

PRELIMINARY GEOTHERMAL INVESTIGATION IN THE BASIN OF KATERINI (NORTHERN GREECE)

Papachristou M.¹, Arvanitis A.² and Kolios N.³

¹Aristotle University of Thessaloniki, Department of Geology, 54124, Thessaloniki, Greece,
mariap@geo.auth.gr

²Institute of Geology and Mineral Exploration, 1st Spirou Louis St., Olympic Village, 13677,
Acharnae, Greece, arvanitis@igme.gr

³Geothermiki Hellas Ltd, Neo Erasmio, 67200, Xanthi, Greece, kolios@agrecofarm.gr

Abstract

This paper describes the results of the preliminary surface geothermal exploration conducted by IGME in the basin of Katerini (Northern Greece). It mainly regards temperature measurements at the wellhead of 73 wells and in the interior of five boreholes, as well as sampling and chemical analyses from 18 selected sites. Based on the collected data, three sub-regions of geothermal interest can be distinguished, the most important of which is the area of Kato Agios Ioannis (to the south of the basin), with temperatures around 27°C at the depth of 340m. Nonetheless, the detailed geothermal investigation of this basin requires further systematic research as well as the drilling of at least one deep geothermal exploration borehole.

Keywords: exploration, temperature, geothermal gradient, isotherms.

Περίληψη

Η παρούσα εργασία περιγράφει τα αποτελέσματα της προκαταρκτικής γεωθερμικής έρευνας που διενεργήθηκε από το ΙΓΜΕ στην λεκάνη της Κατερίνης (Β. Ελλάδα). Οι ερευνητικές εργασίες κατά κύριο λόγο περιελάμβαναν θερμομετρήσεις στην κεφαλή 73 υπάρχουσών υδρογεωτρήσεων, μέτρηση της θερμοκρασίας σε συνάρτηση με το βάθος στο εσωτερικό πέντε (5) γεωτρήσεων και χημικές αναλύσεις 18 δειγμάτων από επιλεγμένες θέσεις. Με βάση τα στοιχεία που προέκυψαν από την κατανομή των θερμοκρασιών, διακρίνονται τρεις επιμέρους περιοχές γεωθερμικού ενδιαφέροντος. Ως σημαντικότερη κρίνεται αυτή του Κάτω Αγίου Ιωάννη (νότια τμήμα της λεκάνης), όπου μετρήθηκαν θερμοκρασίες της τάξης των 27°C σε βάθος 340m. Εν τούτοις, για τη λεπτομερή διερεύνηση των γεωθερμικών συνθηκών στη λεκάνη Κατερίνης, απαιτείται περαιτέρω συστηματική έρευνα και κατασκευή τουλάχιστον μίας ερευνητικής γεωθερμικής γεώτρησης μεγάλου βάθους.

Λέξεις κλειδιά: γεωθερμική έρευνα, θερμοκρασία, βαθμίδα, ισόθερμες.

1. Introduction

The geothermal exploration in Greece has revealed the significant geothermal potential of the country, attributed mainly to its specific geotectonic conditions. High enthalpy geothermal systems

have been discovered in the active South Aegean Volcanic Arc, whereas the systematic geothermal research has identified numerous low and medium enthalpy fields around the country.

The exploitation of geothermal energy has proved to bring significant economic and environmental benefits. The heating of buildings, agricultural and spa facilities, pools, etc., could be achieved with low cost by utilizing low enthalpy (25-90°C) geothermal fluids. In addition, the use of the ground-source heat pumps (GSHP) facilitates the exploitation of lower temperature fluids (< 25°C) from shallow reservoirs in many of the above applications.

The basin of Katerini constitutes basically a rural region, with 38% of the total area being agricultural land. On the other hand, the coastal places are a well-known tourist destination, so, the most important economic activities are related to the agricultural and tourism sectors. For that reason, the investigation of the geothermal conditions in the area could signify several possibilities for effectively exploiting the available geothermal energy in relative applications, which, in turn, could considerably support the local economy and result in positive socioeconomic impacts.

2. General characteristics of the study area

The basin of Katerini belongs to the Pieria Prefecture and forms the southern part of the broader Thessaloniki basin (Central Macedonia, Northern Greece). It is bounded to the north by Aliakmon River, southwards by the alluvial fans of Mt. Olympus, to the east by Thermaikos Gulf and to the west by Pieria Mt. (Fig. 1).

Based on the topography, three elevation zones can be distinguished: (i) the mountainous (>500m), (ii) the hilly (100-500m), and (iii) the coastal plain (0-100m) areas. The plain terrains cover almost 40% of the basin, while the coastline is more than 70km long. The geothermal investigation focused on the hilly and coastal zones. The hydrographic network is well developed with numerous branches. Its structure is controlled by the local geologic conditions and is indicative of the tectonic activity in the area.

The climate in the broader area of Katerini basin is mild with cold winter and dry hot summer (Kottek *et al.*, 2006). The climatic conditions are more temperate near the coast, but severe winters are common in the western (mountainous) parts of the basin. The mean annual air temperature at the basin is 15.5°C in the plain areas and changes by 0.61°C/100m (Tzimourtas, 2001).

3. Geological and Tectonic setting

The basement of the study area is formed by the metamorphic rocks of Almopia sub-zone, which is mainly characterized by the presence of Upper Jurassic ophiolitic formations as well as by deep-sea sedimentary and volcano-sedimentary series (Mountrakis, 1985). Pelagonian metamorphic formations (schists, gneisses, and marbles with overthrusting ophiolitic complexes) are found at the western margin of the basin.

The investigated area is covered by Neogene and Quaternary deposits of 1000-1500m thickness that progressively filled up the basin. The Neogene formations consist of alluvial, fluvial, lacustrine and fluvio-lacustrine sediments, such as conglomerates, lignites, clay, marls, sand and limestones, that occupy the central hilly part of the basin. According to Sylvestrou (2002), the Neogene sediments can be classified in eight (8) formations, based on lithologic data and paleontological evidence: (1) Elatochori Fm, (2) Moschopotamos Fm, (3) Sykea Fm, (4) Ryakia Fm, (5) Lagorachi Fm, (6) Sfindami Fm, (7) Makrygialos Fm, and (8) Lofos Fm (Fig.1). The Formations of Sykea, Ryakia, Lagorachi and Sfindami occupy the largest part of the basin, whereas Elatochori and Moschopotamos Formations outcrop only its south-western border. The most recent Formations (Makrygialos and Lofos) are found at the northern and southern part of the basin, respectively. The detailed Neogene lithology has been described by Sylvestrou (2002).

The Quaternary sediments cover the plain part of the basin and mostly consist of sand and clay with coarse material (gravels and pebbles). They have been deposited in unconformity over the Neogene sediments and their thickness ranges from 15 to 60m (Benda and Stevens, 1981; Sylvestrou, 2002).

The basin is generally characterized by recent and intense tectonic activity. Small NW-SE ‘**en echelon**’ faults have been found at the WSW boundaries, while normal NE-SW dislocation faults have affected the area southwards of Moschopotamos. At the north part of the basin (Kolindros area) the main faults follow the NE-SW to ENE-WSW, NW-SE and E-W directions.

The significant change in the flow direction of the main streams in the central part of the basin is most probably attributable to the activity of an important ENE-WSW fault, as well as to the existence of minor NW-SE conjugate faults. Near the coastal area of Makrygialos (eastern part of the basin), the NE-SW and NNW-SSE faults have dislocated the layers of Makrygialos Fm up to 10m (Sylvestrou, 2002), indicating their post-Pliocene activity. In the same area, a strike-slip fault has been identified by Faugeres (1975), while Sylvestrou (2002) detected two major NE-SW and NW-SE faults, which have affected all recent deposits. In the area of Methoni, a NE-SW normal fault, that was active during Lower Holocene (Faugeres, 1975), affected the Quaternary sediments.

4. Geothermal Investigation

The preliminary-reconnaissance geothermal investigation in the basin of Katerini mainly regarded temperature measurements at the wellhead of 73 water wells during pumping (Fig.2). The geothermal gradient was calculated by temperature measurements in the interior of five (5) boreholes and from available temperature data from past measurements in three (3) water wells. Water sampling and chemical analyses from 18 selected sites was also conducted.

The most important aquifers in the basin are found inside layers with coarse material, e.g. conglomerates and gravels, whereas the discharge from fine-grained sandy aquifers is significantly lower. The flow-rate from the wells in the central part of the basin (Alykes Kitrous-Korinos-Katerini-Kallithea) ranges from 20 to 150m³/h, depending on the aquifer characteristics. The depth of the wells in the hilly zone is 30-416m. In this area, the aquifers are located inside layers of sand or pebbles and in limestones, with generally lower water discharge (20-100 m³/h).

4.1. Wellhead temperatures

The exact location of the measured wells and the corresponding isothermal curves are illustrated in the maps of Fig. 2 and Fig. 3, respectively. Based on the distribution of wellhead temperatures and the shape of the contours, three (3) sub-regions of geothermal interest can be defined: (a) *Kato Agios Ioannis*, (b) *Sevasti*, and (c) the area between *Kitros-Alykes Kirtou-Makrygialos*.

The maximum recorded temperature in the area of *Kato Agios Ioannis* was 24.8°C (Table 1) in the ΛΘ-23 well, which is located 300m northwards of the settlement. The isothermal curves generally trend NNW-SSE (Fig.), however, the thermal anomaly probably extends to the ENE of the village, as it is indicated by the temperatures of ΛΘ-27 and ΛΘ-29 wells. This is probably related to the existence of a W-E fault, which crosses through the village and continues to the east (Mettos *et al.*, 1986).

The geothermal anomaly near *Sevasti* village extends to the NNE, SE, S and SW of the settlement, as well as in the area between *Sevasti* and *Nea Trapezounta*. The wellhead temperatures vary from 18.0 to 20.7°C (Table 1).

The temperatures in the region *Kitros-Alykes Kitrous-Makrygialos* do not exceed 18.3°C (Table 1). However, according to past measurements in the interior of the well AA-1 (located very close to ΛΘ-63), the temperature at the depth of 108m was 19.6°C (3.79°C/100m). The distribution of temperatures in this region is determined by the local tectonic regime, as it is suggested by the shape and trending of the 18°C contour, which follows the direction of two parallel NW-SE faults between Kitros and Thermaikos coast (Mettos *et al.*, 1986).

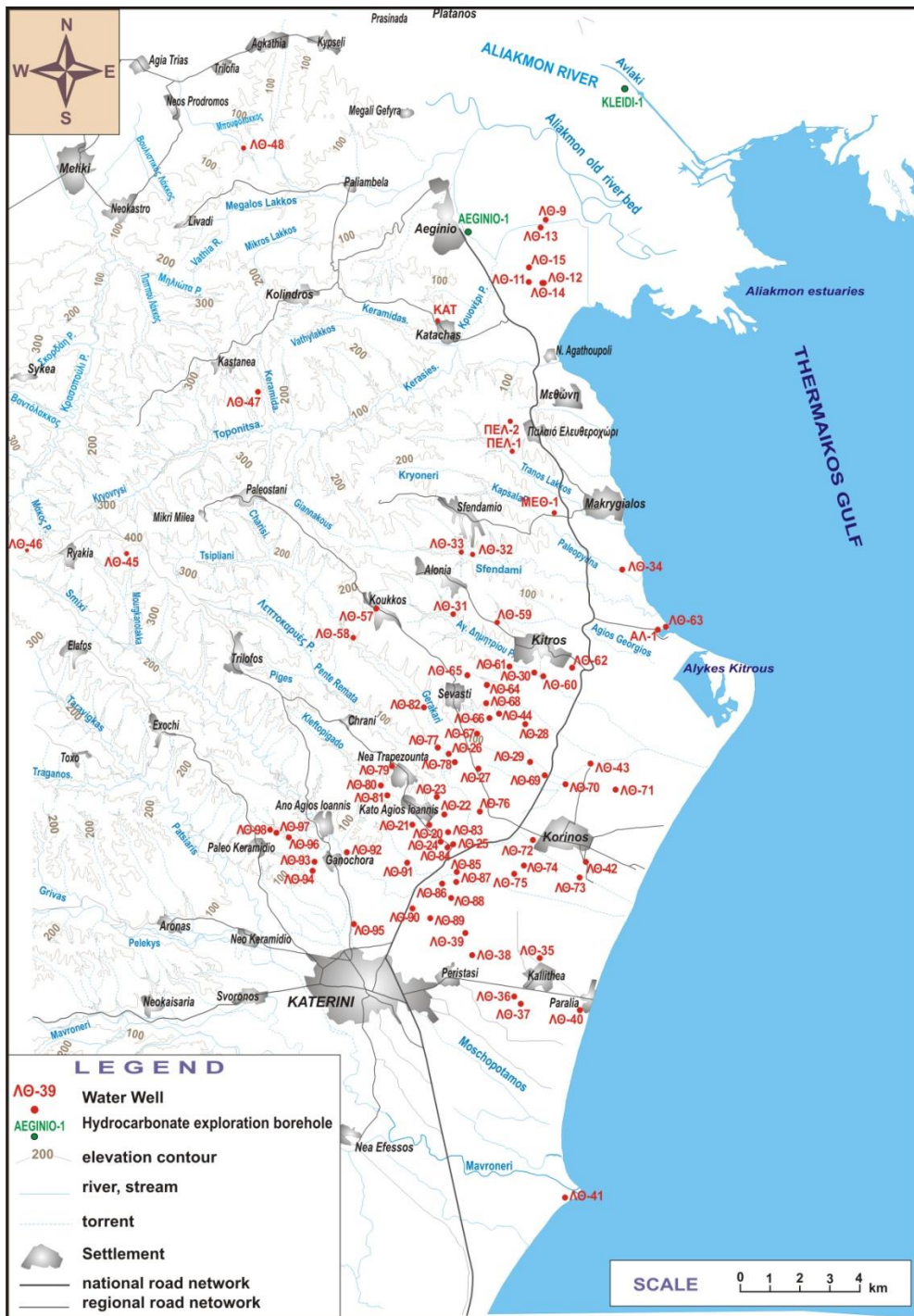


Figure 2 - Topographic map indicating the measured water wells (source: Kolios *et al.*, 2005).

Table 1 - Wellhead temperatures in the 3 regions of geothermal interest (well depth >150m).

Well	Depth (m)	Wellhead Temperature (°C)	Well	Depth (m)	Wellhead Temperature (°C)
Kato Agios Ioannis			Sevasti		
ΛΘ-20	248	23.5	ΛΘ-28	170	19.2
ΛΘ-21	180	21.8	ΛΘ-26	138	18.0
ΛΘ-22	245	21.0	ΛΘ-64	150	18.3
ΛΘ-23	416	24.8	ΛΘ-65	260	20.7
ΛΘ-24	238	23.2	ΛΘ-66	198	20.7
ΛΘ-27	150	21.1	ΛΘ-67	190	19.7
ΛΘ-29	300	21.3	ΛΘ-68	210	18.4
ΛΘ-39	314	22.0	ΛΘ-77	197	19.7
ΛΘ-81	187	20.7	ΛΘ-78	260	20.4
ΛΘ-84	238	23.5			
Kitros- Alykes Kitrous-Makrygialos					
ΛΘ-34	120	18.2	ΛΘ-63	167	18.3
ΛΘ-62	200	18.0			

4.2. Geothermal gradients

The geothermal gradients in the study area have been calculated by temperature measurements inside five (5) boreholes (Fig. 4) and from available literature data. According to the recordings from the meteorological station of Katerini for the period (1951-1996) (Tzimourtas, 2001), the mean annual air temperature that has been taken into account for the gradient calculation, is 15°C for the plain areas and 14.1-15.0°C for the hilly zone.

The wells ΛΘ-12 and ΛΘ-15 are located at the northern borders of the basin, south-eastern wards of Aeginio town. The temperature recorded at the bottom (129m) of the artesian well ΛΘ-15 is 18.8°C and the resulting geothermal gradient is 2.56°C/100m. The temperatures up to the depth of 10m in the well ΛΘ-12 are very low, reflecting the influence of cold superficial aquifers. For that reason, the geothermal gradient was calculated for the depth interval 20-75m and is 3.09°C/100, i.e. similar to the mean value.

The bottomhole (2475m) temperature in the hydrocarbon exploration borehole AEGINIO-1 is 79.5°C (S.P.E.G., 1982b) and the average geothermal gradient is 2.58°C/100m; it should, however, be mentioned that the gradient for the interval 0-1814m is much lower, i.e. 1.74°C/100m. The temperature recorded at the depth of 385m in the well KAT (southern wards of Aeginio town) is 23.6°C, indicating a geothermal gradient of 2.1°C/100m.

The well ΛΘ-48 is located at the northern part of the hilly zone. The temperature at the depth of 285m is 18.7°C. Temperature inversion is observed up to the depth of 50m, attributable to lateral intrusion of cold water. The geothermal gradient that corresponds to the interval 50-285m is 1.7°C/100m.

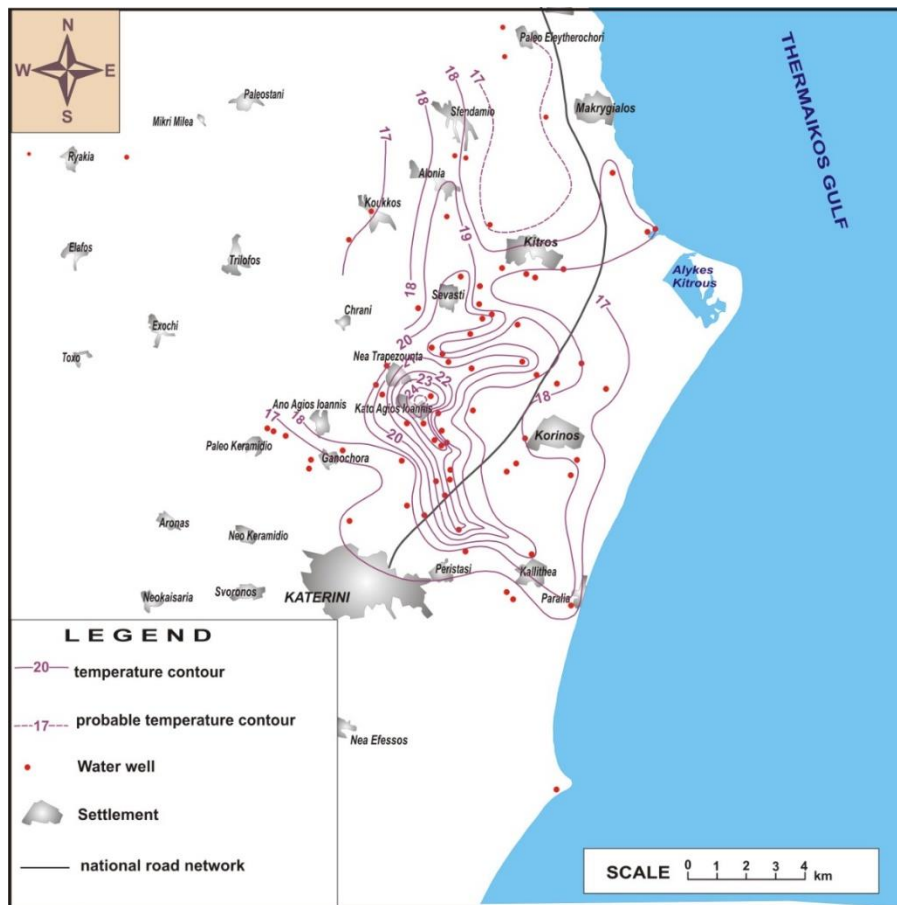


Figure 3 - Temperature contours based on wellhead temperatures (well depth >150m).

The well $\Lambda\Theta$ -47 is located about 6km southern wards of $\Lambda\Theta$ -48, at elevation 233m. According to the temperature logs (Kolios *et al.*, 2005), 24.0°C have been recorded at the depth of 380m. The temperature inversion that is observed at the depth interval 60-85m is attributed to the lateral inflow of cold water from the screen casing between 72-78m. The slope of the temperature curve changes after the depth of 230m, indicating different rates of increasing temperature with respect to depth, i.e. 0.92°C/100m (100-230m) and 3.0°C/100m (230-280m), with the latter being considered as the characteristic gradient for the specific well.

The calculation of geothermal gradient in the area of *Sevasti* is based on the temperatures in the $\Lambda\Theta$ -44 well. The maximum recorded value was 24.7°C at the depth of 270m. According to the temperature profile, three individual curve parts are observed, which correspond to the depths 50-150m, 150-250m and 250-270m. The rate of temperature increase with depth is 0.5°C/100m, 7.1°C/100m and 2°C/100m, respectively. The average gradient for the total depth is 3.6°C/100m.

In the area near the village *Kato Agios Ioannis*, a rough estimate of the geothermal gradient is based upon past measurements in the well $\Lambda\Theta$ -23, according to which, the temperatures at the depth of 340m was 26.7°C. Taking into account the mean annual air temperature at 15.5°C, the geothermal gradient is calculated at 3.3°C/100m. Similarly, for the area *Kitros-Alykes Kitrous*, the temperature at the depth of 108m in the well AA-1, indicates a geothermal gradient of 3.8°C/100m.

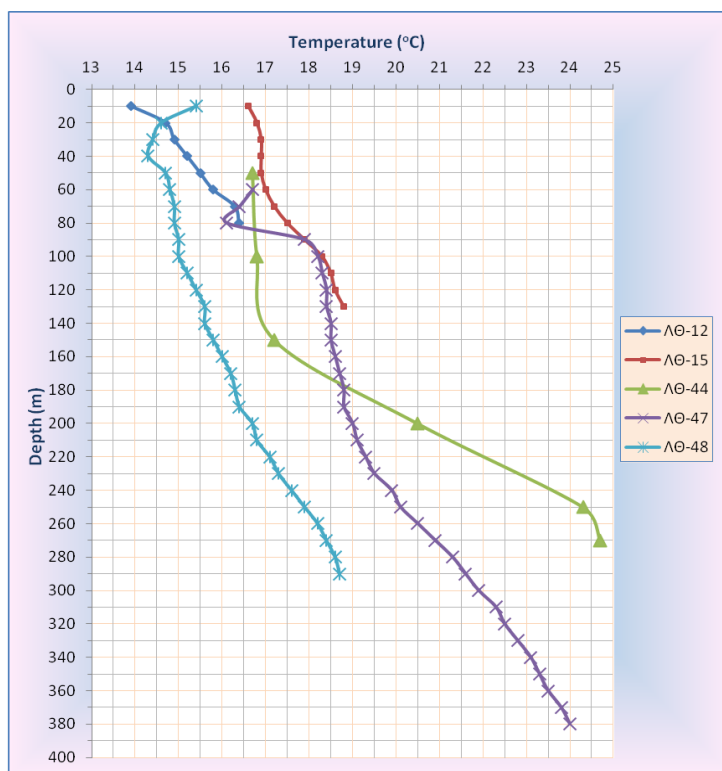


Figure 4 - Temperature profiles from wells in Katerini Basin.

5. Geochemical investigation

In the area eastwards of Aeginio (Figure 2), waters at temperatures of 18.0-20.5°C are classified as Mg, Ca-HCO₃, Na-HCO₃ and Na-HCO₃Cl types (Figure 5A). They have TDS contents of 0.84-1.81 g/l and show pH values of 7.59-7.94 (alkaline waters). The water sample ΛΘ-14 is of the Na-HCO₃Cl type and is characterized by higher TDS level (1.81 g/l). It is rich in Na⁺ (600 mg/l) and Cl⁻ (583.6 mg/l), which indicates the influence of sea water. The neighbouring wells ΛΘ-11 and ΛΘ-15 yield waters of Na-HCO₃ and Mg, Ca-HCO₃ types respectively, with lower salinities.

The water samples southwards of Aeginio are classified as Ca, Mg, Na-HCO₃, Na, Mg-HCO₃, Ca-HCO₃ and Ca-HCO₃ types (Figure 5B). The analyses of the samples from the wells that are located in the lowland and hilly areas of the basin (ΛΘ-20, ΛΘ-21, ΛΘ-22, ΛΘ-24, ΛΘ-25, ΛΘ-26, ΛΘ-30, ΛΘ-31, ΛΘ-32, ΛΘ-33 and ΛΘ-34), indicated groundwater of the Ca, Mg, Na-HCO₃ type. The wellhead temperatures vary from 16.5 to 23.5°C. The TDS is in the range of 0.47-0.73 g/l and the pH of 7.29-7.96 (alkaline waters). Ca²⁺, Mg²⁺ and Na⁺ contribute by 21.8-51.4%, 29.1-47.4% and 18.4-42%, respectively, to the total cationic charges (in meq/l). Their concentrations have been determined to be 45.7-96.2 mg/l Ca²⁺, 29.1-47.4 mg/l Mg²⁺ and 53-108 mg/l Na⁺. The dominant anion is HCO₃⁻ (370.9-539.2 mg/l) constituting 62.9-77.5% of the total anionic charges. The SiO₂ contents range from 14.2 to 30.8 mg/l.

The water samples from ΛΘ-23(ΑΓ-1), ΛΘ-27, ΠΕΛ-1 and ΑΛ-1 belong to the Na, Mg-HCO₃ type. Their temperatures range from 19.6-24.8°C. They have low TDS (0.42-0.54 g/l) and alkaline character (pH=7.45-7.88). Na⁺ and Mg²⁺ contribute to the total cationic charges (in meq/l) by 33.5-58.5% and 23.3-48.8%, respectively. The corresponding Na⁺ and Mg²⁺ concentrations are 70-110 mg/l and 22.4-54 mg/l. The dominant anion is HCO₃⁻ (341.6-386.7 mg/l), contributing by 64.7-81.6% to the total anionic charges. The samples ΛΘ-23(ΑΓ-1) and ΛΘ-27 are plotted on the

boundary line between Na, Mg-HCO₃ and Ca, Mg, Na-HCO₃ types. The well AA-1 yields water of Na, Mg-HCO₃ type, despite its vicinity with the sea.

In the western part of the basin, close to the village of Ryakia, the wells ΛΘ-45 and ΛΘ-46 yield waters of Na-HCO₃ and Ca-HCO₃ types, respectively (Figure 5B). The temperature of the ΛΘ-45 well is 18.1°C. The water is slightly alkaline pH (7.6) with TDS at 0.39 g/l. The water from the ΛΘ-46 well has low temperature (14.8°C), low TDS (0.39 g/l) and neutral pH (6.96). The dominant cation is Ca²⁺ (124.9 mg/l, 82.2% of the total cationic charge). This sample can be considered as the most representative cold water in the basin that comes from a shallow aquifer.

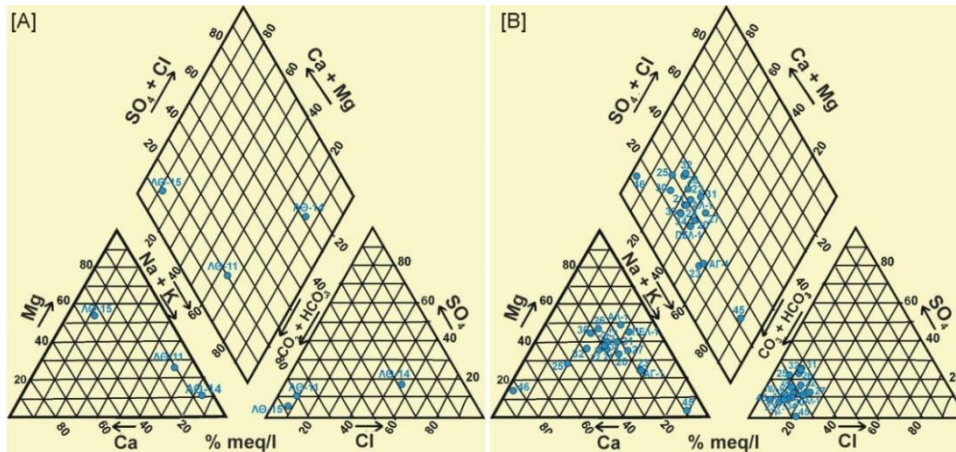


Figure 5 - Piper (1944) trilinear diagram of groundwaters from (A) the Aeginio - Nea Agathoupoli area and (B) southwards of Aeginio.

The composition of groundwater is defined by geochemical processes and factors, such as the dissolution of carbonate, silicate and clay minerals, feldspars and mica. The cold waters of the wider area are enriched in Ca²⁺ and Mg²⁺, due to their circulation in shallow aquifers composed of sandstones, sands and pebbles. The increased Ca²⁺ and Mg²⁺ concentrations in shallow and cold waters can be attributed to the dissolution of carbonate minerals, which constitute the cement of the clastic sediments. Fluctuation of Ca²⁺ concentrations in the groundwater is either attributable to different residence time within the sediments or to the lithological differentiation of the formations through which the groundwater has circulated. The Na⁺ cations are derived from the dissolution of the plagioclase feldspars and clay minerals. Waters coming from deeper aquifers (sands and pebbles), which are interbedded among clayey sediments, show higher Na⁺ contents. Hence, the water samples from the wells located in the lowland and hilly areas of the Katerini basin belong to the Ca, Mg, Na-HCO₃ and Na, Mg-HCO₃ types. The increased concentrations of Na⁺ and HCO₃⁻ can be attributed to the combined effect of calcite/dolomite dissolution and the Ca-Na ion-exchange controlled by the presence of clay minerals. These geochemical processes result in the formation of Na-enriched waters. The correlation diagrams show that the concentrations of various chemical species (Na⁺, K⁺, SiO₂, Cl⁻, Ca²⁺, HCO₃⁻, CO₃²⁻, NH₄⁺, SO₄²⁻, Mg²⁺, B, F και Br) is not associated to the water temperature.

6. Discussion-Conclusions

The results of the reconnaissance geothermal investigation in the basin of Katerini suggest three individual sub-regions of geothermal interest, which, in order of priority, are: (i) the area of *Kato Agios Ioannis*, (ii) the area of *Sevasti*, and (iii) the area between *Kitros-Alykes Kitrous* and *Makygialos*.

The maximum temperatures were recorded near the village of *Kato Agios Ioannis*, where 26.7°C were recorded at the depth of 340m. The geothermal gradient of 3.29°C/100m in this area is slightly higher than the mean earth value. The temperature contours generally trend NNW-SSE, but, evidently, the thermal anomaly is extending to the east, probably due to the existence of a W-E fault.

The calculated geothermal gradient near *Sevasti* is 3.67°C/100, based upon measurements in only one well. Nevertheless, the wellhead temperatures, which vary from 19.2-20.7°C, are lower than in the region of Kato Agios Ioannis, where they reach 24.8°C.

The area between *Sevasti* and *Nea Trapezounta* seems less promising, with the wellhead temperatures not exceeding 20.4°C. The wellhead temperatures in the area *Kitros-Alykes Kitrous-Makrygialos* are 18-18.2°C; however the temperature of 19.6°C at the depth of 108m, which was measured in one well, indicates a geothermal gradient (3.8°C/100m) above the mean earth value.

The chemical analyses showed that the groundwater of *Katerini* basin is classified as Ca, Mg, Na-HCO₃ and Na, Mg-HCO₃ water. No correlation between ions and temperature could be established, which means that the chemical character of the groundwater in this area mostly depends on the local lithology and mineral composition.

The geological structure and the stratigraphy of the basin specify the thickness of the Neogene sediments to more than 1000m, which benefits the drilling of deep exploration boreholes. Given the estimated geothermal gradients, significant temperatures could be encountered before entering the bedrock formations.

The available data suggest that the systematic geothermal and drilling exploration should initially focus on the area of *Kato Agios Ioannis*. On the other hand, the exploitation of the shallow and high yield aquifers from existing water wells (by using geothermal heat pumps), which could be immediately realised, constitutes an efficient and cost effective solution for the heating and/or cooling of a building, pool, greenhouse, etc.

7. Acknowledgements

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8. References

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