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GEOTHERMAL DRILLING ACTIVITY IN THE AKROPOTAMOS AREA (MACEDONIA, NORTHERN GREECE)

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Abstract

The Akropotamos area constitutes a new geothermal field located in the eastern coastal zone of the Strymonikos Gulf in Macedonia (Northern Greece). After a detailed and systematic reconnaissance study including water temperature measurements at the heads of the existing irrigation and water supply wells, 6 new geothermal wells were constructed. This geothermal drilling program was performed by the Institute of Geology and Mineral Exploration during October 2003 - February 2006. Temperature and fluid conductivity logs were carried out into these boreholes during their drilling and after their completion. Well AKR-1 has a depth of 275 m and produces thermal waters at a temperature of 83°C with artesian flow rate 150 m³/h and large amounts of dissolved CO_2. Well AKR-2 of 410 m yields 25 m³/h of waters at 46°C. Well AKR-3 was drilled down to 515 m and the temperature of 88.9°C was measured at 498 m. This well yields about 200 m³/h CO_2-rich geothermal fluids at a temperature of 90°C with artesian flow. Next to this borehole, well AKR-4 was drilled at 180 m penetrating a shallow aquifer with waters reaching 49.7°C. During pumping test with constant flow rate, this well yielded 40 m³/h water of 48°C. Well AKR-5, 422 deep, was drilled in the western part of the study area close to the Strymon river's mouth. The temperature of 27.8°C was recorded at 280 m into this borehole. The last well AKR-6 was drilled down to 545 m in the eastern part of the field. The temperature of 38°C was recorded at depth of 503 m. Pumping tests were performed in wells AKR-2 and AKR-4. This geothermal drilling project has resulted in the official characterization of the Akropotamos - Kavala area as a "proven low enthalpy geothermal field".

Key words: *Akropotamos, Macedonia, geothermal field, geothermal wells, Strymonikos Gulf, Kavala, CO_2.*

1. Introduction

The Akropotamos area constitutes a new low enthalpy geothermal field located in the eastern coastal zone of the Strymonikos Gulf in Macedonia (Northern Greece). During 2002-2006 the Institute of Geology and Mineral Exploration (I.G.M.E.) of Greece performed a systematic geothermal investigation in the area extended between the mouth of the Strymon river and the Eleftheres thermal springs (Fig. 1). After a detailed and systematic reconnaissance study including evaluation of geological and tectonic setting of the wider area, water temperature measurements at the heads of the existing irrigation and water supply wells and geophysical surveys, six (6) new production geothermal wells were constructed at depths of 180-545 m and produce waters up to 90°C. This drilling activity proved the existence of one of the most important low enthalpy geothermal fields of Greece in the area. This paper presents the results of the geothermal drilling project in the Akropotamos - Kavala field supported financially by the 3rd Community Support Framework 2000-2006 (Operational Programme "Competitiveness").

2. Geological and tectonic setting

The Akropotamos geothermal area belongs to the wider area of the Strymon basin. This basin is a typical post-orogenic graben. It has been formed between the Serbomacedonian Massif (SMM) to the west and the Rhodope Massif (Pangeon Unit) to the east and it has been filled with Neogene and Quaternary sediments of a total thickness reaching about 4000 m. Various depositional palaoenvironments (continental, fluvial, fluviolacustrine, lacustrine-marshy, marine, brackish, deltaic) were created during Neogene-Quaternary and their succession make the stratigraphy very complicated (Syrides, 2000). The typical stratigraphic column of the basin consists of the older Miocene formations (basal conglomerates and breccias, alternations of clays, sandstones, dark brown marls, lignite layers, petroliferous limestones), 700-800 m Pliocene sediments (layers of clays, conglomerates, travertines, marls, red clays, sandstones, siltstones, limestones, lignites) and 900-1000 m of Pleistocene deposits (alternations of sands, clays, sandstones, marls, siltstones, conglomerates and limestones) (Lalechos, 1986; P.P.C., 1988). The Strymonikos Gulf (or Orfanos Gulf) can be considered as an offshore extension of the Strymon basin southeastwards separated from the continental Strymon basin by a horst (tectonic uplift) close to the present estuary of the Strymon river. Noussinanos (1991) considers the northern part of the Orfanos Gulf to correspond to a post-Alpine basin in a shallow marine environment ("shallow water") and the southern part of the Orfanos Gulf to belong to a "transitional" environment. According to Lalechos (1986) during Miocene there was no connection between a lake prevailed extended to the continental basin and the Miocene Sea of the Orfanos Gulf because of a probable barrier from the metamorphic basement. Sediments composed of marls with intercalation of anhydrite layers and deeper layers of hard sandstones and limestones were revealed in a cross-section of a road next to the sea and these formations can be correlated with offshore well APOLLONIA-1 (AP-1) drilled in the Strymonikos Gulf (Fig. 1) indicating that during Pliocene a fault had separated the continental area of the Strymon basin and the Orfanos Gulf (Lalechos, 1986). Oil exploration borehole AP-1 of 3146 m depth has penetrated Pleistocene-Holocene deposits (0-1250 m), Pliocene sediments (1250-1875 m) and Miocene formations (1875-3146 m). Holocene - Pleistocene deposits consist of alternating sands, clays and sandstones with locally lignite intercalations and fragments of Bivalvia (Lamellibranchia). Pliocene - Miocene sediments are composed of alternating sandstones, siltstones, clays and marls. Alternations of dolomites, sandstones, limestones and anhydrites dominate near the base of Miocene formations (Lalechos, 1986). In borehole AP-1 the temperatures of 59-67 and 121-130°C were registered at depths of 1335 and 3146 m respectively and the average geothermal gradient is estimated to be 36.5°C/km. During the Upper Miocene, the South Kavala Ridge (tectonic uplift in a NW-SE direction, South-East of the Akropotamos area, Fig. 1) emerged to separate the Prinos - Kavala basin from the Orfanos Gulf (Pollak, 1979).

The Akropotamos area lies close to the "Strymon line", which is the tectonic contact between the Serbomacedonian and Rhodope Massifs. Therefore, the geological basement of this area consists of gneisses, amphibolites and schists belonging to the Serbomacedonian Massif (Kerdylia series) to the West and marbles (dominant rock type) and schists belonging to the Pangeon Unit (Rhodope Mas-

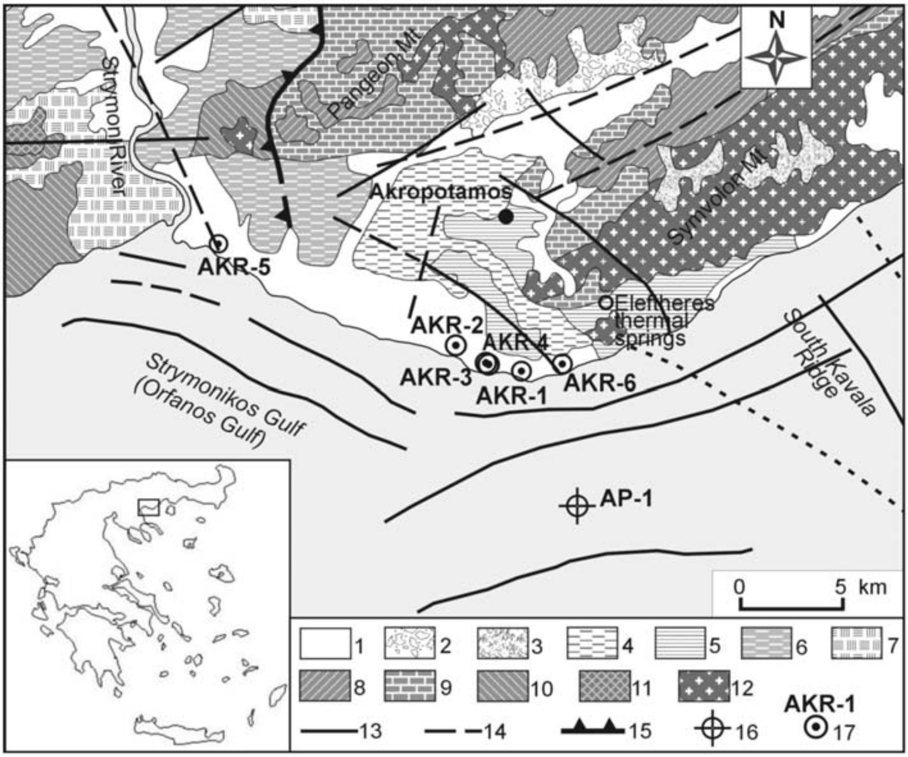

Fig. 1: Simplified geological map of the Akropotamos area with the sites of geothermal wells [1: Alluvial deposits in valleys and coastal deposits, 2: Alluvial fans and older talus cones - Scree, 3: Pleistocene lacustrine and continental deposits: clays, loams, sands, conglomerates, 4: Pleistocene marine deposits: marls, clays, sands, conglomerates, coastal terraces, 5: Pliocene marine deposits: conglomerates, sands, clays, marls, marly limestones, 6: Mio-Pliocene lacustrine and terrestrial sediments: conglomerates, sands, marls, clayey material, marly limestones and clays, 7: Mio-Pliocene marine deposits: the above-mentioned detrital sediments, 8: Amphibolites, gneisses, schists with marble intercalations (Rhodope Massif), 9: Marbles or crystalline limestones (Rhodope massif), 10: Amphibolites, gneisses, schists with marble intercalations (Serbomacedonian Massif). 11: Gneisses (Serbomacedonian Massif), 12: Tertiary granitoids, 13: Fault, 14: Probable fault, 15: Strymon tectonic line, 16: Oil exploration borehole, 17: Geothermal well]. The compilation of this map is based on the geological map of Greece at a scale of 1:500,000 (I.G.M.E., 1983) with some additional tectonic structures derived from the 1:500,000-scale seismotectonic map of Greece (I.G.M.E., 1989) and some modifications according to Lalechos (1983) and Pollak (1979).

sif) to the East. Tertiary granitoids have intruded into the crystalline rocks of the basement (Eleftheriadis G. et al., 2001). The oldest Miocene sediments of the Akropotamos area consist of lacustrine and fluvial-lacustrine deposits with conglomerates, sands, coarse-grained sandy marls and sandstones with a total thickness more than 500 m. Eastwards thick laminated biogenic limestones of Middle Miocene age of high secondary porosity are located. The sedimentary series was developed uniformly towards the Pliocene. Pliocene sediments consist of travertine deposits, sands and clays of marine origin and calc-sandstones. Southwards the entire series is covered by recent coastal and fluvial - torrential deposits and scree.

The fault pattern of the Akropotamos area is dominated by NW-SE and NE-SW faults. The NW-SE faults with a greater population are activated as oblique sinistral normal faults and they have high dip angles. The NE-SW faults are very common in the area, probably related to the Kavala-Xanthi-Komotini fault zone (Mountrakis and Tranos, 2004). These faults are activated as oblique dextral-normal faults. During Lower Quaternary the wider area of Akropotamos was affected by NW-SE and NE-SW striking faults. Two main tectonic blocks are observed in this area: the Akropotamos horst and the Pieria graben (east of the investigation area). The wider area was activated due to the presence of the North Anatolian Fault Zone.

The thermal springs of Eleftheres located about 3 km east-northeast of the study area constitute the only geothermal manifestation in the wider area. Their water temperature is 38.7-53°C. These springs are situated in the Marmaras river Valley occurring in a NNW-SSE direction in the Symvolon granitoid (Miocene granodiorite) although the marbles of the Pangeon Unit dominate in the area. The presence of the springs is related to a fault or intersecting faults (P.P.C. and E.N.E.L., 1979; Gavrielides, 1990).

3. Geothermal drilling activity in the Akropotamos area

3.1 General

A detailed and systematic reconnaissance study was carried out in the Akropotamos area extended between the mouth of the Strymon river and 3 km west of the Eleftheres thermal springs. This study was performed during 2002-2003 including evaluation of geological and tectonic setting of the wider area, water temperature measurements at the heads of the existing irrigation and water supply wells, water sampling and chemical analyses and geoelectric surveys. Based on the results of this research, 6 exploration - production geothermal wells were constructed by I.G.M.E in the investigation area during the period October 2003 - February 2006. The sites of these wells are shown on the map of Figure 1: The results of this drilling activity are presented as follows.

3.2 Geothermal well AKR-1

Geothermal well AKR-1 was drilled in the coastal zone, south of the national road Thessaloniki - Nea Peramos - Kavala. The coordinates of the drilling site are X:504423 and Y: 4507391 (Greek Grid, GGRS1987). Its elevation is approximately 9 m a.s.l. This well was drilled during October-December 2003. It has a depth of 275 m. Pliocene and Miocene sediments were penetrated. These sediments consist of chaotic conglomerates, clayey-marly formations, fractured limestones and calcareous conglomerates. The geothermal reservoir is located at 240-275 m depth composed of calcareous conglomerates. The lithologic column and the mechanical diagram with the main construction features of well AKR-1 are shown in Fig. 2. The wellbore was drilled at a diameter of 15´´ to a depth of 40 m and drilling was then continued at a diameter of 9 5/8´´ down to the final depth of 275 m. The casing of this borehole has a diameter of 10 ¾´´ at 0-40 m and 6 5/8´´ at 0-275 m. Screens were placed at 233-275 m. The well was cemented from the surface to 40 m depth. Well AKR-1 produces about 150 m^3/h waters of 83°C with artesian flow. The electrical conductivity of water is 7718 μS/cm. The produced geothermal fluids contain significant quantities of carbon dioxide (CO_2).

3.3 Geothermal well AKR-2

Geothermal well AKR-2 was constructed at a distance of 3.2 km WNW of well AKR-1 in the coastal zone. Its coordinates are X: 501353 and Y: 4508475 (Greek Grid, GGRS1987) and its elevation is approximately 7 m. It was drilled during January-April 2004. The total drilled depth was 422 m and the borehole was cased down to 410 m. The section from the surface to 45 m was drilled at a diam-

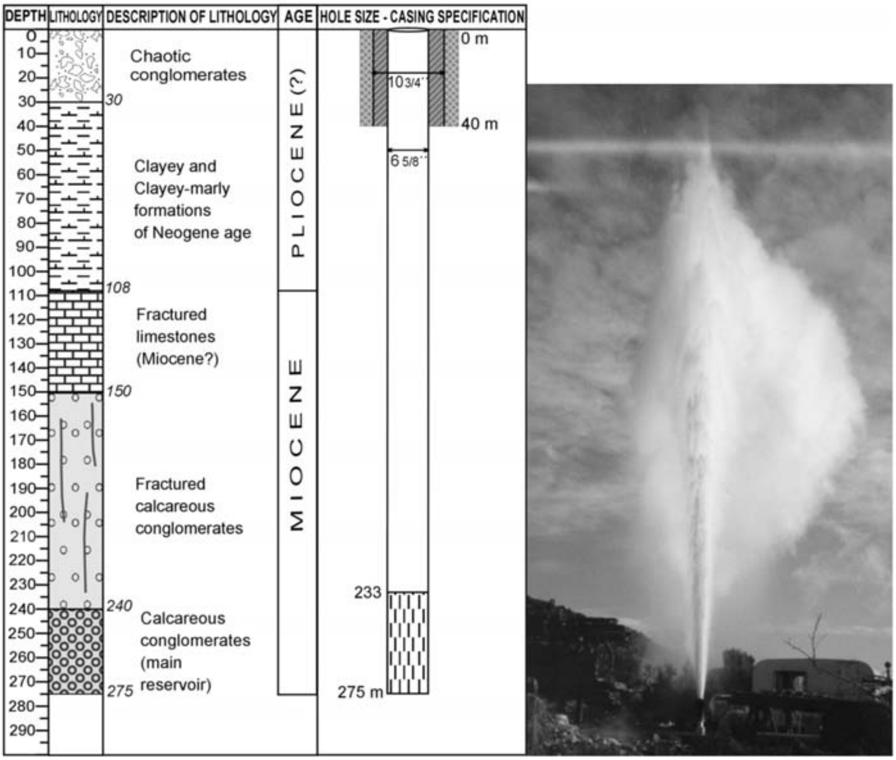

Fig. 2: (left): Lithologic column and mechanical diagram of geothermal well AKR-1; (right): Photo showing the artesian flow rate of geothermal well AKR-1.

eter of 15´´ and drilling continued at a smaller diameter (9 5/8´´) below 45 m. The casing of this borehole has a diameter of 10 ¾´´ at 0-45 m, 6 5/8´´ at 0-48 m and 5´´ at 48-410 m. Screens were placed at 294-410 m. The borehole was cemented from the surface to 100 m depth.

Well AKR-2 penetrated a sedimentary sequence composed of sands, pebbles, gravels, unconsolidated calcareous conglomerates, unconsolidated clayey sandstones, clays, marls and coarse-grained sandstones. The geothermal aquifer is located at depths of 282-422 m composed of coarse-grained sandstones. Temperature and water conductivity logs were performed in borehole AKR-2. The temperature of 48°C was measured at 360 m (Fig. 3). Considering that the mean annual surface temperature of the area is 16.8°C, the average geothermal gradient is calculated to be 8.70 °C/100 m from the surface to 360 m depth. The results of water conductivity logs recorded in this borehole at various dates are shown in Fig. 4. Measurements dated 20/4/2004 and 25/5/2004 showed an enormous increase between 70 and 190 m depth and the maximum value reached 15800 μS/cm at 130 m on 20/4/2004. This indicates a probable intrusion of sea water into the unconsolidated calcareous conglomerates located at 65-120 m depth influencing a large part of this well. This increase was not recorded on 29/4/2004 and the electrical conductivity rose gradually down to 344 m reaching 3680 μS/cm.

A 24-hour pumping test at a constant flow rate of 25 m^3/h was performed. The final drawdown was measured at 44.6 m. The static water level was 7 m before pumping. The water temperature remained constant at 46°C during the pumping test and the electrical conductivity of the pumped water was 3334-3600 μS/cm.

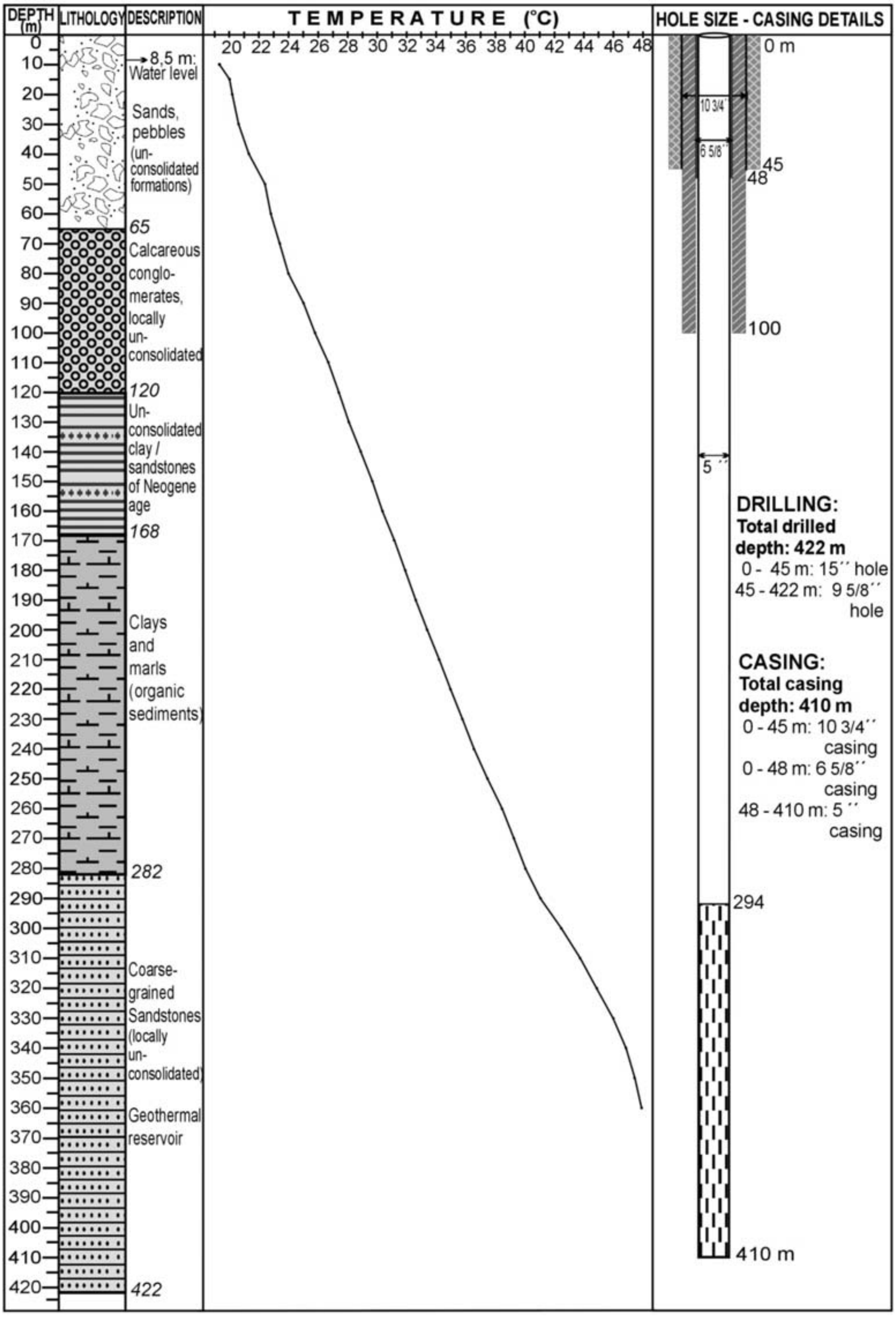

Fig. 3: Geothermal well AKR-2.

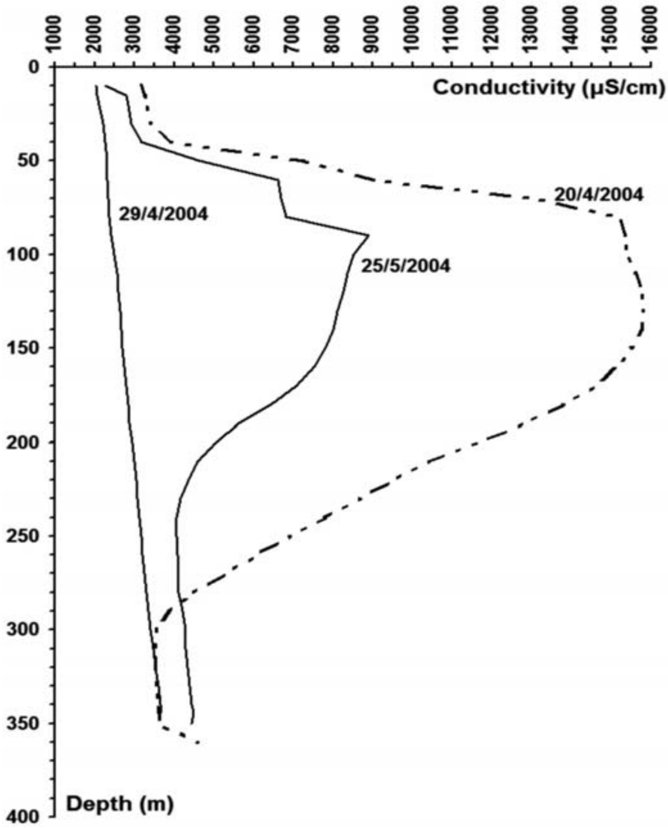

Fig. 4: Water conductivity logs in geothermal well AKR-2.

3.4 Geothermal well AKR-3

Geothermal well AKR-3 was drilled at a distance of 1.62 km southeast of well AKR-2 in the coastal zone (Fig. 1). Its coordinates are X: 502858 and Y: 4507783 (Greek Grid, GGRS1987) and its elevation is approximately 2 m. It was constructed during May-October 2004. The total well depth is 515 m. Sands, clays, sandstones and conglomerates were penetrated. The lithology of this borehole is shown in Fig. 5. A deep geothermal aquifer is located at 480-515 m depth. This aquifer is made up of sandy sandstones and contains geothermal fluids of about 90°C. A shallow aquifer composed of coarse-grained sandstones and conglomerates is located at 102-185 m depth containing thermal waters of 48-49°C. Microfossils have been found at depths of 96-102, 258-270, 360-372, 480-492 and 510-515 m. Among them, the presence of *Tectochara escheri* (Charophyta) found in the lower layers of this borehole (486-515 m depth) is of special interest and suggests a Miocene to Middle Pliocene age for these strata. The total casing depth is 515 m. Screens were placed from 440 to 515 m depth (Fig. 5). Temperature and water conductivity logs were performed in this borehole at different times. The maximum measured temperature was 88.9°C at depth of 498 m. Considering that the mean annual surface temperature of the area is 16.8°C, the average geothermal gradient is calculated to be 14.48°C/100 m from the surface to 498 m depth. All conductivity measurements show a significant increase between 100-230 m depth and the maximum

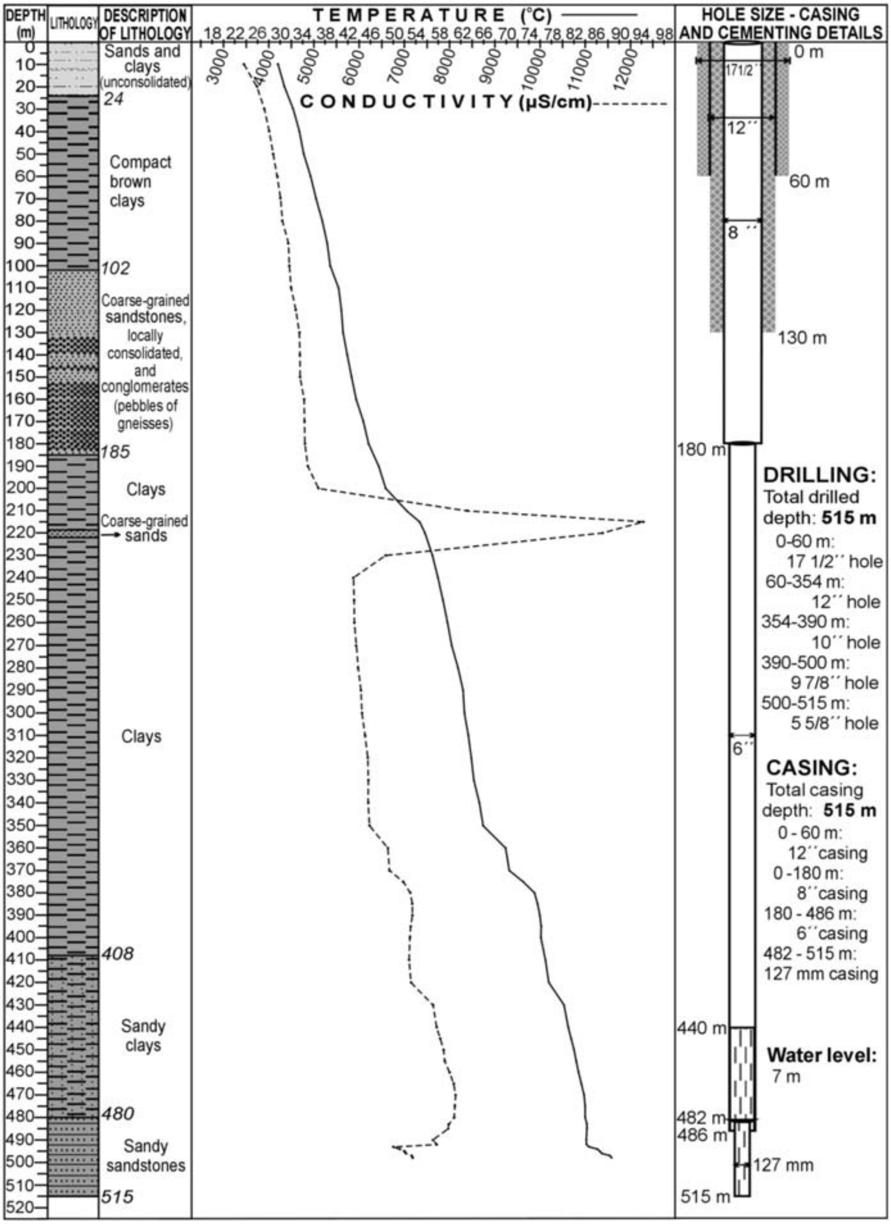

Fig. 5: Geothermal well AKR-3.

value was 14000 μS/cm at 215 m registered on 9/9/2004. This indicates the presence of brackish water in a shallow aquifer. This brackish water has a temperature of 48-50°C. Fig. 5 shows the conductivity vs. depth curve based on logs carried out on September 27, 2004. Well AKR-3 produces about 200 m^3/h waters of 90°C with artesian flow. The electrical conductivity of water is 5858 μS/cm. The produced geothermal fluids contain significant quantities of CO_2.

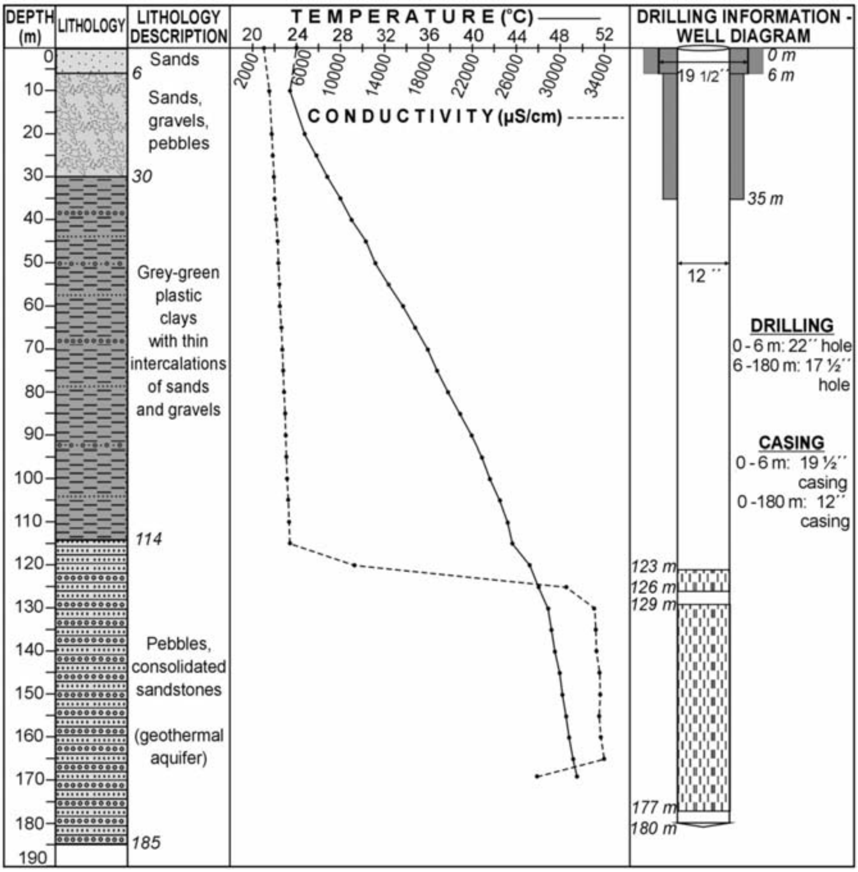

Fig. 6: Geothermal well AKR-4.

3.5 Geothermal well AKR-4

Geothermal well AKR-4 was drilled next to well AKR-3, only a few meters away (Fig. 1). Its coordinates are X: 502862 and Y: 4507796 (Greek Grid, GGRS1987). It was constructed during April-June 2005. The total well depth is 180 m. Borehole AKR-4 penetrated a sedimentary sequence composed of sands, gravels, pebbles, grey-green plastic clays with thin intercalations of sands and gravels and finally pebbles and consolidated sandstones (Fig. 6). The latter sediments located at 114-185 m depth make up a hot aquifer containing waters of 46-49.7°C. Temperature and water conductivity logs were performed in borehole AKR-2 on September 12, 2005. The maximum temperature of 49.7°C was measured at depth of 168.86 m. Considering that the mean annual surface temperature of the area is 16.8°C, the average geothermal gradient is calculated to be 19.48°C/100 m between the surface and 168.86 m depth. Water conductivity log showed a rapid and high increase below 115 m depth and the maximum value of 34000 µS/cm was recorded at 165 m depth (Fig. 6). This increase in water conductivity indicates a high percentage of seawater in the shallow geothermal aquifer due to probable seawater intrusion into this aquifer. Step-drawdown and constant-rate pumping tests were carried out after the completion of the well. The static water level was 3 m before pumping. A step-drawdown test was performed on June 23, 2005. The well was pumped for 2 hours each in two steps at discharge rates of 28 and 40 m^3/h respectively and the total drawdown was 32.77 m at the end of the test. The

24h constant-rate pumping test was performed at a flow rate of 40 m^3/h and the drawdown at the end of this test was 37.12 m. The water temperature was increased from 47°C (in the beginning of the constant-rate test) to 48°C (after 16 hours pumping) and remained constant until the end of this test. Electrical conductivity of the pumped water was 36990-37360 μS/cm.

3.6 Geothermal well AKR-5

Well AKR-5 was drilled 2.2 km southeast of the Strymon river estuary at a small distance from the coast. Its coordinates are X: 489165 and Y: 4514004 (Greek Grid, GGRS1987) and its elevation is about 1.5 m. Well AKR-5 was drilled down to 422 m and penetrated a sedimentary sequence composed of unconsolidated sands (0-45 m depth), coarse-grained sands (45-50 m), alternations of compact sands and clays of Neogene age (50-180 m), alternations of Neogene compact sands and clays with dominant clay material (180-280 m), aquifer sands (280-320 m), clays (320-330 m), aquifer sands derived from gneisses (330-350 m), clays (350-380 m) and impermeable organic material (380-422 m). The wellbore was drilled at a diameter of 17½´´ from the surface to 12 m depth and drilling then continued at smaller diameters below 12 m (drilling was 11´´, 9 7/8´´, 7 ½´´ and 5 5/8´´ in diameter at depths of 12-48, 48-218, 218-330 and 330-422 m respectively). Well AKR-5 was cased down to 422 m and 12´´, 10´´, 8´´, 6´´ and 4´´ casings were set at depths of 0-12, 0-48, 0-218, 170-290 and 278-422 m correspondingly. The total casing length is 542 m. The annular space around the outside of the 12´´ surface casing was cemented. The annular space between the 12´´ and 10´´ casings from the surface to 12 m depth was cemented too. Cementing was also performed around the outside of the 8´´ casing down to 60 m depth. Screens were placed at depths of 280-340, 355-363, 375-383 and 416-418 m. Temperature and water conductivity logs were performed in borehole AKR-5 on October 11, 2005. The static water level was 3.2 m below the surface. The temperature of 27.8°C was measured at depth of 280 m. Considering that the mean annual surface temperature of the area is 16.8°C, the average geothermal gradient is calculated to be 3.93°C/100 m from the surface to 280 m. Water conductivity log showed a gradual increase with depth. Electrical conductivity values ranged from 10138 to 19500 μS/cm at depths of 4-280 m. Below 120 m the water conductivity values were higher than 18000 μS/cm indicating the influence of seawater on the sandy aquifers.

3.7 Geothermal well AKR-6

Well AKR-6 was drilled 1.9 km east of well AKR-1 and approximately 3 km SW of the Eleftheres thermal springs (Fig. 1). Its coordinates are X: 506291 and Y: 4507527 (Greek Grid, GGRS1987) and its elevation is about 13 m. It was constructed during October 2005-February 2006. Well AKR-6 was drilled down to 545 m depth and penetrated a sedimentary sequence composed of scree and travertine limestones (0-42 m depth), Neogene sandy clays (42-96 m depth), unconsolidated conglomerates and breccias alternating with marls (96-135 m), clays and marls (135-174 m), sandy clayey-marly sediments (174-192 m), flyschoid formations (192-246 m), consolidated organic clays and sandy clays (246-486 m), grey-green clays and fine-grained sands (486-492 m), fine-grained sands (492-516 m), clays with gravels and small pebbles (516-522) and finally grey-green clays with fine-grained sands and gravels (522-545 m). The wellbore was drilled at a diameter of 22´´ from the surface to 6 m depth and drilling then continued at smaller diameters below 6 m (drilling was 17´´, 9 7/8´´ and 5 5/8´´ in diameter at depths of 6-117, 117-492 and 492-545 m respectively). Well AKR-6 was cased down to 545 m and 19½´´, 10´´, 6´´ and 4´´ casings were set at depths of 0-6, 0-117, 102-492 and 485-545 m correspondingly. The total casing length is 573 m. The annular space around the outside of the 19½´´ surface casing was cemented. Cementing was also performed around the outside of the 10´´ casing down to 60 m depth. Screens were placed at depths of 497-515, 521-533 and 539-545 m. Temperature and water conductivity logs were performed in AKR-6 at various dates. The temperature of 38°C was recorded at 503 m depth and the average geothermal gradient is calculated to be 4.2°C/100 m from the surface to this depth. The conductivity logs have registered values higher than 6600 μS/cm reaching up to 36940 μS/cm.

4. Conclusions

In the Akropotamos area, the preliminary geothermal investigation resulted in a drilling program including the construction of 6 exploration - production wells (AKR-1, AKR-2, AKR-3, AKR-4, AKR-5 and AKR-6). All these wells were drilled in the coastal zone of the Strymonikos Gulf at depths of 180-545 m. The main geothermal interest is focused on the area between wells AKR-2 and AKR-1 along the coastal zone (Fig. 1), where geothermal waters of 46-90°C are produced from depths of 130-515 m. Two geothermal aquifers have been recognized in this area: (a) a shallow aquifer at 100-185 m depth containing high-conductivity (14000-38000 μS/cm) waters of 46-49.7°C and (b) a deeper reservoir at 240-515 m containing lower conductivity (3600-8160 μS/cm) waters of up to 90°C. Wells AKR-1 and AKR-3 produce about 150 and 200 m^3/h CO_2-rich waters of 83 and 90°C respectively with artesian flow. The Akropotamos area has been characterized officially as "a proven low temperature geothermal field" and its boundaries have been defined by a Ministerial Decision (Official Gazette 1058/B′ / 02.06.2009) based on the geothermal study carried out by I.G.M.E.

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