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Prospective Medium Enthalpy Geothermal Resources in Sedimentary Basins of Northern Greece

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ABSTRACT

In Northern Greece there is a large number of low enthalpy geothermal fields with water temperatures of 30-100°C. These fields are located at very shallow depths (30-500 m) in the post-orogenic basins of the area (e.g. basins of Strymon, Nestos Delta, Xanthi-Komotini, Evros) and in the island of Samothrace. The geological and tectonic conditions are favorable for the presence of medium enthalpy (T=100-150°C) geothermal fields at greater but exploitable depths (up to 2000 m) not excluding the high enthalpy ones. For example, the temperature of 122°C was determined at depth of 1377 m in a geothermal exploration borehole in the Nestos Delta basin. The active and extensional tectonics, the crustal thinning and the magmatic intrusions (Tertiary plutonic and volcanic rocks) increase the regional heat flow and they are responsible for the positive geothermal anomaly in many places of the basins. The significant thickness of the Tertiary and Quaternary sediments (permeable strata alternating with impermeable ones) creates some interesting and exploitable supplementary uppermost reservoirs. Sometimes the large and open faults, which affect the metamorphosed basement, create horsts covered by the overlying sedimentary sequences. The tectonically fractured metamorphic substratum often made up of carbonate rocks (Mesozoic-Paleozoic limestones and marbles) permits the formation of important deep pressure reservoirs with very good permeability.

The medium enthalpy geothermal fluids can be used for power generation by the utilization of the binary (Rankine or Kalina) cycle systems with good financial results due to the expected high temperatures of the fluids and the important flow rates. The increased need for electric energy in Northeastern Greece and the legally fixed price per KWh_e make this enterprise attractive.

1. INTRODUCTION

Many low enthalpy geothermal fields with water temperature of 30-100°C at very shallow depths (30-500 m) occur in the Tertiary sedimentary basins of Northeastern Greece (Eastern Macedonia and Thrace) and in the Samothrace Island. The geological and tectonic conditions in this region are favorable for the presence of medium enthalpy (T=100-150°C) geothermal fields at greater but exploitable depths (up to 2000 m) not excluding the high enthalpy ones. This paper deals with these prospective medium enthalpy geothermal resources in the main post-orogenic basins and in the Samothrace Island using data from deep oil and geothermal exploration boreholes and emphasizing the interest in three characteristic areas: the Nestos Delta basin, the Evros Delta (Alexandroupolis) basin and the Samothrace Isl. The medium enthalpy geothermal fluids can be used for power generation by the utilization of the binary (Rankine or Kalina) cycle systems with good financial results due to the expected high temperatures of the fluids and the important flow rates.

2. GENERAL GEOLOGICAL AND TECTONIC SETTINGS IN NORTHEASTERN GREECE

The wider region of northeastern Greece extending between the Strymon River on the West and the Evros River on the East (Greek-Turkish borders) belongs mainly to the crystalline mass of Rhodope (Figure 1). Small parts of this area belong to the Circum-Rhodope belt (southern and northeastern Evros area) and to the Serbomacedonian massif (western part of the Strymon basin). The Rhodope massif consists of gneisses, marbles and mica schists. Tertiary granitoids intruded the Rhodope metamorphic rocks at various times from Eocene to Miocene. The western boundary of the Rhodope Massif in Greece is delineated by the “Strymon line” a major tectonic zone, which separates it from the Serbomacedonian Massif. The Circum-Rhodope Zone consists of low-grade meta-sediments and meta-igneous rocks (phyllites, green schists and post-sediments of an old flysch, where bodies of basic eruptive rocks are intercalated) continuing upwards with semi-metamorphic formations (Maltezou and Brooks, 1989; Rondoyanni et al., 2004).

Following the Alpine orogenic event molassic sedimentation was initiated in the Paleogene, which was associated with graben formation and faulting. The molassic sediments were deposited in large basins during the Middle Hellenic orogenic belt (Middle/Upper Eocene – Oligocene) in the region behind the front of orogenesis or parallel to this one (Noussinanos, 1991). Molassic sediments were deposited widely in the molassic basin of Evros (conglomerates, sandstones, marls and marly limestones of Middle Eocene – Oligocene age). Neogene and Quaternary sediments were deposited later in the Strymon, Xanthi - Komotini, Nestos Delta, and Evros (Orestiada – Alexandroupolis) basins.

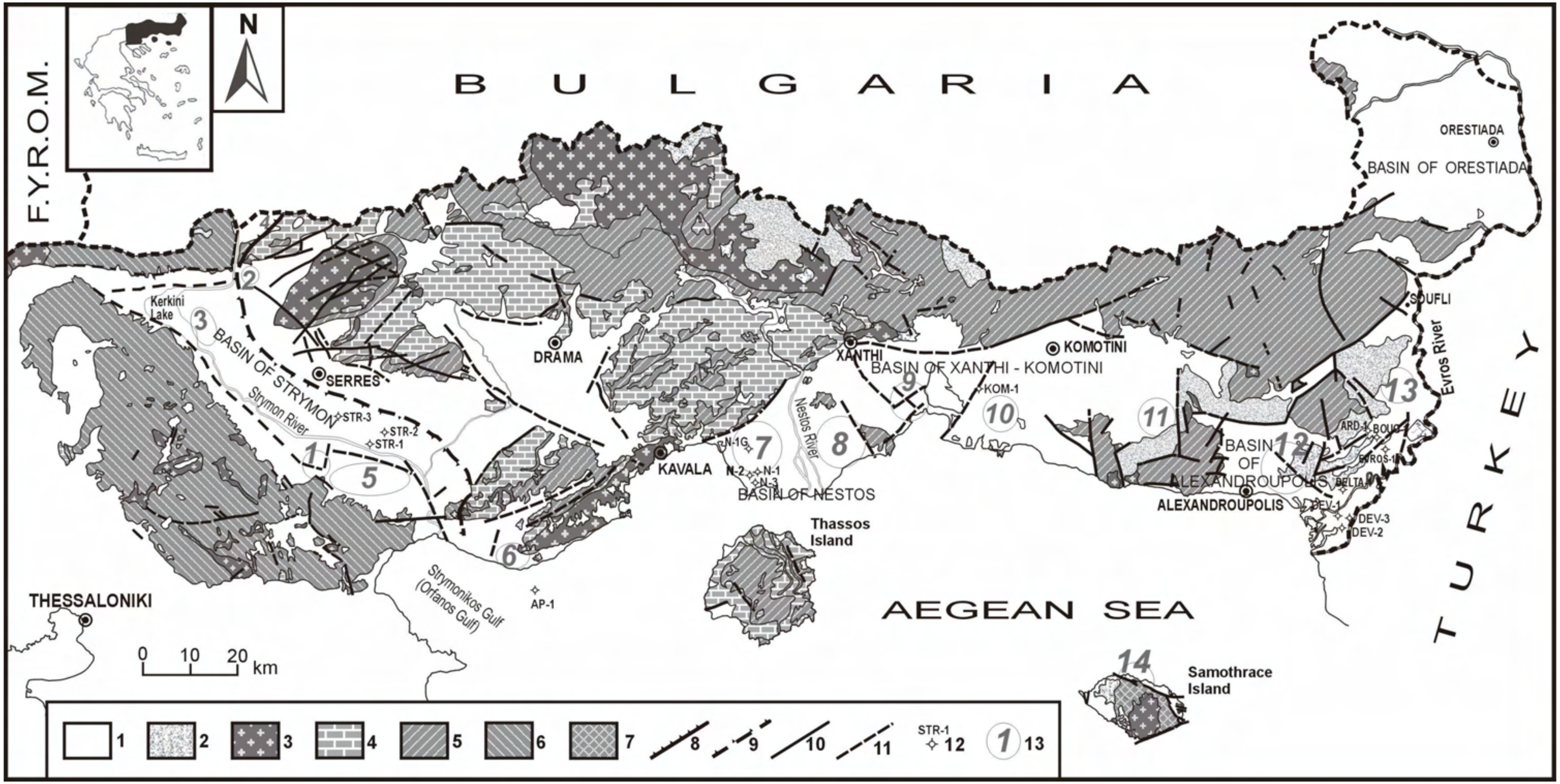

Figure 1: Simplified geological map of NE Greece (Eastern Macedonia and Thrace) with the locations of the Tertiary sedimentary basins and the main geothermal fields [1: Tertiary and Quaternary sediments, 2: Tertiary volcanic rocks, 3: Granites and granodiorites, 4: Marbles and limestones, 5: Metamorphosed rocks of Rhodope Massif, 6: Metamorphosed rocks of SRB Massif, 7: Low-grade metamorphosed rocks of Circum-Rhodope Belt, 8: SRB & Rhodope contact, 9: SRB & Rhodope probable contact, 10: Faults, 11: Probable faults, 12: Deep exploration boreholes, 13: Low enthalpy geothermal fields (the numeration of the fields is as follows: 1:Therma-Nigrita, 2: Sidirokastro, 3: Lithotopos-Iraklia, 4: Agitsro, 5: Ivira-Achinos-Mavrothalassa, 6: Akropotamos, 7: Eratino, 8: Magana-Neo Erasmio, 9: Nea Kessani, 10: Mitrikou Lake, 11: Sappes, 12: Aristino-Alexandroupolis, 13: Tychero, 14: Therma-Samothrace)]

The wider area is characterized by the occurrence of an Oligo-Miocene volcanism whose products show a calc-alkaline chemical character (Fytikas et al., 1979) indicating active continental margins in the past.

Eastern Macedonia and Thrace areas have been affected by faults with ENE-WSW, WNW-ESE and about N-S (NNW-SSE, NNE-SSW) main directions. The most important structure of this area is the Kavala-Xanthi-Komotini fault zone (KXKF) with a general E-W strike and total length of about 120 km subdividing the area into two different landscape parts: (a) the northern mountainous part that made up of the crystalline rocks of the Rhodope massif and (b) the southern flat or plain part, which consists of Eocene-Early Oligocene post-alpine mollase type sediments, Late Oligocene-Early Miocene volcanogenic rocks and younger Neogene and Quaternary sediments. The KXKF seems to be the coalescence of inherited structures that made up four main segments of different geometry and architecture: the Kavala-Xanthi (NE-NW), the Xanthi-Iasmos (WNW-ESE to E-W), the Iasmos-Komotini (ENE-WSW) and the Komotini-Sappes (WNW-ESE) fault segment. (Rondoyanni et al., 2004; Mountrakis and Tranos, 2004). The most fault surfaces bear slikenlines that indicate normal to oblique normal movements. However, older strike slipe slickenlines have been also traced. The kinematics of the KXKF has been better defined in the part between Xanthi and Komotini and two stress regimes have been defined to drive its reactivation since the Late Miocene: (a) the former has an almost vertical maximum principal stress axis (s_1) and a subhorizontal least principal axis (s_3) oriented along NNE-SSW, whereas (b) the latter is the contemporary stress field and has a vertical maximum principal stress axis (s_1) and at least principal stress axis (s_3) along N-S orientation. The Xanthi-Iasmos and Komotini-Sappes fault segments stand as fault bridges between the large inherited NE-SW to ENE-WSW fault segments and both of them are modified by the reactivation of neoformed E-W faults especially at the fault bending parts (Mountrakis and Tranos, 2004). According to Rondoyanni et al. (2004) in the area extended to east of Komotini, the horizontal component of the movement dominates on oblique-slip to strike-slip faults of N-S direction that they could be considered as second order structures located and reactivated in the zone between the existed major dextral fault zones that dominate in North Aegean, where an extensional component is also present. The recent faults of this area are controlled by the active transtensional stress field with s_3 axis of NNE-SSW direction.

In general, after the last compressional phase, the Oligocene - Miocene extension and unroofing of the Rhodope massif took place (Kilias and Mountrakis, 1998). During the Eocene-Oligocene NE-SW subhorizontal extension affected the SRB massif with tectonic unroofing of the SRB (Kilias et al., 1999). Except of the post-Middle Miocene NE-SW extension, in the wider area of North Aegean the following extensional phases with strike-slip motion are considered (Lyberis, 1985; Mercier et al., 1987, 1989; Pavlides and Mountrakis, 1987; Voidomatis et al., 1990): (a) Late Miocene-Early Pliocene with WNW-ESE direction forming NE-SW faults, (b) Pliocene-Lower Pleistocene with a NE-SW direction of s_3 creating NW-SE faults and reactivating the older ones, (c) Middle Pleistocene-present with N-S extension reactivating the pre-existing NW-SE or NNE-SSW faults with normal or strike-slip movement and forming a new group of E-W normal faults over the older fault network. These extensional phases are mainly responsible for the creation of the North Aegean Trough and the surrounding basins. The 300-km long North Aegean Trough (NAT) extends as a continuation of the North Anatolian Fault as far as the Sporades basin in the west and it is controlled by en echelon faults showing normal character although there is also evidence for important dextral slike-slip movement. The Northern Greek mainland is an intracontinental domain of extension neotectonics (Pavlides et al., 1990).

The dextral moving Anatolian fault system of the North Aegean can influence the kinematics and the geodynamics of the wider area. This fault system has reactivated the pre-existing faults on its surrounding area keeping them “open” and active. According to Koukouvelas and Aydin (2002) the northern Aegean basins and the faults which represent the diffused termination of the North Anatolian Faults System are consisted with the mechanical principles of strike-slip tectonics. The overall deformation pattern in northern Greece is that of a transtensional intracontinental regime. The recent and active deformation of the North Aegean could be due either to (a) a N-S extensional regime in back arc conditions and the influence of the westward motion on the Anatolian block, or (b) the influence of a transtensional shear zone in intracontinental conditions as the termination of the North Anatolian Fault along the North Aegean. The main strike-slip motion takes place along NAT fault zones (Pavlides et al., 1990).

Therefore, (a) the active tectonics, (b) the crustal thinning, (c) the magmatic intrusions (plutonic and volcanic rocks), (d) the increased regional heat flow, (e) the large open faults which affect the metamorphic basement and the overlying sedimentary sequence, (f) the existence of impermeable layers that can act as an “impervious cap” and (e) the presence of aquifers within the permeable sediments constitute the favorable conditions for the formation of geothermal fields in the sedimentary basins of northeastern Greece.

3. POST-OROGENIC SEDIMENTARY BASINS WITH GEOTHERMAL INTEREST IN NORTHERN GREECE

The Tertiary sedimentary basins of Strymon, Nestos Delta, Xanthi-Komotini and Evros Delta in the Rhodope region (Northern Greece) are fault-controlled and of large area extent (Figure 1). Their directions differ across the region (the Strymon basin has a NW-SE orientation, the Nestos Delta - Prinos basin with NE-SW orientation and the Xanthi-Komotini basin in an approximately E-W direction). A mollassic series of conglomerates, sandstones, marls and marly limestones with lignite horizons dates from Middle Eocene - Oligocene and probably up to the base of Miocene and it has been formed in the Xanthi-Komotini and Evros Delta (Alexandroupolis) basins. Neogene and Quaternary sediments filled all the basins in Eastern Macedonia and Thrace (Northern Greece).

3.1 The Strymon Basin

The basin of Strymon is a typical post-orogenic graben, which is still active. It has been formed between the Serbomacedonian massif (SRB) on the West and the Rhodope massif on the East. The eastern margin of this basin is composed of marbles, gneisses and mica schists. The Vrondou granitic complex dated between 28 and 32 Ma (Marakis, 1969; Durr et al., 1978; Kolocotroni, 1992) intrudes these metamorphic rocks of the Rhodope massif. The SRB massif (on the West) consists of schists, leucocratic, augen and migmatic gneisses, amphibolites and marbles (lower unit). Late Paleozoic, Cretaceous and Paleogene granitoid bodies intruded into the SRB massif

(Kilias et al., 1999). The total thickness of the Neogene and Quaternary sediments at the center of the basin is estimated to be close to 4000 m. Various depositional palaoenvironments (continental, fluvial, fluviolacustrine, lacustrine-marshly, marine, brackish, deltaic) were created during the 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, siltstones, sandstones, dark brown marls, lignite layers, petroliferous limestones), 700-800 m Pliocene sediments (layers of evaporates, conglomerates, travertines, marls, red clays, sandstones, siltstones, limestones, lignites) and 900-1000 m of Pleistocene sediments (alternations of shales, sands, clays, sandstones, marls, conglomerates and limestones) (Lalechos, 1986; P.P.C., 1988). In the wider area of the Strymon basin the principal faults are oriented in NNW-SSE, NNE-SSW to NE-SW and WNW-ESE to W-E directions. Small volcanic edifices (probably alterated rhyolites) outcrop at the margins of the Strymon basin (Strymoniko, Sitsi-Kamen) associated with the extension tectonics of the region.

The geothermal conditions in the Strymon basin are favorable as a result of the active extension tectonics and the increased heat flow. Tertiary granitoids of Vrondou and Pangeon increased the regional heat flow. In addition, the large, deep and "open" faults of the basin are favorable for the uprising of the geothermal fluids at relatively shallow and exploitable depths or at surface. The general geological settings are favorable for the formation of geothermal field, as: (a) the existence of conglomerates and breccias on the top of the basement and as interbedded strata, b) the presence of an impermeable cap consisting of Neogene clayey and marly sediments and (c) the water circulation intro the permeable sediments and the fractured crystalline rocks supplying continually the reservoir (Arvanitis, 2003).

The Strymon basin is of primary geothermal interest containing several geothermal fields (fields of Therma – Nigrita, Sidirokastro, Lithotopos – Iraklia, Agistro and Ivira – Achinos – Mavrothalassa) and being one of the largest geothermal regions in Greece with almost the half of direct use installed capacity of the country (Karydakis et al., 2005). The temperature of the waters ranges from 40 to 74^{o}C and they come from relatively shallow depths (50-650 m). The geothermal anomaly occurs mainly to deep fault systems which are normal and strike-slip structures. The majority of the waters are classified as Na-HCO_3 type with T.D.S. 0.3-2.5 g/l (low salinity). Furthermore, the waters of the Nigrita field are rich in CO_2 (about 3.7 kg/m^3 water). The exploitation of geothermal energy is limited to greenhouses heating (Nigrita and Sidirokastro), balneology and bathing pools (Nigrita, Sidirokastro, Agistro), culture of the microalga Spirulina (Nigrita) and subsurface heating for asparagus cultivation (Nigrita). In the areas of Lithotopos – Iraklia and Ivira – Achinos the geothermal research is still ongoing (some interesting exploration boreholes have been drilled).

In the central part of the Strymon basin three deep exploration oil boreholes (STR-1, STR-2 and STR-3 at depths of 3651, 2678 and 3144 m respectively) were drilled.

In borehole STR-1 the average geothermal gradient is 31^{o}C/km and the temperatures of 57, 75, 95, 106 and 135 ^{o}C were measured at depths of 1209, 1752, 2505, 2884 and 3651 m correspondingly (P.P.C., 1988; S.P.E.G., 1982b). The lithostratigraphy of this well is: 0-870 m Pleistocene deposits, 870-1711 m Pliocene sediments and 1711-3651 m Miocene formations. The values of the thermal gradient are calculated to be 3.60^{o}C/100 m at 1700 m, 3.25^{o}C/100 m at 2200 m, 3.0^{o}C/100 m at 3000 m and 2.96^{o}C/100 m at 3650 m (P.P.C., 1988).

In borehole STR-2 the temperatures of 59 and 89^{o}C were registered at 1506 and 2678 m respectively. Boreholes STR-1 and STR-2 suggest the existence of a good reservoir within the Miocene sediments of the basin. For these wells good to very good porosity (18-33%) and permeability have been determined for various horizons up to depth of 1500 m.

Borehole STR-3 has a depth of 3144 m and the measured temperatures are 64 and 96^{o}C at 1910 and 3144 m correspondingly (P.P.C., 1988).

The basement and the deeper Neogene reservoirs of the basin preserved fossil saline thermal waters and brines of sedimentary marine origin (B.R.G.M. and I.G.M.E., 1982; Shterev et al., 1995). The geothermal gradient for the Strymon basin has been estimated to fluctuate from 25 to 36^{o}C/km at depths over than 2000 m (P.P.C., 1988).

A new very promising area has been explored during 2003-2006 in the coastal zone of the Strymonikos Gulf (western part of Prefecture of Kavala). 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 tectonic uplift (horst) close to the estuary of the Strymon River. According to Lalechos (1986) during Miocene there was no connection between a lake prevailed extended to continental basin and the sea of 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 borehole APOLLONIA-1 (AP-1) drilled in the Strymonikos Gulf indicating that during the Pliocene a fault had separated the continental area of Strymon and the Orfanos Gulf (Lalechos, 1986). In the eastern part of the coastal zone of the Strymonikos Gulf and particularly in the Akropotamos area six production geothermal wells were drilled by I.G.M.E. at depths of 180-545 m identifying bicarbonate fluids with temperatures of 51-90^{o}C at 275-515 m. In general, the thermal waters of this new field are rich in CO_2 with artesian flow rates. The geothermal research is still ongoing.

3.2 The Nestos Delta Basin

The Nestos Delta basin lies East of the Kavala City (between E. Macedonia and Thrace) where the Delta of the Nestos River has been formed covering an area of 450 km^2 (onshore part of the basin) with an axis in ENE-WSW direction (the offshore extension of this basin is known as "the Prinos basin"). It is separated from the Xanthi-Komotini basin by the Avdira-Fanari ridge (horst), which is composed of the metamorphosed rocks. The basin is bounded by two major faults in the N70^o and N160^o directions. According to Chiotis (1993) the formation of the Nestos Delta – Prinos basin is ascribed to the NE-SW extensional tectonics associated with a 12 km displacement along the Kavala-Xanthi-Komotini dextral strike-slip fault.

The basement of the area consists of metamorphic rocks of the Rhodope massif (mainly gneisses, amphibolites and marbles) and it has been multiply deformed and metamorphosed during several tectonic episodes. From geophysical and well explorations it is known that on the metamorphic basement of this area there are unconformable sediments of Miocene (marls, sandstones, siltstones, lignites, clays, conglomerates and anydrites) lagoon facies (Lalechos, 1986). The typical stratigraphic column for the basin consists of 800-900 m of Plio-Quaternary sediments at the upper part and 700-900 m of Miocene sediments in the lower parts (P.P.C., 1988). The Nestos sedimentary basin started its formation at the end of the Lower Miocene (Serravalian), after the main compressive phase of Eocene age. Sedimentation began with clastic – deltaic continental deposits alternating generally with fine-grained sandstones, mudstones and argillites. These were followed by conglomerates with intercalation of lignite (Middle – Upper Miocene). During the Upper Miocene the sedimentation continued with an evaporitic sequence consisting of anhydrites alternating with thin layers of sandstones, clays and marls (Proedrou, 1979). The Plio-Quaternary sediments are characterized by deltaic deposits lying unconformably over the previous series. These formations are composed of loose sandstones and clays at the basin margins and marine and lacustrine sediments in the central part of the basin. The total thickness of this sedimentary sequence is about 3500-4000 m (Lalechos and Savoyat, 1979).

In the region, a first extensional phase (Oligocene) created a first basin trending approximately N50^o. This structure was dissected by successive extensional faults about N120-140^o (Lyberis, 1985; Mercier at al., 1989). During Quaternary time, a new extensional regime with N-S tensional direction enhanced the present morphology and activated faults principally in the N70^o direction.

Two significant low enthalpy geothermal fields are located in the Nestos Delta basin: (a) the geothermal field of Neo Erasmio – Magana lies at the eastern edge of the Nestos basin and west of the Avdira horst with water temperatures ranging from 40 to 65^{o}C and (b) the field of Eratino - Chrysoupolis on the western side of the Nestos River.

The geothermal field of Neo Erasmio – Magana is a characteristic example of low enthalpy field where the stratified aquifers are supplied by an active fault system that affects the substratum of the migmatitic gneisses. The geothermal reservoir is situated at depths between 200 and 400 m within the basal part of the post-alpine sedimentary sequence and mainly at the top of the metamorphic basement. The values of the geothermal gradient are very high (up to 25^{o}C/100 m). The thermal fluids rise through NNW-SSE trending major fault system in the area of the Neo Erasmio village from a deeper reservoir within the metamorphic basement. During their ascent the thermal fluids enter the Neogene conglomerates and the Paleogene sediments, which act as confined reservoirs. So, the geothermal fluids have a lateral leakage towards the permeable formations causing an extension of the thermal anomaly in E-W direction. The water temperatures range from 40 to 65^{o}C. The waters with T.D.S. values between 0.57 and 10.1 g/l are classified into two main categories: Na-CI and Na-HCO_3CI waters (Kolios et al., 2005).

An important geothermal anomaly has been discovered in a 40 km^2 area on the west side of the Nestos River delta (Eratino – Chrysoupolis area). The area is characterized by an elevated geothermal gradient, 3-4 times higher than the normal one. The anomalous area is well concealed by a thick (up to 550 m) impermeable sedimentary series and the geothermal potential is disguised by shallow aquifers with fresh meteoric superficial waters. Generally, the basement is characterized by high temperature creating high thermal gradient due to the granitic intrusions into the Rhodope Massif (Fytikas and Kolios, 1992; Kolios et al., 2005). From the reflectance index of vitrinite in organic material in drilling cores, it is calculated that the region was heated to a maximum temperature of 270^{o}C during the Serravalian because of the granitic intrusions into the sedimentary basin (Chiotis, 1985). The geothermal anomaly is elongated along N140^o direction and it coincides with the Eratino horst which is a tectonic uplift of the basement southeast of the Eratino village. It appears furthermore that the anomaly is associated with an important N140^o fault system that affects the substratum. On the basis of the seismic and gravimetric data the basement was revealed at depth of about 700 m in this horst. The entire area shows an intense geothermal anomaly with gradient values mainly in the range 80-100^{o}C/km. The temperatures of 60.9^{o}C at 430 m and 69.7^{o}C at 530 m were recorded in exploration boreholes (Fytikas and Kolios, 1992). On the basis of drilling data an interesting geothermal reservoir containing thermal waters at temperature of 75^{o}C is located at 555–655 m within calcarenitic formation consisting of limestones, sandstones (oolitic and micritic limestones and calcareous and gritty horizons) and intercalations of clays and marls. The geothermal waters in the Eratino geothermal field belong to the Na-CI group. All these thermal waters have deep circulation and they are derived from the transitional zone between the relatively shallow geothermal reservoir at 550 m and its cover. Their salinity is relatively high (8.2–15.2 g/l) due to enrichment with ions from marine – brackish sediments in which the waters circulated (Kolios et al., 2005).

Three deep oil exploration boreholes (N-1, N-2 and N-3 at depths of 3159, 3970 and 3851 m respectively) were drilled during the period 1976-1978 west of the Nestos River Delta and out of the main geothermally anomalous area.

In borehole N-1, with a depth of 3159 m, the temperatures of 55^{o}C, 85^{o}C and 115^{o}C were measured at 1096, 2400 and 2970 m correspondingly (S.P.E.G., 1982b; P.P.C., 1988). This well has drilled Plio-Quaternary sediments (0-779 m) and Miocene formations (779-3120 m). The Upper Miocene (779-1194 m) is characterized by the "evaporitic zone". The basement (marbles, chlorite schists, quartzites) is found at 3120 m. The maximum temperature is 126.4^{o}C and it was registered at depth of 3156 m. The average value of the geothermal gradient for this borehole is estimated to be 3.48^{o}C/100 m. By the temperature profile of this well it has proved that the geothermal gradient is higher into the Lower Miocene continental sediments and one interesting aquifer is located at 2374-2400 m with porosity reaching 20%. In N-1 the values of 9-15% porosity and 7-15 mD permeability were measured between 1781 and 1786 m depth. Low values of these physical characteristics and especially 4-7% porosity and 0.03-0.05 mD permeability were recorded between 1940 and 1949 m (S.P.E.G., 1982a).

Borehole N-2 of 3970 m depth has drilled Plio-Quaternary (0-953 m) and Miocene (953-3958 m) sediments (953-1545 m: "evaporitic zone"). The Lower-Middle Miocene formations (1545-3958 m) consisting of alternations of sandstones, siltstones and clays indicate continental – deltaic palaoenvironment. The crystalline basement (at 3958 m) is mainly composed of amphibolitic and chlorite schists with a few intercalations of quartzites and marbles. The temperatures of 93, 102, 127 and 164^{o}C were registered at 2370, 2774, 3104 and 3960 m respectively in well N-2 (S.P.E.G., 1982b; P.P.C., 1988). The downhole temperature logging has showed normal increase up to 2400

m. In the deeper Lower Miocene formations the geothermal gradient is significant indicating a crystalline substratum with temperature of 180^{o}C and relatively low thermal conductivity into the overlying Lower Miocene sediments. Therefore, the temperature of 178^{o}C at 4000 m depth might be registered within exploration borehole N-2. The average geothermal gradient is estimated to be 41^{o}C/km. In N-2 the values of 8-9% porosity and 0.3-1.9 mD permeability were measured between 3080 and 3088 m (S.P.E.G., 1982a).

Oil exploration well N-3 has a depth of 3851 m and its lithostratigraphic column is: 0-830 m Plio-Quaternary sediments, 830-3838.5 m Miocene formations (830-1212 m: "evaporatic zone") and 3838.5-3851 m crystalline basement (chlorite schists with minor quartzites). The temperatures of 56, 105, 138 and 160^{o}C were recorded at depths of 1047, 2482, 3601 and 3851 m respectively. The values of the thermal gradient are calculated to be ~3.50^{o}C/100 m for depth <1000 m, 3.50^{o}C/100 m at 1047 m, 3.40^{o}C/100 m at 2482 m, 3.30^{o}C/100 m at 3601 m and 3.60^{o}C/100 m at 3851 m. The thermal profile for this well shows a normal and constant rise of the temperature down to 2500 m while between 2500 and 3600 m the geothermal gradient is higher. Within the base of the sedimentary sequence, where the basal conglomerates dominate, the geothermal gradient has a significant increase and the temperature of 160^{o}C was recorded in the substratum. This high value of temperature indicates the thermal conditions of the metamorphic basement and it is encouraging for the presence of medium enthalpy geothermal fluids in the area not excluding the high enthalpy ones.

The detailed study of the thermal profiles of deep oil boreholes N-1, N-2 and N-3 on the western side of the Nestos River Delta (out of the main geothermal area) has showed that the geothermal gradient is normal (3.0^{o}C/100 m) within the Plio-Quaternary and Upper Miocene sediments and increases considerably in the Lower Miocene formations (N1: 4.7^{o}C/100 m, N2: 5.6^{o}C/100 and N3: 4.3^{o}C/100 m). This happens because of the existence of the Lower Miocene formations with low thermal conductivity that they decrease the heat flow from the crystalline basement with thermal anomaly towards the surface trapping the heat in the basement. Considering the thermal conditions of the substratum, the research and detection of medium enthalpy geothermal fluids in areas where the basement is uplifted and the impermeable Lower Miocene formations are thinned or absent is the ideal target for the geothermal exploration.

The only geothermal exploration well of intermediate depth (N-1G) was drilled in the zone of the highest thermal gradient at the center of the Eratino geothermal field (in the vicinity of the Eratino village, West of the Nestos River). The temperature of 122^{o}C was measured at 1377 m (Sotiropoulos, 1989), which corresponds to an average gradient of 78^{o}C/km. It showed that: (a) the upper sedimentary sequence consists of 550 m of clays, marls, sands and conglomerates constituting the impermeable cover of a geothermal reservoir located just below, at 550 – 650 m depths. In this part, the thermal gradient is high (up to 120^{o}C/km). (b) The reservoir formation consists mainly of sandstones, oolitic limestones, micro-conglomerates and cemented gravels (calcarenitic formation) alternating with thin impermeable clay intercalations. The total thickness of these aquifers is estimated to be approximately 40 m containing geothermal fluids at 70^{o}C heated probably by conduction. (c) The deepest Neogene sediments (650-760 m) consist mainly of basal conglomerates, which are impermeable due to their argillaceous matrix. (d) The crystalline basement (below 760 m) is intensively fractured and it is composed of gneisses and amphibolites with minor quartzites and mica schists. The permeability is low due to hydrothermal alteration and fillings of calcite and clay

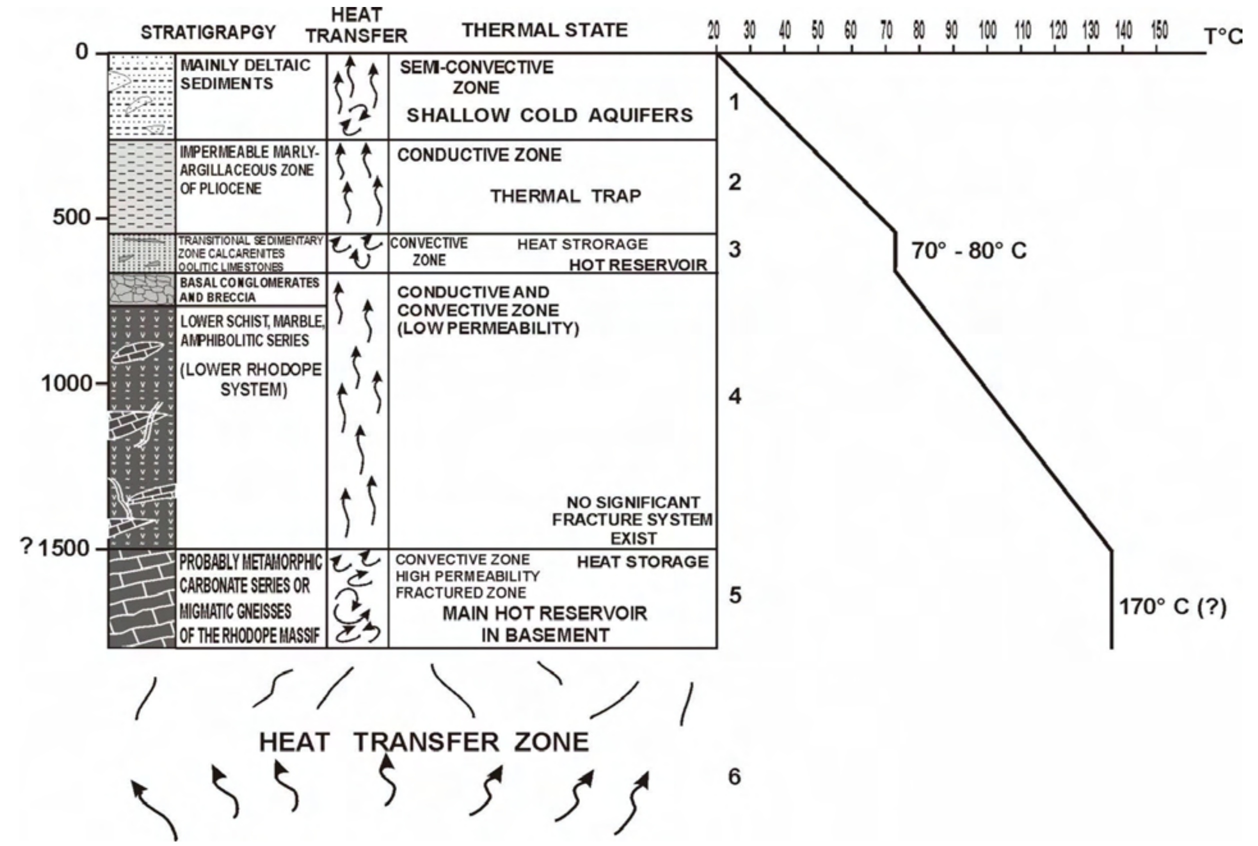

Figure 2: The geothermal model in the Nestos Delta basin (Fytikas and Kolios, 1992)

minerals. The Miocene sediments are absent in this area of the main geothermal interest.

On the western side of the sedimentary basin of the Nestos River two main hydrothermal targets exist (Figure 2): (a) the permeable zone in the lowest part of the sedimentary sequence (formation No.3) and (b) the fractured and permeable (carbonate?) parts of the metamorphic basement (formation No.5). Low enthalpy (70°C) geothermal fluids occur at 600 m depth (formation No.3) and medium enthalpy ones probably exist into the basement (formation No.5). These fluids have an equilibrium temperature of 150-180°C and probably constitute an important and extensive reservoir within the substratum. The existence of such a reservoir is necessary to justify the extended thermal anomaly covering an area of about 40 km^2 in a region without active but only fossil magmatism. The geology and lithology of the basement together with the high values of the geothermal gradient indicate that: (a) the crystalline series acts initially as a cap for the hot hydrothermal system and (b) this reservoir is located at a depth of 1500-1800 m with a temperature in order of 150-180°C and should be the source, which heats the overlying formations and the secondary reservoir by conduction. No well-defined fracture zone was encountered by borehole N-1G, at the center of the area of high thermal gradient, except for some small fractures in the altered lower marble – amphibolitic series (formation No.4) which are favorable for heat transfer (both conductive and convective) towards the sedimentary (secondary) reservoir (formation No.3).

3.3 The Xanthi - Komotini Basin

The Xanthi – Komotini basin lies east of the Xanthi city covering an area of about 1600 km^2 between the Rhodope Mounts and the Aegean Sea in Central Thrace. This basin mainly made up of clastic sediments is of Eocene – Quaternary age and it reaches its maximum depth at the foot of the Rhodope mountain chain and its minimum in the vicinity of the coast, where the Nea Kessani geothermal field is located.

Geologically the area belongs to the Rhodope massif. The crystalline basement consists of gneisses, mica schists, marbles and amphibolites (Kolios, 1993). The total thickness of the sediments reaches 3500 m at places. The typical stratigraphic column for this basin is: 300-400 m Plio-Pleistocene deposits (sands, clays, gravels/micro-conglomerates), 700-900 m Miocene sediments (alternations of clays, marls and siltstones) and 500-600 m Eocene-Oligocene formations at the deeper parts.

The Nea Kessani geothermal field is a very important low enthalpy system in Greece. The maximum temperature registered within the wells is 82°C. The main hot reservoir is located at shallow depth (150-400 m) with temperatures ranging from 75 to 80°C. It is made up of Eocene – Oligocene clastic sediments overlain by a cap-rock of Oligocene flysch formations, Pliocene lacustrine sediments and Quaternary alluvial deposits. Sometimes, the alluvial deposits host aquifers with cold superficial waters. The geothermal anomaly occurs mainly due to fault systems trending WSW-ENE and NNW-SSE. The waters are of the Na-CI/?CO_3 and Na-HCO_3 types. The hydrothermal system is characterized by rise of thermal fluids from depth. The fluids rise through a major fault system or along the intersection of the SSE-NNW and ENE-WSW fault systems from a deep reservoir. This deeper reservoir is probably made up of marbles of the Rhodope metamorphic basement. During their ascent, the thermal fluids enter the arkosic aquifer, which acts as a secondary shallow confined reservoir. There is little or no interconnection between the thermal reservoir and either the deep or shallow aquifers of the cap-rock. Most of the hot water is cooled conductively as it flows through the arkosic reservoir towards the marginal parts of the field. The temperature distribution is homogeneous vertically within the reservoir. The water rising from depth probably undergoes significant chemical modifications during its ascent towards the surface because of its high CO_2 content. Some changes in the pressure could be due to the changes in the viscosity and the density of the fluids associated with their temperature (Kolios, 1993; Grassi et al., 1996; Kolios et al., 2005).

Deep oil borehole KOM-1 with a depth of 1736 m was drilled in the central part of the Xanthi - Komotini basin. The temperatures of 60 and 72°C were measured at 1300 and 1736 m (P.P.C., 1988) indicating a slight possibility for the detection of medium enthalpy geothermal fluids in the central part of the Xanthi-Komotini basin.

The presence of the Nea Kessani low enthalpy geothermal field close to the southwestern margin of the basin indicates the probable existence of medium enthalpy geothermal fluids within the deeper reservoir probably made up of marbles of the Rhodope Massif. This reservoir might be the target of a systematic geothermal exploration for the detection of medium enthalpy resources in the area.

3.4 The Evros Delta (Alexandroupolis) Basin

The Evros Delta basin constitutes the southern part of the wider Neogene - Quaternary basin of Orestiada - Alexandroupolis close to the borders with Turkey and Bulgaria. It is estimated to occupy an area of approximately 2000 km^2 all within the Western Thrace region (P.P.C., 1988).

The huge sedimentary basin of the Evros Delta covers an area of 700 km^2. The Evros River and its tributaries flow within the basin which extends within Turkey as well.

The basin occasionally reaches depths of 3500 to 4000 m and it is bounded by major faults. The Paleogene – Eocene sediments have been deposited unconformably upon the Mesozoic formations or to the west upon the gneisses, amphibolites and ophiolites of the Rhodope massif. The marine Paleogene sediments (average thickness of about 2000 m) consist of sandstones, marls, limestones, polygenic volcanic breccias, tuffs and siltstones. The Neogene and Quaternary sediments (maximum thickness of 1500 m) consist of clays, siltstones, sandstones, lignite layers and in the upper section of the sedimentary sequence sands, sandstones and clays exist. The beginning of the marine Tertiary transgression in the Evros basin is suggested during the Middle Eocene (Lutetian).

Volcanic activity developed in the wider area during the Oligocene – Lower Miocene (33 to 23 Ma). In the region of Alexandroupolis and Soufli, the volcanic products mainly outcrop between the Evros River on the East and the Rhodope Massif on the North showing a calc-alkaline chemical character. Volcanics are mainly distributed to a NE-SW trending strip matching with one of the most important regional tectonic trends. The volcanic products consist of pyroclastics, tuffs and tuffites alternated with sediments of Priabonian and Oligocene age. Ignimbrites occur in the Dadia area. Domes and lava flows outcrop in the external part of the basin. Volcanic products have been affected by alteration processes. Two main fault systems in NNW-SSE and NNE-SSW directions controlled the spatial evolution of sedimentation and volcanism.

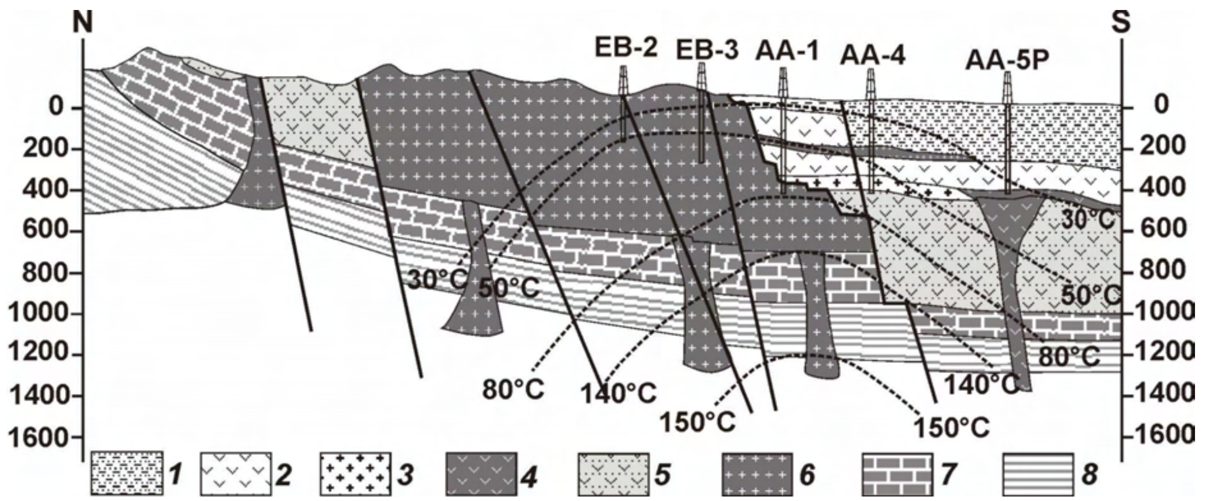

Figure 3: The hydrothermal model of the Aristino geothermal field [1: Red sands, clayey sands, gravels, pebbles, cobbles (Pleistocene), 2: Clays, pebbles and cobbles from volcanics (Miocene), 3: Alternations of sands, marls and fine-grained sandstones, acid tuffs (Oligocene), 4: Rhyolites (Oligocene), 5: Calcarenites of Nipsa, tuffs and tuffites (Upper Eocene), 6: Andesites (domes) (Upper Eocene), 7: Nummulitic limestones (Middle Eocene), 8: Clayey-marly series (Middle Eocene)] **(Kolios et al., 2005)**

The thermal springs of Traianoupolis with water temperature at 50^{o}C indicate initially the geothermal interest in the Evros Delta basin. The geothermal interest in the area is associated with the favorable stratigraphy, the active tectonics with faults in the N70^{o} and N160^{o} directions, the uprising of the isothermal curves towards to the surface, the alternations of the volcanics with the pyroclastites, the volcanic activity and the magmatic bodies related to heat production.

The geothermal field of Aristino covering an area of about 30 km^2 is located west of the Traianoupolis thermal springs. The geothermal anomaly is located at the places where the magmatic bodies and the active faults occur (Figure 3) and it seems to be developed gradually northwards. The hydrothermal aquifers are located in the altered volcanic formations and pyroclastites of high secondary permeability. One geothermal reservoir with water temperatures T>86^{o}C are located at about 360 m depth within the volcanic products (pyroclastites). Another hydraulic system with water temperature of 50^{o}C is developed at depths of 200 m in the area of the primary geothermal interest. This is a case of superficial hydraulic system with local geothermal interest located NE of the Aristino village and heated by conduction. The recharge area of the hydrothermal system in the Aristino field is likely placed in the Rhodope Mounts northwards and the Aegean Sea southwards. Possibly this hydrothermal aquifer is supplied through faults by the underlying deeper reservoir containing higher temperature waters. Southwards and at the deeper levels of the basin, geothermal reservoirs containing waters with temperatures up to 32^{o}C are developed in the base of the Neogene sediments at depths >350 m. The geothermal waters in the Aristino field are of the Na-CI type in chemical composition. Their TDS values range from 4.3 to 10.5 g/l and their Ca^{2+} and SO_4^{2-} contents are relatively high. The thermal waters from the springs of Traianoupolis belong to the same type. The chemical constituents of samples suggest that these waters may result from mixing between meteoric and sea water. Based on stable isotope contents the contribution of marine sources in the deep geothermal system is ~23%. The isotopic data also suggests that the meteoric component of the mixtures is old water (Poutoukis and Dotsika, 1998). The waters coming from the upper aquifer zone (~200 m) have a similar chemical composition with the ones derived from the deeper aquifer (>350 m). The hot waters which come from a local shallow reservoir heated by conduction NE of the Aristino village are of the Na-SO_4 type; they are of meteoric origin and their mineralization is due to hydrolysis of argillo-siliceous minerals (Kolios et al., 2005). The Na/K, K/Mg, Li/Mg and Na/Li geothermometers agree with the isotope data attributing a temperature of 130-140^{o}C to the deep geothermal waters of Aristino and Traianoupolis area (Poutoukis and Dotsika, 1998).

Deep oil exploration boreholes EVROS-1, DELTA-1, DEV-1, DEV-2, and DEV-3 were drilled in the Evros Delta basin. Borehole EVROS-1 of 2658 m was drilled during 1956-57 for defining the Neogene sediments of the area. In order to study the sedimentary sequence another exploration well, DELTA-1, was constructed during 1962-63 at depth of 3548 m. Oil exploration boreholes DEV-1, DEV-2 and DEV-3 were drilled in the Evros Delta basin during 1981-1982.

Borehole DEV-1 has a depth of 4229 m. The stratigraphic column of this well is: 0-650 m Plio-Quaternary deposits (alternations of sands, clays and sandstones), 650-1153 m Miocene sediments (clays, siltstones, sandstones, dolomites with layers of lignites), 1153-3270 m Oligocene - Eocene formations (limestones, alternations of marls, sandstones and siltstones, tuffs, polygenic conglomerates, polygenic and volcanic breccias) and 3270-4229 m basement (quartzitic, dioritic porphyres) (S.P.E.G., 1982a,b; Lalechos, 1986). The temperatures of 68, 96, 136 and 146^{o}C were measured at 1600, 2740, 3975 and 4229 m respectively (S.P.E.G., 1982a,b).

The stratigraphy of borehole DEV-2 drilled to a total depth of 3213 m was: 0-600 m Plio-Quaternary deposits (sandstones, clays, gravels), 600-1650 m Miocene sediments (alternations of clays, clayey-sandstones and conglomerates with layers of lignite), 1650-2980 m

Oligocene formations (alternations of clays, sandstones, conglomerates and siltstones), 2980-3148 m Eocene formations (alternations of limestones, conglomerates, siltstones and marls) and 3148-3213 m Substratum (diabases). The temperatures of 81, 90 and 100°C were registered at 2000, 2500 and 3000 m correspondingly.

Exploration oil borehole DEV-3 has a depth of 2860 m. The temperatures of 62.7, 104 and 108°C (Horner corrected) were recorded at depths of 1520, 2650 and 2860 m respectively. The values of geothermal gradient were calculated to be 2.9°C/100 m for depth <1500 m, 2.8°C/100 m at 1520 m, 3.2°C/100 m at 2620 m and 3.1°C/100 m at 2860 m. In this borehole for the upper 1000 m the porosity of the interesting horizons was found to vary between 17 and 31% (P.P.C., 1988).

North of the Evros River Delta, exploration wells ARDANION-1 (ARD-1) and BOUGIONOU-1 (BOUG-1) were drilled during 1955-56 and 1961 at depths of 2323 and 1745 m correspondingly. In ARD-1 the temperature of 98°C was measured at 2322 m (S.P.E.G., 1982b).

4. GEOTHERMAL CONDITIONS IN THE SAMOTHRACE ISLAND

The island of Samothrace, in the NE Aegean Sea, belongs to the Circum-Rhodope Belt (Kaufmann et al., 1976), a series of Triassic-Jurassic continental margin sedimentary and volcanic rocks outboard of the crystalline Serbomacedonian and Rhodope Massifs. The island consists of the following main geological units (Kotopouli at al., 1989; Tsikouras and Hatzipanagiotou, 1995): (a) The "Basement Unit" which is the stratigraphically lowest formation [a variety of low-grade metamorphic rocks (meta-conglomerates and argillaceous turbidites and slates with minor quartzites, limestones, slates, breccias and metavolcanic rocks)]. (b) The "Ophiolite Unit" [cumulate gabbros, non-cumulate gabbros, diorites, diabases and basalts]. All these rock-types are cut locally by doleritic intrusions. In several places the contact between the ophiolites and the basement appears to be normal with steeply dipping instrusive contacts suggesting an autochthonous or at least parautochthonous origin. (c) Clastic series. The "Ophiolitic Unit" is uncomformably covered by neritic, clastic sedimentary rocks of Eocene age (sandstones, shales). (d) A large Cenozoic granitic intrusion occupying the central part of the island has caused contact metamorphism in the ophiolites and the basement. (e) Two series of Cenozoic volcanic rocks of acid-intermediate composition occur in the peripherical areas of Samothrace. (f) Neogene and Quaternary deposits (Neogene conglomerates, sandstones, limestones and marls with total thickness reaching 150 m and Quaternary talus, sands and loams). The main neotectonic structures that dominate the mountainous island of Samothrace are: (a) the southeastern coastal fault with typical morphotectonic structures (triangular facet, high angle slopes) which is a segment of the North Anatolian-North Aegean Trough fault zone system and (b) an oblique slip-normal fault extended almost parallel to the north coast of the island for almost 14 km and related with thermal manifestations. The total neotectonic fault pattern of Samothrace fits well enough the transtensional tectonic model (Pavlides et al., 2005).

Many hot springs with water temperatures of 35-58°C occur in Samothrace especially in the Therma and Psarotherma areas. The hydrothermal system is characterized by rise of thermal fluids from depth through deep fault systems or along the intersection of faults systems from a deep reservoir. Three shallow wells S-1, S-2 and S-3 at depths of 120, 120 and 40 m respectively were drilled within the thermal area near existing spas and yielding a high flow rate of fluids and water temperature up to 100°C (Angelidis, 1998). The thermal waters are of the Na-CI type with high T.D.S. values (up to 31 g/l) and rich in Na^+, CI^-, Ca^{2+}, Li^+, Sr^{2+}, SiO_2, B, Br^- and I^- contents. With the aid of the chemical geothermometers of SiO_2, Na/K, Na-K-Ca and Na-Li the deep temperature is estimated to be 140 - 250°C. Moreover, temperatures >200°C are estimated by the use of the isotopic $O^{18}(SO_4^{2-}$-$H_2O)$ geothermometer (Dotsika, 1991). The acceptance of these high temperatures can be explained by the favorable geological and tectonic settings of the island. Therefore, the use of the chemical and isotope geothermometers (Dotsika, 1991) classifies the Therma area of the Samothrace Isl. in the "medium-high enthalpy" geothermal fields of Greece, providing a very intense and remarkable geothermal interest to this island. The presence of waters with temperatures of 100°C at 40 m depth strengthens the hope for this geothermal situation in the area.

5. UTILIZATION OF PROSPECTIVE MEDIUM ENTHALPY GEOTHERMAL FLUIDS FOR POWER GENERATION AND HEAT IN NORTHEASTERN GREECE

Based on geological and geothermal data, the most suitable areas for power generation by the utilization of the binary cycle systems are the basins of Nestos Delta and Evros Delta as well as the Samothrace Island. This choice is based on the economic criteria of each area and the possibilities for the use of the thermal energy during a year.

From technico-economical side, the most suitable area is considered the Nestos Delta basin for the following reasons:
(a) The temperature of 122°C was already registered at depth of 1377 m and significant reservoirs are expected at greater depths with satisfactory discharges of fluids.
(b) The area is located close to the sea as well as next to springs and river whence water for cooling could be taken.
(c) There is an area available for the installation of the binary cycle plant for electricity generation.
(d) The area is flat or plain where the agriculture is intensive.
(e) There are aquaculture ponds (fish farms) which can use the geothermal energy for heating during the winter.
(f) In the same area there is an airport (the airport of Kavala) with needs for heating and cooling all the year round. The geothermal energy can be also used in the neighbouring organized industrial area of Kavala.
(g) Considering pumping flow rate 50 kg/s of geothermal fluids with temperature of 150°C, the total (thermal and power) capacity is estimated at 25 MWt. By the use of binary cycle the power capacity is calculated to be 4 MWe and the annual electricity can reach 28 GWh with load factor 80%. The annual revenues from power sales come to 2,000,000 € considering the selling price of 74 €/MWh (Table 1). The increased need for electric energy in Northeastern Greece and the legally fixed price per KWh make this enterprise attractive.
(h) The significant gains for the area will come along from the utilization of the thermal energy in direct heat applications as 20 ha greenhouses and 120 ha with soil heating for off-season asparagus production (asparagus is cultivated widely in the area) and in parallel in the anti-frost protection/heating of aquaculture ponds along the coastal zone (Table 1). In addition, the thermal energy can be used in the industrial area for space heating and dehydration of many vegetable products or fruits during the summer with parallel storage of energy within low enthalpy reservoirs.

Table 1: Cogeneration of heat and power from probable geothermal fluids in Eastern Macedonia and Thrace

Expected fluid temperature	150ºC at depths 1600-1700 m
Expected flow rate	50 kg/s
Power capacity	4 MWe with binary cycle (Rankine or Kalina®)
Residual thermal capacity	21 MWt
Construction cost of power plant*	10 M€ (~2500 €/kW installed capacity)
Annual produced electricity	28 GWh (load factor 80%)
Annual revenues from power sales	2 M€ (74 €/MWh)
Geothermally heated greenhouses	20 ha covered area
Soil heating for off-season asparagus production	120 ha

* *It does not include the exploration cost and the cost of drilling of production and reinjection wells.*

According to Mendrinos and Karytsas (2005) the probable geothermal potential of the sedimentary formations at depths 1-3 km suitable for power generation in the basins of Strymon, Nestos Delta, Xanthi-Komotini and Evros is estimated to be 4750 MWt for temperatures of 90-120^{o}C (on the basis of storage heat of these formations with a recovery degree of 25% in 20 years). The corresponding potential for electricity generation with Rankine cycle plants estimated at about 400 MWe (Mendrinos and Karytsas, 2005).

Therefore, the medium enthalpy geothermal energy is very attractive in Northern Greece because:
(a) Energy centers could be established in the land.
(b) The geothermal energy is available for 24 hours (day and night) with significant capabilities and it doesn't be influenced by weather changes as the other renewable energy sources (solar, wind).
(c) It also contributes to the development of the modern agriculture which is the main advantage of the area as wells as to the tourism by the use of geothermal fluids in hotels and spas.
(d) In the case of cogeneration of heat and power, geothermal energy becomes particularly attractive having the possibility to exploit water at temperature as low as 30ºC.
(e) The low and medium enthalpy geothermal energy is very important for the contribution of the Renewable Energy Sources to energy balance of Greece.

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