineralization. The infiltration of meteoric waters plays an important role in the exposed parts of the Jurassic reservoir and the adjacent zones: they replace and freshen the connate waters and considerably change their features. Transitional or mixed types of mineral waters are formed in the buffer zone between meteoric and fossil waters (Shterev and Meladiotis 1993).

The first afore-mentioned group of thermal waters is considered (Shterev and Meladiotis 1993) genetically more inhomogeneous than the second one, includes atmospheric, marine and mixed waters and is represented by waters with HCO_3 or/and HCO_3-CI composition. The SO_4^{2-} reduction or its absence (0-1.7 mg/l) characterizes all the geothermal waters. The SiO_2, Br, Li and Sr contents in the thermal waters are similar to those of the sub-thermal ones and certainly with not high values.

The sub-thermal waters from the Sani-Afytos-Kassandria area are of mixed type indicating mixing between fresh, superficial waters with deeper and more saline ones. Tritium values of the Kassandra fresh waters cover a wide range from 0.46 to 31.2 TU indicating active and fast aquifer recharge (Jackelen et al., 1986). In general, all waters in the Chalkidiki Peninsula (thermal, fresh, sub-thermal) were proved (Jackelen et al., 1986) to be of meteoric origin.

Table 3 - Estimation of the deeper geothermal waters by the use of chemical geothermometers

Sampl e	T(°C) at well-head	T(°C) SiO_2	T(°C) Na/K	T(°C) Na-K-Ca	T(°C) K/Mg
KG-2	34.0	64.1	30.5	85.9	44.4
KG-4	36.0	62.9	22.9	75.0	44.3
KG-5	31.7	85.6	58.1	96.0	33.5
KG-2P	34.0	69.7	33.4	85.3	43.5

The chemical geothermometers of SiO_2 (Fournier 1981), Na/K (Arnorrson *et al.* 1983), Na-K-Ca (Fournier and Truesdell 1973) and K/Mg (Giggenbach *et al.* 1983), which were applied to the geothermal waters KG-2, KG-4, KG-5 and KG-2P, suggest the temperatures given in Table 3. The Na/K and K/Mg geothermometers suggest very low temperatures (23-58 °C) for the deep geothermal waters. The geothermal waters are plotted (Fig. 7) on the triangular Na-K-Mg diagram according to Giggenbach (1988). On this diagram is found that only the position of sample KG-5 is within the area of immature waters. Tbe other samples KG-2, KG-4 and KG-2P lay very close / on the boundary curve between the immature and the partial equilibrium waters indicating a possible reservoir temperature of about 100 °C. Hence, using chemical geothermometers the deep temperature is estimated in 80-100 °C. This value is similar to the measured temperatures at the bottoms of deep oil boreholes KAS-1, KAS-2 and KAS-3 (70 °C at 1785 m in KAS-2, 75 °C at 1975 m in KAS-3 and 75 °C at 1904 m in KAS-1).

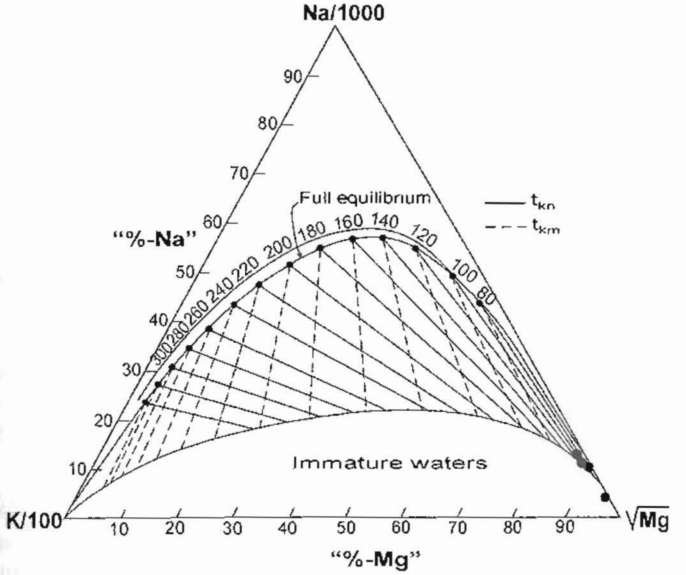

Figure 7 - Evaluation of Na-K-Mg temperature for the geothermal waters KG-2, KG-4, KG-5 and KG-2P on diagram after Giggenbach (1988)

From borehole KG-4, gas sample was collected in special plastic bags (Aldrich) and it was analyzed by gas chromatography VARIAN Model 3700. The dominant gas was CH_4 with a content of 77 % v/v, while N_2 was 21.8 % v/v. Other gasses were also detected like H_2 (1 % v/v) and CO_2 (0.2 % v/v). H_2S was not detected. The flow rate measurements proved that for a liquid phase flow rate of 12 m^3/h the gas phase flow rate is 2.4 m^3/h (under T=20 °C and P=1 atm). In general, the group of the sodium-chloride waters, like sample KG-4, is characterized with methane gas content.

By soil-gas survey, an attempt was made for the recognition of faults nsing the soil-gasses He, ^{222}Rn, CO_2 and CH_4 as fault tracers in the area of the Kassandra Prison (Fig. 2). The distribution of radon and methane anomalous values (>1.40 ppm CH_4) shows NNW-SSE and SE-NW directions according to the main orientations of the faults in the area. The CO_2 anomalous concentrations (>0.73 % v/v) are elongated along NE-SW direction in the Kassandra Prison area. High values of the helium (>30 ppb) are noted in specific sites.

7. Summary and Conclusions

The Sani-Afytos area in the Kassandra penisula is of geothermal interest. The basement of the area is built up of Mesozoic metamorphic rocks of the Axios Zone [mainly Upper Jurassic carbonate rocks (limestones)] and is covered by Paleogene, Neogene and Quaternary sediments with a significant thickness (up to 3610 m or more). The Neogene formations are dominated by clayey sediments. Two main fault systems trending NW-SE and NE-SW dominate in the Sani-Afytos-Kassandria area affecting the morphology. A fault trending NNE-SSW, between Sani and Potidea, constitutes the probable continuation of the Olynthos dextral strike-slip fault southwards.

The geothermal interest in the Kassandra Peninsula is focused in the Miocene formations at depths >500 m and up to 1000 m (the Plio-Miocene sediments of the area have a thickness of about 1000 m). Into the Neogene sediments, thermal aquifers (with temperature up to 50 °C) are detected within conglomerates at 400-1000 m with total thickness >200 m. The systematic and detailed thermometric survey in the Sani-Afytos-Kassandria area with water temperature measurements at the wellhead and/or at the bottom of the existing irrigation and water supply wells proved the presence of subthermal (20-28 °C) waters at depths of about 300 m. The geothermal gradient in the study area can be evaluated as normal or close to the normal (3-4 °C/100 m). The shape of the isothermal curves at depths of 150 and 200 m shows SW-NE and NW-SE directions and coincides with the main tectonic structures.

Four geotbermal (three exploration and one production) wells with depths of 422-583 m were drilled in tbe Sani-Afytos area by I.G.M.E. The average geothermal gradient for the exploration boreholes is calculated to be 3.27-3.65 °C/100 m for their entire depth. The maximum temperature of 36 °C was measured at 583 m. Aquifers are located within the intercalations of sands, gravels, sandstones and conglomerates of the clayey Upper Miocene sediments. The production well with depth of 520 m was drilled in the area between Sani and the Kassandra Prison. Screens were placed at 482-520 m. During its production and exploitation phase, this well may discharge 50-55 m^3/h geothermal waters with a constant temperature of 34 °C and prospective drawdown at 22-25 m. Considering that the flow rate of this well is 13.81 kg/s (50 m^3/h), the water temperature is 34°C (inlet temperature of a plant) and the outlet temperature (after use) is 20 °C, the thermal capacity is calculated to be 0.81 MWt and the heat load is estimated to be about 700000 kcal/h corresponding to energy savings of 0.07 TOE/h.

The geothermal waters (T≥30°C) in the Sani-Afytos-Kassandria area are classified in two groups of waters: Na-HCO_3 and Na-Cl (saline). The SO_4^{2-} reduction or its absence (0-1.7 mg/l) characterizes all the geothermal waters. The sub-thermal waters are of mixed type and are classified in various categories. With the aid of chemical geothermometers the deep temperature was estimated in 80-100°C. This value is similar to the measured temperatures at the bottoms of deep oil boreholes. The analysis of the gas phase from one exploration borehole proved that the dominant gas was CH_4 with a content of 77 % v/v whereas H_2S was not detected.

The existence of low enthalpy geothermal waters with temperatures of 35-40°C in the Sani-Afytos-Kassandra area is of major importance, as their exploitation will enable significant energy savings directly applicable in several tourism and new lucrative activities. The preliminary geothermal investigation and the drilling project carried out by I.G.M.E. revealed the existence of a new low enthalpy system in the Kassandra Peninsula, which is now called as the "geothermal field of Sani-Afytos" according to the Decision of the Hellenic Ministry of the Development (July 2005) ["Characterization and classification of the Geothermal Fields of Country" (Greece)].

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