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GEOTHERMAL EXPLORATION IN THE ALEXANDRIA AREA, THESSALONIKI BASIN (MACEDONIA, NORTHERN GREECE)

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Abstract

The area of Alexandria is located in the Thessaloniki basin that has been filled with more than 4 km of sediments. In 1980, oil exploration borehole AL-1, 1,705 m deep, was drilled north of the town of Alexandria and the temperatures of 39 and 65°C were recorded at depths of 700 and 1,705 m respectively. During 1996-2000, two geothermal exploration boreholes were drilled at depths of 532 and 620 m penetrating Quaternary and Pliocene sediments and the temperatures of 30.1 and 33.4°C were measured at 500 and 611 m respectively. The preliminary geothermal investigation resulted in the construction of the first production well (GN-1P). It was drilled to a depth of 805 m penetrating clays, sands, tuffs, marls, clayey marls, marly limestones, gravels, sandstones and conglomerates. The borehole was cased down to 805 m and screens were placed at various depths below 607 m. Temperature and electrical conductivity values of 35.1-37.2°C and 5,100-8,200 μS/cm respectively were recorded at depths of 607-800 m. This well discharges 30-40 m^3/h waters at 34.1°C with artesian flow and provides 130 m^3/h waters at 35.5°C with pumping. The produced geothermal water with TDS of 2.18 g/l belongs to the Na-Cl type differentiated from the shallow waters. The thermal capacity of well GN-1P is calculated to be 1.65 MWt.
Keywords: *sedimentary basin, hydrothermal system, production well.*

Περίληψη

Η περιοχή της Αλεξάνδρειας βρίσκεται στη Λεκάνη Θεσσαλονίκης, η οποία έχει πληρωθεί με ιζήματα πάχους άνω των 4 km. Το 1980, κατασκευάσθηκε βόρεια της πόλης της Αλεξάνδρειας η γεώτρηση έρευνας υδρογονανθράκων AL-1, βάθους 1705 m, στην οποία καταγράφηκαν οι θερμοκρασίες των 39 και 65°C σε βάθη 700 και 1705 m αντίστοιχα. Μεταξύ 1996 και 2000, ανορύχθηκαν δύο γεωθερμικές ερευνητικές γεωτρήσεις, βάθους 532 και 620 m, οι οποίες διέτρησαν Τεταρτογενή και Πλειοκαινικά ιζήματα και στις οποίες μετρήθηκαν θερμοκρασίες 30.1 και 33.4°C σε βάθη 500 και 611 m αντίστοιχα. Η προκαταρκτική γεωθερμική έρευνα οδήγησε την κατασκευή της πρώτης παραγωγικής γεώτρησης (ΓΝ-1Π). Ανορύχθηκε μέχρι βάθος 805 m διατρύοντας αργίλους, άμμους, τόφφους, μάργες, αργιλο-μάργες, μαργαϊκούς ασβεστόλιθους, χάλικες, ψαμμίτες και κροκαλοπαγή. Η γεώτρηση σωληνώθηκε μέχρι τα 805 m και φίλτρα τοποθετήθηκαν σε διάφορα βάθη κάτω από τα 607 m. Τιμές

θερμοκρασίας και ηλεκτρικής αγωγιμότητας 35.1-37.2°C και 5100-8200 μS/cm αντίστοιχα καταγράφηκαν σε βάθη 607-800 m. Η γεώτρηση παρουσιάζει αρτεσιανή ροή με 30-40 m^3/h νερών των 34.1°C και παρέχει με άντληση 130 m^3/h νερών θερμοκρασίας 35.5°C. Το παραγόμενο γεωθερμικό νερό με ΣΔΑ 2.18 g/l είναι του τύπου Na-Cl και διαφοροποιείται από τα ρηχά νερά. Η θερμική ισχύς της γεώτρησης ΓΝ-1Π υπολογίζεται σε 1.65 MWt.
Λέξεις κλειδιά: *ιζηματογενής λεκάνη, υδροθερμικό σύστημα, παραγωγική γεώτρηση.*

1. Introduction

The onshore Thessaloniki basin, covering an area of about 4,200 km^2 in Central Macedonia (Northern Greece), constitutes a large post-orogenic NNW-SSE graben. It has been created by faulting since Eocene and filled with Paleogene, Neogene and Quaternary sediments reaching a total thickness of more than 4 km. During 1961-1980, eleven (11) oil exploration boreholes were drilled to depths of 666.4-4,085 m. Borehole temperature measurements have shown that the mean geothermal gradient is around the normal value. In addition, borehole data provide useful information about the structure and lithostratigraphy of the basin. Fluctuations in the thickness of the sedimentary sequence have proven the existence of local tectonic structures. Important properties of these sedimentary rocks, like porosity and permeability, have also been determined at various depths.

The Alexandria area constitutes part of the Thessaloniki basin located north of the homonymous town. Evaluating the data from oil borehole ALEXANDRIA-1 (AL-1), 1,705 m deep, detailed geothermal exploration was carried out by the Institute of Geology and Mineral Exploration (I.G.M.E.) north of the town of Alexandria in two time periods (1996-2000 and 2003). These exploration projects were supported financially by the 2nd and 3rd Community Support Framework. Two geothermal exploration boreholes were drilled during 1996-2000 and one production well was constructed in 2003. This paper presents the results of the geothermal exploration in the Alexandria area.

2. Geological and Tectonic Setting

Geotectonically, the post-orogenic basin of Thessaloniki belongs to the Axios Zone and is located between the Circum Rhodope Belt to the east and the Pelagonian Zone to the west (Figure 1A). It was formed during the extensional phase of Eocene. Based on drilling data and geophysical surveys, the basement of the basin is made up of schists, ultrabasic rocks, ophiolites and marbles. Flysch formations of Maastrichtian - Priabonian age have been observed (Lalechos, 1986). Paleogene, Neogene and Quaternary sediments have been filled the basin and their total thickness exceeds 4 km. The Eocene - Oligocene formations, 0-1,644 m thick, are composed of reef limestones, marls, sandstones, conglomerates, microconglomerates, clays, siltstones and breccias. The Miocene sediments consist of conglomerates, sandstones, clays, sands, microconglomerates, marls, limestones and siltstones and their thickness ranges between 0 and 1,466 m (data from oil exploration boreholes). The Plio-Quaternary sediments reach thickness of approximately 1,000 m and consist of volcanic tuffs and stones and trachyandesitic material, clays, marls, sands, gravels, conglomerates, micro-conglomerates, sandstones and organic/lacustrine/marly/clastic limestones. Quaternary sediments also include alluvial deposits, scree, travertines and conglomerates. The distinction between the Plio-Pleistocene and Miocene sediments is very difficult due to their similar lithological and sedimentological characteristics, while the Eocene-Oligocene and Oligocene-Miocene (unconformity) boundaries are clearer (Lalechos, 1986; Alexiadis, 1988).

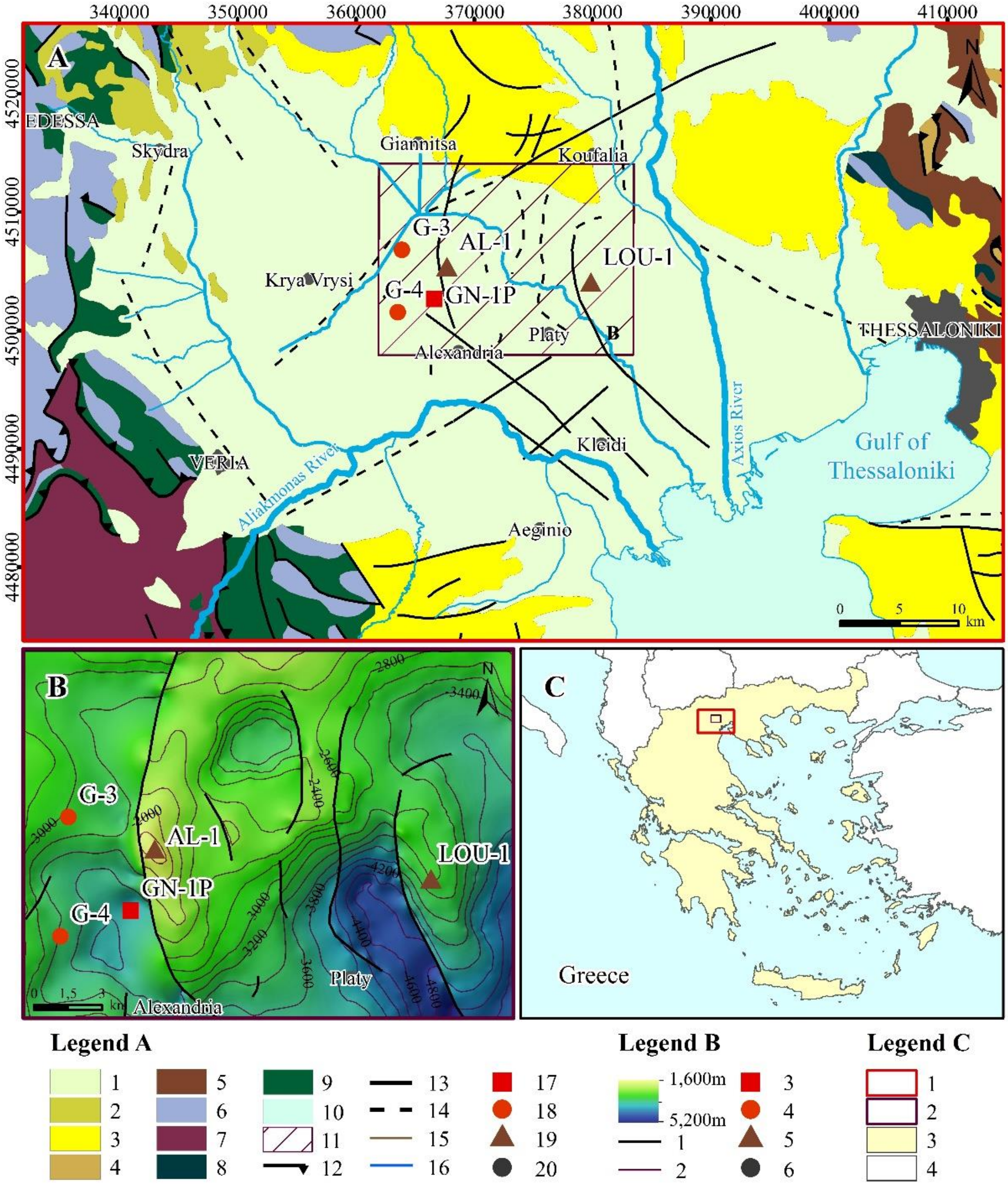

Figure 1 - (A) Simplified Geological map of the Thessaloniki basin, based on Geological Map of Greece at scale of 1:500,000 (IGME, 1983), Lalechos (1986) and seismic data, showing the sites of oil and geothermal wells in the Alexandria area (1: Quaternary deposits, 2: Volcaniclastics and tuffs, 3: Neogene sediments, 4: Serbomacedonian Massif, 5: Circum Rhodope Belt, 6: Axios Zone, 7: Pelagonian Zone, 8: Basic and ultra basic rocks, 9: Ophiolites, 10: Sea, 11: Study area B-Alexandria area, 12: Thrust, 13: Visible Fault, 14: Probable or invisible fault, 15: Geological boundary, 16: River, 17: Geothermal production well, 18: Geothermal exploration borehole, 19: Oil exploration borehole, 20: Town/Village). (B) The 3D model of the Alexandria structure based on seismic data (1: Fault, 2: Isobaths, 3: Geothermal production well, 4: Geothermal exploration borehole, 5: Oil exploration borehole, 6: Town/Village). (C) Reference map (1: Study area A -Thessaloniki basin, 2: Study area B -Alexandria area, 3: Greece, 4: Other countries).

The present structure of the basin has resulted from many tectonic movements due to various compressional and extensional phases since Upper Jurassic - Lower Cretaceous. The Lower Eocene extensional phase led to the formation of the graben by large faults. The tectonic evolution of the area continued until Quaternary. Based on the results of seismic surveys, some major NW-SE and NW-SW faults and the tectonic structures (anticlines-horsts) of Alexandria and Loudias have been identified (BEICIP, 1980; Lalechos, 1986; Alexiadis, 1988). The Alexandria structure is located north of the homonymous town (Figure 1B). Based on seismic interpretation (BEICIP, 1980), this structure is an anticline with a NNW-SSE axis and its western side is bounded by a NNW-SSE reverse fault which acted until the beginning of the Miocene sedimentation (Alexiadis, 1988).

3. Exploration Boreholes Drilled in the Alexandria Area

3.1. Geothermal Evaluation of Oil Exploration Borehole ALEXANDRIA-1

In 1980, oil exploration borehole ALEXANDRIA-1 (AL-1) was drilled on the identified tectonic structure, at a distance of 6.5 km north of the town of Alexandria (Figure 1A, B). The coordinates of the drilling site are: 40º41΄29΄΄N and 22º26΄09΄΄E (Coordinates X=367687.3 and Y=4505389.8 in *CGS*-GGRS-1987/Greek Grid). The borehole has a total depth of 1,705 m. The metamorphic basement made up of ophiolites (peridotites, gabbros, diabasis) has been located at 1,600 m depth. An overlying sedimentary sequence composed of Eocene-Oligocene formations, Miocene sediments and Plio-Quaternary deposits has been penetrated. The Plio-Quaternary deposits (0-607 m depth) consist of grey-brown soft clays, fine- to coarse-grained sands, gravels and microconglomerates. The Miocene sediments have a thickness of 311 m (607-918 m depth) and include alternations of grey or grey-green soft clays with unconsolidated fine- to coarse-grained sands and sandstones. Layers of microconglomerates also occur. The Oligocene-Eocene formations with a total thickness of 682 m (918-1,600 m depth) consist of clays, siltstones, sandstones, microconglomerates and basal consolidated breccias/conglomerates. A light grey green clayey zone occurs from 918 to 960 m depth. An unconformity at depth of 1,305 m can be considered as the Eocene-Oligocene boundary (Alexiadis, 1988; S.P.E.G., 1982).

In borehole AL-1, the temperatures of 39 and 65ºC were measured at depths of 700 and 1,705 m respectively. Strata with porosity of 17-26% and very good permeability have been identified between 300 and 1,000 m depth. Aquifers are located in sands, sandstones, conglomerates and microconglomerates. Small amount of CH_4 were detected below 800 m depth. Strata of geothermal interest have been identified within the first 1,000 m depth at the following depth intervals 300-670, 675-685, 695-705, 757-776 and 776-960 m. These strata contain aquifers composed of sandstones and microconglomerates with porosity of 17-26% and very good permeability. The temperatures of 33, 38, 39, 41 and 44ºC have been recorded at depth intervals of 300-670, 675-685, 695-705, 757-776 and 776-960 m respectively (P.P.C., 1988).

3.2. Geothermal Exploration Boreholes

During 1996-2000, two geothermal exploration boreholes (G-3 and G-4) were drilled north of Alexandria (Figure 1A, B). Exploration borehole G-3 (Coordinates X=363895 and Y=4506808 in *CGS*-GGRS-1987/Greek Grid) reached a total depth of 532 m. Quaternary deposits consisting of sands, cobbles, clays, fluviotorrential and volcaniclastic materials and lacustrine limestones were penetrated down to 210 m. Below 210 m depth, Pliocene sediments composed of lacustrine limestones, sandstones, conglomerates, volcaniclastic material and alternations of sands, sandstones, biogenic calcareous clays, calcitic sandstones and conglomerates were encountered. The hole was cased down to 531.5 m (5΄΄ and 2΄΄ diameter casing strings were set at depths of 0-220 and 220-531.5 m respectively). The temperature of 30.1ºC has been measured at 500 m depth (Atzemoglou *et al.*, 2000; Kolios *et al.*, 2005).

Exploration borehole G-4 (Coordinates X=363543 and Y=4501554 in *CGS*-GGRS-1987/Greek Grid) was drilled to a total depth of 620 m. Quaternary and Pliocene sediments were penetrated at depths of 0-225 and 225-620 m respectively. The Quaternary deposits include alternating clays and sands, water-bearing conglomerates and unconsolidated coarse-grained conglomerates. The Pliocene sediments consist of altered argillizated pyroclastic materials, argillizated volcano-sedimentary materials with intercalated layers of calcarenites, sandy volcaniclastic calcarenitic materials and sandy clays with fragments of altered volcanics. Casing strings having 5´´ and 2´´ diameters were set at depths of 0-225 and 225-611 m respectively. The temperature of 33.4ºC has been measured at 611 m depth (Atzemoglou *et al.*, 2000; Kolios *et al.*, 2005).

4. Geothermal Production Well GN-1P

Taking into account the water temperatures (20.2-23.4ºC) measured at 90-160 m deep irrigation and water supply wells and based on the results of the above-mentioned exploration boreholes, the first geothermal production well (GN-1P) was drilled 4 km NNW of Alexandria during April-August 2003 (Figure 1A, B). The coordinates of the drilling site are X=366638 and Y=4502672 (in *CGS*-GGRS-1987/Greek Grid).

This production well was drilled down to a total depth of 805 m penetrating Plio-Quaternary and Miocene sediments. The Plio-Quaternary sediments reach 587 m depth and their detailed stratigraphy is as follows (Kolios *et al.*, 2005): topsoil (0-2 m depth), grey-green clays and fine-grained sands (2-30 m), grey-green clays and small volcanic gravels (30-110 m), tuffs and clayey-marly materials (110-210 m), marly limestones (locally silicified) and yellow marls (210-255 m), grey-green plastic fossiliferous clays (255-260 m), grey-green clays containing gravels (260-270 m), clayey marls containing calcareous gravels (270-290 m), yellow clays and gravels (290-302 m), coarse-grained quartzite sands (302-314 m), grey-green clays with intercalated sands and gravels (314-415 m), unconsolidated sands and gravels (415-423 m), brown clays (423-431 m) and finally alternating thin layers of sandstones, unconsolidated sands, biogenic marly calcarenites and conglomerates (431-587 m). Between 587 and 805 m depth, Miocene clastic sediments occur consisting of alternating layers of clays, clayey marls, sands and gravels (microconglomerates). The most coarse-grained sediments of this clastic series, i.e. sands and microconglomerates, have a rather high permeability.

Drilling was carried out using drill bits of different diameter at different depth intervals, i.e. 20, 17½ and 11´´ drill bits were used at depths of 0-31, 31-430 and 430-805 m respectively. The hole was cased down to 805 m depth. Different sizes of casing strings were set. An 18´´ diameter surface casing was installed down to a depth of 31 m to prevent surface water intrusion. Casing strings with diameters of 12´´ and $6^5/_8$´´ were set at depths of 0-430 and 361-805 m respectively. Screens having a total length of 120 m were placed at various depths below 607 m (607-619, 631-637, 643-649, 655-667, 673-679, 685-691, 697-709, 715-727, 739-769 and 775-793 m). Water-bearing zones in the 0-430 m depth interval were isolated using cement (0-50 and 200-430 m) and aggregates and clayey materials (50-200 m). Well GN-1P has an artesian flow yielding 30-40 m^3/h geothermal waters at 34.1ºC. The occurrence of gas bubbles is observed in the flowing water.

Gamma ray, resistivity and SP (Spontaneous Potential) loggings were performed in well GN-1P down to a depth of 445 m. Gamma-ray log showed higher values (up to 150 CPS) in the 70-210 m depth interval due to the presence of grey-green clays with small volcanic gravels, tuffs and clayey-marly materials. Below 220 m depth, gamma-ray values fluctuate between 10 and 60 CPS corresponding to continuous alternations of clays, sands and gravels. SP log showed values fluctuating between 820 and 1,140 mV in the 190-445 m depth interval due to alternating permeable and impermeable layers. Temperature and water conductivity logs were also carried out in well GN-1P. The temperatures of 34.7, 34.8, 34.9, 35.0, 35.1, 36.4, 36.6 and 37.2ºC have been recorded at depths of 100, 250, 350, 500, 600, 700, 750 and 800 m respectively. At the same depths, the electrical conductivity values of 5,012, 5,034, 5,045, 5,080, 5,100, 7,360, 7,380 and 8,200 μS/cm have been registered. Thus, the conductivity increases below 600 m depth. The uprising thermal water and the artesian flow cause a nearly uniform temperature distribution within the well. Taking into account the temperature and electrical conductivity values, it can be considered that the most active aquifers are located in the 603-660 and 750-800 m depth intervals. Flow rates from water-bearing zones into the well through the screens were measured in the 535-799 m depth interval using a flowmeter and the results have proven that the largest percentage (about 53%) of the produced geothermal water comes from the 758-795 m depth interval. The flow of water toward the screens is turbulent in some depth intervals due to high pressure and probable gas expansion in the casing (Kolios *et al.*, 2005).

After completing, cleaning and air-lifting the production well, pumping tests were conducted in October 2003. Three types of pumping tests were performed including step-drawdown, constant-rate and recovery tests. The step-drawdown test was carried out on October 6, 2013. The well was pumped at flow rates of 80, 110 and 144.5 m^3/h and the duration of each step was 2 hours. At the end of this step test, the total drawdown was 33.20 m. The evaluation of the results of this test has shown that the critical discharge Q_c exceeds 145 m^3/h (Q_c>150 m^3/h), the linear aquifer (and well) loss coefficient B has a value of 527 x 10^{-4} bar/(kg/s) (very good value) and the value of the non-linear well loss coefficient C is 7 x 10^{-4} bar/$(kg/s)^2$ (moderate value due to friction losses inside the screens, flogging of the screens, turbulences at the screens and inside the well etc). The water temperature increased from 35 to 35.5ºC during the step test (the temperature rose by 0.5ºC after 5 hours of pumping). The 72-hour constant-rate pumping test was performed on October 7-10, 2003. The flow rate was 130 m^3/h and the drawdown reached 41.05 m at the end of the test (water level before pumping: 0 m). Based on the results of this test, the following hydraulic properties of the geothermal aquifer have been determined: transmissivity T=7.296 x 10^{-4} m^2/s, hydraulic conductivity K=6.08 x 10^{-6} m/s, permeability k=4.482 x 10^{-13} m^2=0.4482 darcy and permeability-thickness product k.H=5.38 x 10^{-11} m^3. The water temperature increased from 35 to 35.5ºC. The temperature rose by 0.5ºC after 45 min of pumping and remained almost constant at 35.5ºC until the end of the test (minor exceptions showed temperatures of 35 and 35.2ºC at 3½ and 5 hours from the start of pumping respectively). Recovery tests were performed at the ends of the step-drawdown and constant-rate pumping tests. After the termination of the step-drawdown test, water-level measurements in the pumping well showed a very quick recovery. The residual drawndown s´ was calculated to be 0.9 m at 35 min after the pump was switched off. This fast recovery indicates the great potential of the penetrated geothermal aquifer. After the end of the constant-rate pumping test and taking into account the water-level measurements in the well, the residual drawdown s´was computed to be 9.80 m after 4 hours since pumping stopped. Using these recovery data, the values of transmissivity, T, and hydraulic conductivity, K, were calculated as follows: T=8.50 x 10^{-4} m^2/s and K= 7.08 x 10^{-6} m/s. These values are similar enough to those which have been computed based on the constant-rate pumping test data.

5. Water and Gas Chemistry - Geothermometry

5.1. Water Chemistry

The geothermal water produced from well GN-1P has a temperature of 35.5ºC, being classified as Na-Cl type (Figure 2A). The most representative sample was taken at the end of the 72-hour constant-rate pumping test. It shows a high electrical conductivity (3,868 μS/cm) and an alkaline character (pH=7.99). The TDS value is 2.18 g/l. This geothermal water is rich in Na^+ (710 mg/l) and Cl^- (1,226.2 mg/l). Na^+ contributes 80.5% to the total cationic charge (in meq/l), while the dominant anion is Cl^- constituting 92.1% of the total anionic charge. The Ca^{2+} and Mg^{2+} concentrations are low and they have been determined to be 79.8 and 40.7 mg/l respectively. The K^+ content is 6 mg/l. The geothermal water is characterized by extremely low concentration of SO_4^{2-} (1.7 mg/l). The HCO_3^- content in the water has been found to be only 176.9 mg/l contributing 7.7% to the total anionic charge (in meq/l). The water analysis has shown that Li^+ is absent (0.0 mg/l), the SiO_2 content is low (19.90 mg/l) and the boron concentration is elevated (4.8 mg/l).

The above-mentioned geothermal water differs chemically from the cold waters of the Alexandria area. The shallow and cold waters coming from irrigation and water supply wells are of the Ca-

HCO3, Ca,Mg-HCO3, Ca,Mg,Na-HCO3 types (Figure 2A) depending on the participation of the major cations in the total cationic charge. These waters have TDS in the range of 0.24-0.31 g/l (fresh waters) and show pH values of 7.48-8.08 (alkaline waters). Water samples with temperatures of 30.1 and 33.4ºC taken from exploration boreholes G-3 and G-4 belong to the Na-HCO3 and Na,Ca-HCO3 types respectively (Figure 2A). They are characterized by very low salinity (TDS levels 0.68 and 0.26 g/l) and a slightly alkaline character (pH 7.38 and 7.58).

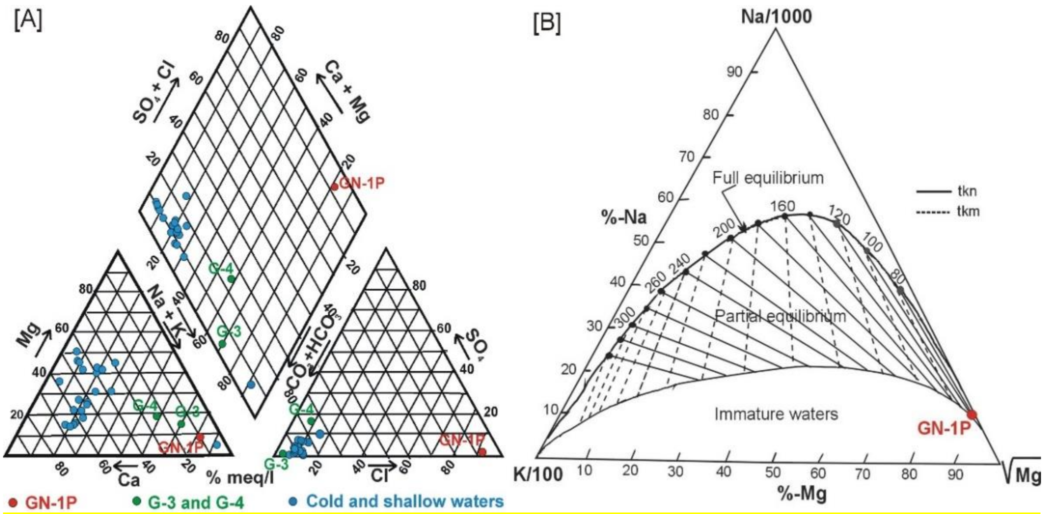

Figure 2 - (A) Piper (1944) trilinear diagram of hot (GN-1P, G-3, G-4) and cold waters from the Alexandria area. (B) Water sample GN-1P is plotted on the Giggenbach (1988) ternary diagram.

The SiO_2 content of geothermal water from well GN-1P is very low (19.9 mg/l), and even lower than that of colder waters (28.7-76.5 mg/l). In contrast, the relatively high concentration of boron (4.8 mg/l) indicates a geothermal origin. The SO_4^{2-} contents are low (1.7 mg/l in geothermal water, 0-21.1 mg/l in cold waters and 0.2-37.2 mg/l in samples G-3 and G-4). The Cl/SO_4 ratio value in geothermal water is extremely high (988.3), and much higher than its values in other waters and seawater (0.5-100.0). Water sample GN-1P shows a $[Cl^-]/[HCO_3^-]+[CO_3^{2-}]$ ratio of 11.9, which is much higher than its values in colder waters (0.033-0.213), indicating the deeper origin of this water sample. The Br content in geothermal water is very low (0.010-0.17 mg/l). It should be noted that the Mg^{2+} concentration in water from well GN-1P is 40.7 mg/l and this value is lower than that of seawater. The Na/K ratio value in geothermal water has been computed to be 201.9 and this value is extremely high compared with that listed in seawater (i.e. 35). It is clear that the water coming from well GN-1P is differentiated from seawater and local shallow waters. The elevated Na^+ and Cl^- levels may be explained by entrapment of water in large lenses of clastic sediments or along faults and deposition of microcrystalline salt in marine sediments (Tzimourtas, 1991). It is remarkable that the NaCl content in the formation water ranges from 1,000 to 2,000 ppm at depths of 0-1,000 m (P.P.C., 1988). The value of 2,000 ppm at approximately 1,000 m depth is almost equal to the sum of Na^+ and Cl^- concentrations (710 + 1,226.2 = 1,936.2 mg/l) in geothermal water extracted from 600-800 m depth through well GN-1P. At depths of 1,000-1,575 m, the NaCl content in the formation water is higher (1,500-3,000 ppm) (P.P.C., 1988). Correlation diagram between Na^+ and TDS for all collected water samples has shown that there is a very good relationship (R^2= 0.98) between them indicating that Na^+ contributes significantly to TDS. Additionally, diagrams between ion contents and water temperatures for all these water samples indicate that there is no linear correlation and therefore their chemical characteristics have been affected by the lithology and mineral composition of the geological formations through which the fluids have passed and/or where they have been stored (aquifers). In general, geothermal water GN-1P is characterized by higher concentrations of Na^+, Cl^-, Mg^{2+}, Ca^{2+} and B compared with cold waters. Correlation plot Na+K vs. Ca+Mg (in meq/l) for all water samples shows that three main water groups can be distinguished according to the participation of these cations: group A includes geothermal water GN-1P (high Na+K, moderate Ca+Mg), group B contains water sample G-3 (moderate Na+K, moderate Ca+Mg) and group C consists of the colder waters plus sample G-4 (low Na+K, moderate, moderate Ca+Mg).

All water samples are saturated with respect to quartz (0.366<SI<1.143), undersaturated with regard to gypsum (-4.636<SI<-2.278) and oversaturated with respect to talc (0.298<SI<4.288). The geothermal water is saturated with regard to calcite (SI=0.604), aragonite (SI=0.468) and dolomite (SI=1.378) indicating its tendency to precipitate these carbonate minerals. The remaining cold and sub-thermal waters are in equilibrium or weakly saturated with respect to these minerals showing lower SI (Saturation Index) values. The scaling and corrosion tendencies of geothermal water from well GN-1P have also been determined. The Langelier Saturation Index (LSI) value has been calculated to be +0.63 indicating that this water has a slight tendency to deposit $CaCO_3$. The computed value of the Ryznar Stability Index (RSI) is 6.73, suggests a very slight tendency to form scale and lies practically within an equilibrium zone (stability or neutral zone). Regarding the corrosivity of geothermal water GN-1P, it should be noted that the Total Key Species (TKS) have been calculated to be 1,405 mg/l, the Cl fraction in TKS is 87.3% (the Cl ion favours the corrosion) and the pH value is 7.99 (the lower the pH, the greater the corrosive tendency of the water).

5.2. Gas Chemistry

Due to observed gas bubbles in the flowing water from artesian production well GN-1P, gas sample was taken and analyzed by gas chromatography. The dominant gas is N_2 with a content of 99.4% v/v. Other gases include CO_2 (0.4% v/v) and O_2 (0.2% v/v).

5.3. Geothermometry

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) has been applied to the geothermal water from well GN-1P to estimate the deeper reservoir temperatures. Due to the absence of lithium (0.0 mg/l), the application of lithium-based geothermometers was impossible. The SiO_2 geothermometer (Fournier, 1981) provides value 63.3ºC. As already mentioned, there is no any correlation between SiO_2 content and temperature, the silica solubility in geothermal water is much less than in cold waters and the dissolved SiO_2 comes from the dissolution of silicate minerals in shallow geological formations. This means that the SiO_2 content does not reflect the deeper reservoir conditions and the temperature of 63.3ºC proposed by the SiO_2 geothermometer cannot be considered to be reliable, despite it seems to be a realistic value. The Na-K geothermometer (Arnorrson *et al.*, 1983) gives a reservoir temperature of 31.1ºC, which is lower than the measured outlet water temperature. The Na-K-Ca geothermometer (Fournier and Truesdell, 1973) provides better results than the previous one and the estimated temperature is 73.1ºC. This value appears to be reasonable but it is not considered to be true. The Na-K-Ca geothermometer is based on the temperature-dependent solubility of feldspars and the ion-exchange reactions between feldspars. The Na-K-Ca temperature is affected by changes in concentrations due to dilution. When Na^+, K^+ and Ca^{2+} come from geochemical processes which are not controlled by the feldspar ion-exchange reactions, the Na-K-Ca geothermometer gives false temperature values. Thus, Na^+ and K^+ ions may come from clays as a result of water-sediment interaction and subsequent ion-exchange. In the Alexandria area, the geothermal water GN-1P comes from aquifer consisting of clays, clayey marls, sands and gravels. High Mg^{2+} concentrations in waters may also result in erroneous results. Geothermal water GN-1P has been plotted on the Giggenbach (1988) ternary diagram and its position has been marked on the boundary line between ‘partial equilibrium’ and ‘immature’ waters. This position shows that the probable temperature of the deeper reservoir is 80-100ºC (Figure 2B). The K-Mg geothermometer (Giggenbach *et al.*, 1983) applied on the same water gives a temperature of 41.8ºC. Taking into account the estimated temperatures using the above-mentioned chemical geothermometers, the probable temperature of the deep reservoir ranges from 70 to 90ºC indicating a low enthalpy geothermal resource. Temperature measurements in deep oil exploration borehole AL-1 have shown values of 44ºC and 65ºC at depths of 960 and 1,705 m respectively (P.P.C., 1988). In addition, temperatures of 74, 83 and 89ºC have been recorded at depths of 1,520, 2,614 and 3,090 m respectively in neighbouring oil exploration borehole LOU-1 (LOUDIAS-1) in the Thessaloniki basin (Figure 1). These values fall within the range of temperatures estimated using the chemical geothermometers and Giggenbach trilinear diagram (1988).

6. Utilization of Geothermal Energy from Production Well GN-1P

Geothermal well GN-1P produces waters at 35.5ºC with pumping. These waters can be used for some geothermal applications. Considering that (a) the pumping rate is Q=130 m^3/h, (b) the water density at 35.5ºC is ρ=994.1 kg/m^3, (c) the specific heat capacity of water at 35.5ºC is c_p=4.177 kJ/kg.K, (d) the difference between inlet and outlet temperatures is Δt=35.5-24.5=11ºC and (e) 4.184 J=1 cal, then the thermal energy of water produced from well GN-1P is estimated to be E_t=1,419,185 kcal/h. This thermal energy corresponds to thermal installed capacity of 1.65 MWt. In addition, the thermal energy E_t=1,419,185 kcal/h is approximately equivalent to 0.142 TOE/h (TOE: Tonne of Oil Equivalent).

The Alexandria area constitutes a rural area. Therefore, the geothermal energy can be used for agricultural purposes depending on local conditions and needs. Specifically, the geothermal water from production well GN-1P can be used for (a) soil heating for off-season asparagus cultivation, (b) greenhouse heating, (c) swimming pool heating and (d) air-conditioning of buildings utilizing the discharge water temperature (24.5ºC) by means of geothermal heat pump systems. The off-season asparagus cultivation may be carried out by subsoil heating in connection with low tunnel technology. The soil can be warmed by the direct flow of the geothermal water through buried PP pipes. The total annual heating demands of the asparagus cultivation have been estimated to be 1,584,000 kWt. In the Alexandria area, a 0.8-ha greenhouse exists and the water from well GN-1P can be used for its heating. The total annual heating demands of this greenhouse have been computed to be 1,171,600 kWt. The heating of a swimming pool constitutes another possible geothermal application. An outdoor swimming pool of 1,000 m^2 with water temperature at 26ºC requires annual thermal energy of about 848,100 kWt for heating season from April to October taking into account the thermal benefits from solar radiation.

7. Conclusions

A low enthalpy geothermal field has been discovered north of the town of Alexandria (Northern Greece). The existence of this field is associated with an anticline with a NNW-SSE axis. Temperature measurements in geothermal exploration boreholes G-3 and G-4 have shown values of 30.1 and 33.4ºC at depths of 500 and 611 m respectively. Based on the results of a preliminary geothermal investigation, geothermal production well GN-1P was drilled reaching a depth of 805 m. A geothermal aquifer is located at depths of 600-800 m and composed of sands and gravels (microconglomerates) alternating with layers of clays and clayey marls. This aquifer contains water at temperature of 35.1-37.2ºC and electrical conductivity of 5,100-8,200 μS/cm. Geothermal well GN-1P can produce 130 m^3/h water at 35.5ºC. The geothermal water is classified as Na-Cl type showing electrical conductivity of 3,868 μS/cm, alkaline character (pH=7.99) and TDS value of 2.18 g/l. Chemical geothermometers applied to this water indicate probable reservoir temperatures of 70-90ºC. These estimates coincide with the measured temperatures of 65 and 89ºC at depths of 1,705 and 3,090 m in neighbouring oil exploration boreholes AL-1 and LOU-1. The thermal energy from water produced well GN-1P is calculated to be 1,419,185 kcal/h and can be used in various applications that require low temperatures.

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