GEOTHERMAL EXPLORATION IN GREECE

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Abstract

This paper provides a comprehensive review of geothermal exploration taken place in Greece and provide an integrated presentation of all geological, geochemical, and geophysical surveys that have been carried out, especially the geothermal areas which are most suitable for geothermal power generation. The examined areas are the islands of the Aegean volcanic arc Milos, Nisyros and Santorini, the North Aegean islands of Miocene volcanism Lesvos and Chios, the island of Samothraki and the basins of Nestos, Xanthi and Alexandroupolis.

Keywords: geothermal exploration; geology; tectonic settings, geological structures, surveys

1. Introduction

The aim of this paper is to provide a review of geothermal exploration in Greece. For this purpose those geothermal areas are considered, which the authors evaluate as most suitable for power generation. The most important of them are the islands of the Aegean volcanic arc Milos, Nisyros and Santorini, the North Aegean islands of Miocene volcanism Lesvos and Chios, the island of Samothraki and the basins of Nestos, Xanthi and Alexandroupolis, the location of which on the map is shown in figure 1.

Geothermal exploration in Greece started in 1970 by the Institute of Geological and Mineral Exploration (IGME). The exploration programme included standard surveys, such as geological, geophysical and geochemical, including recent volcanoes, thermal flow, ground temperature maps, etc. Initially the programme covered areas considered to contain high enthalpy hydrothermal resources, especially in Milos and Nisyros Islands, and was financed by the State and the Public Power Corporation (PPC). Since the 1980's, following the energy crisis, the exploration programme has been extended to low enthalpy fields as well, with priority in northern and central Greece.

The explorations had as a result the detection of low, middle and high enthalpy fields all over the Greek territory and especially in Macedonia and Thrace regions and the Aegean Islands.

In Northern Greece (Eastern Macedonia and Thrace regions) elevated regional heat flow and a large number of low enthalpy geothermal fields were identified with water temperatures of 30-100°C at shallow depths (30-500 m) in the basins of

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Strymon, Nestos Delta, Xanthi-Komotini, Evros and in the island of Samothrace. The geological and tectonic conditions are favourable for the presence of medium enthalpy (T=100-150°C) and perhaps high enthalpy geothermal resources at greater but exploitable depths down to 2-3 km.

Fig. 1: Areas in Greece suitable for geothermal power generation.

2. Milos island

2.1 Geological setting of geothermal relevant structures

Geology and tectonic setting

Milos is a volcanic island located at the Aegean volcanic arc, characterized by quaternary volcanic activity (0.5-1.5 million years old). The latest volcanic activity on the island was estimated by *(Fytikas, 1977)* that occurred about 480.000 years ago, although some recent studies indicate a more recent dating. The geologic setting of the island can be simplified as follows:

- The deeper metamorphic basement comprising green schists (with chlorite) intercepted by vents of quartzite with K-feldspar (adularias) and epidote. The basement outcrops at the south-eastern part of the island at the coast.

- A layer of neogene sediments of 50-180 m thick, which comprises base conglomerate and limestone, and is characterized by very high permeability. This layer outcrops at the southern central part of the island.
- Volcanic tuffs, lahars, or partly to intensely altered tuffs towards kaolin or montmorilonite (argillic alteration)
- Lava domes and lava flows of perlitic structure
- Recent alluvia deposits

According to PPC (*Public Power Corporation, 1986)*, the lava domes and lava flows of Fyriplaka were formed 100.000 years ago, together with the main phreatic craters of the island. The same report also presents a detail chemical, mineralogical and petrologic study of the above geological formations.

Milos is tectonically active with many major earthquakes during the last 100 years, some of them have changed the hydrothermal flow pattern and altered the thermal manifestations. They were all shallow with hypocentres at 5 km depth and all had the pattern characterising magma activity at depth.

The geology of the island and the main surface faults are presented in figure 2.

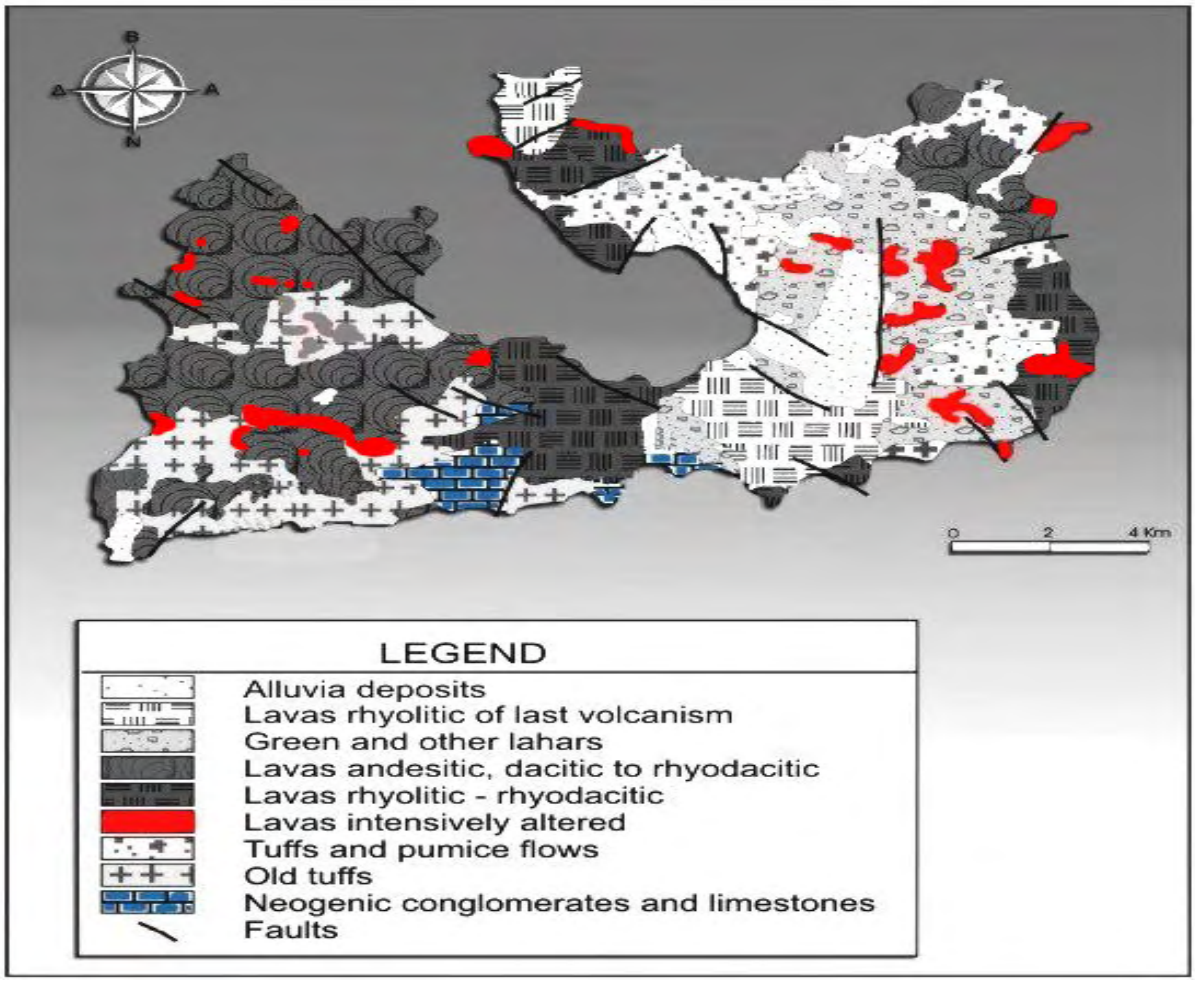


Fig. 2: *Geology and main faults of Milos island* *(adapted from Drakoulis et. al., 2005).*

Temperature and transmissivity range

The five deep wells drilled on the island yield two phase fluids from a liquid dominated reservoir, which exists within the neogene sediments (250°C temperature in well MA1 only) and within the fractures of the metamorphic basement (310-325°C in all five wells). The corresponding transmissivities have been estimated from pressure drawdown tests as 3,2-8,4 Darcy.meters in wells MA1, MZ1, M1 and M3 and as 0,14-2,3 in well M2 (*Mendrinos, 1988*).

2.2 Assessment of reservoir

(Mendrinos and Karytsas, 2006)

Geothermal Exploration Methodology

Geothermal exploration on the Milos island started in 1971 by the Institute of Geological and Mineral Exploration of Greece (IGME) with the following exploration surveys:

- Geological mapping.
- Mapping of thermal manifestations.
- Soil and water sampling and geochemical analysis.
- Thermal gradient mapping by drilling shallow boreholes (50-80m depth) and measuring bottom hole temperature.
- Schlumberger resistivity surveys of the east half of the island carried out by IGME and CGG in 1972 and 1973 respectively.
- Drilling the first two deep wells MA1 and MZ1 in 1975-1976.

The above information was complemented in 1977, by ENEL, which carried out on behalf of the Public Power Corporation of Greece (PPC) the following surveys:

- Volcanologic, hydrogeologic, thermal, stratigraphic and structural features
- Geochemical investigation with samples from hot springs, shallow and deep wells
- Logging and testing deep wells MA1 and MZ1

In 1981 three deep wells M1, M2 and M3 were drilled by the Public Power Corporation of Greece, in Zefyria plain, reaching depths 900-1350 m. The project was supported by the European Commission.

Between 1982 and 1984, a gravity survey and additional DC-Schlumberger resistivity surveys were carried out by the Institute of Geological and Mineral Exploration on behalf of the Public Power Corporation of Greece. These surveys were part of a wider project on Milos geothermal exploration, which was supported by the European Commission, and also included volcanologic, petrologic, mineralogical, tectonic and geomorphologic studies of Milos and nearby islands.

Between 1985 and 1987 the European Commission supported a series of geophysical investigations on the island including MT soundings by 4 European teams (Technical University of Braunschweig, BRGM, University of Edinburgh, and the University of Frankfurt), monitoring of micro earthquakes by RWTH-Aachen, the Institute de Physique du Globe de Paris and BRGM, as well as self potential and magnetic surveys by IGME.

In 1991 CRES estimated the conductive heat flow over the island of Milos, by integrating the temperature gradients near the surface.

During the summers of 1996-1999 sampling and analysis of submarine springs near Milos coast was done by a team of scientists from the National History Museum of London, the National University of Athens, the University of Nottingham, the Scottish Universities Environmental Research Centre, the College of Staten Island, the University of London and the University of Bristol.

Results and experience gained

The geology of the island includes from top to bottom lavas, alluvia deposits, volcanic products (tuffs, hydrothermally altered tuffs, lahars and breccias), neogene sediments and the metamorphic basement (schists). The gravity survey indicated that the top of the basement is located deeper at depths 600-800m around the bay of Milos. The thermal manifestations, as well as geochemical and passive microseismic surveys indicate the presence of an active deep hydrothermal system beneath the east and the south-central-east parts of the island. Geothermal gradients and earlier DC soundings pointed at Zefyria plain, the south-central-east part of Milos and Adamas as the most promising areas for production drilling, area which was further broadened by MT and AAMT soundings.

Passive seismic surveys indicated that the hydrothermal system extends down to 5km through a system of active faults and fracture zones. The magnetic survey, hydrothermal alterations and some geochemical data indicate that the west part of the island is also of geothermal interest, but no deep wells have been drilled there yet.

Drilling with many shallow and five deep wells proved the existence of the following three main types of fluids for geothermal exploration: (a) low enthalpy (up to 100°C) shallow water table in areas of high temperature gradient, (b) 100-250°C water within the neogene sediments in places where it is present at sufficient depth and has enough thickness, and (c) high enthalpy pressurized water of 300-325°C temperature within the faults and fracture zones of the basement at depths between 1-5 km.

2.3 Utilisation

At present, a handful of houses and one hotel use shallow groundwater of 45-60 °C temperature for space heating and for a swimming pool.

3. Santorini island

(Fytikas et al., 1989)

3.1 Geological setting of geothermal relevant structures

Geology

The Santorini archipelago comprises the islands of Thera (Santorini) and Therasia, and the Aspronisi islet and surrounds the circular depression of the Santorini caldera. It was formed during the catastrophic Minoan eruption 3600 years ago. Post-caldera volcanic activity began close to 197 BC and formed the two small islands of Palea Kameni and Nea Kameni located near the centre of the caldera. Most dacitic lava flows of Nea Kameni erupted during the last four centuries and four eruptive periods occurred between 1925 and 1950. The lava flows and pyroclastic deposits of Santorini show typical calc-alkaline compositions, from high-Al basalts to rhyodacites. The volcanic rocks lie on top of the basement consisting of Mesozoic-Cenozoic schists and marbles. Today the thermal springs of Palea Kameni discharge steam-heated seawater, whereas the thermal springs of Thera are fed by steam-heated seawater mixed with groundwater. In addition, in Nea Kameni steaming grounds, are encountered *(Marini et al., 2002).*

The volcanic activity occurred on top of the metamorphic basement that outcrops at the south-eastern part of the island. This basement consists of a phyllitic epimetamorphic series of Mesozoic age. Microcrystalline thick-layered limestones with a total thickness exceeding 600 m overthrusted the phyllites. The age of this formation is Upper Triassic, to Upper Cretaceous.

In the early Quaternary, the first volcanic activity occurred, depositing pyroclastics and lavas which cover the entire range of the typical calc-alkaline suite. The oldest volcanic deposits outcrop in the south-west part of the island, produced by volcanic centres located in the actual southern submarine area. The products of these centres are pyroclastics (tuffs, tuffites, hyaloclastites, scoriae, pumices and ashes), domes, lava flows and pillow lavas of andesitic-dacitic composition. A great part of these series is formed by dacitic submarine tuffs and tuffites with a thickness greater than 200 m. At the upper part of the pyroclastic series, up to 200 m above sea level, there are sedimentary levels with marine fossils which testify to the intense tectonic activity of the area in the last 2 million years. The entire series is slightly hydrothermally altered - mainly caolinized.

Volcanic activity in Santorini continued with Megalo Vouno, Thera, Mikros Profitis Ilias, Therasia and Skaros volcanic centres alternating effusive, explosive and extrusive activity. The last paroxysmal eruption was the Minoan phreatoplinian explosion, which formed the pumice fall, and flow and surge deposits that cover the entire Santorini area. The post-Minoan volcanic activity was mainly restricted to the area of Palaea and Nea Kameni islets.

Tectonic setting

The tectonic setting of Santorini is very intense and complicated, due also to the various subsequent caldera collapses. This is also proved by the fault system around

1939 – 1940 Nea Kameni volcanoes, Ashes, Scoriae, Quartz latiandesitic lavas, Andesitic ashes and scoriae, Andesitic lavas, Upper pumice series, Rhyodacitic lavas, Pyroclastic volcanics, Rhyodacitic lower pumice series, Quartz latiandesitic lavas, Tuffs with scoria, Andesitic lavas with scoriae, Quartz latiandesitic tuffs, Dacitic extrusive lavas Dacitic pumice tuffs, Quartz andesitic lavas, Lower tertiary semimetamorphic greenschists facies, Upper Triassic crystalline limestones

Fig. 3: Geological Map of Santorini (Thera) island and associated islets. (Institute for Geology and Mineral Exploration of Greece)

the metamorphic basement and the dykes, which outcrops in the northern part of the island. The presence of an extension, active till now, in the central Aegean, with a NW-SE direction, is confirmed both by the neotectonic data of this region and the study of the source mechanism of the recent earthquakes.

3.2 Geothermal Exploration

Geological surveys carried out on the island of Santorini identified a region of geothermal interest in Akrotiri-Megalochori area at the south part of the island, where intensively hydrothermally altered formations are present. The heat flow survey included more than 100 temperature measurements and water samplings from local springs, water wells and boreholes. Eleven slim boreholes were drilled reaching depths down to 200 m defining the area of the highest geothermal gradient, the maximum value of which was estimated as 16° C/100 m.

Chemical analysis classified the waters in the alkaline-chloride type, indicating the mixing of 'deep' hot, meteoric and sea water. The geothermometers of SiO_2, Na-K, Na-K-Ca indicated probable origin temperature of the deep fluids between 120° and 180° C. Possible origin depths have been estimated as 800-1000 m.

Today the thermal springs of Palea Kameni discharge steam-heated seawater, whereas the thermal springs of Thera are fed by steam-heated seawater mixed with diluted groundwater (*Chiodini et al., 1998*). Low-pressure steaming grounds, heavily affected by air addition, are present at Nea Kameni. Furthermore, the salinity of two hot springs is higher than the one of seawater, indicating boiling seawater origin and the presence of an active high enthalpy hydrothermal system.

In a second phase, a series of geo-electric soundings were carried out, which however did not yield satisfactory results, probably due to low depth current penetration. A gravity survey was carried out, which indicated a Bouguer gravity anomaly in the North-South direction. The interpretative section based on the gravity data and on magnetic measurements, confirmed the presence of a Graben with a maximum depth of the basement around 1500 m in the central part of the area.

Three more shallow but deeper bore holes were drilled, in order to gather better information on the geothermal gradient in impermeable formations, the nature of the deep geothermal fluids and the tectonic structure of the basement. Well S1, located near Megalo Vouno at the North part of the island, reached a depth of 270m with maximum measured temperature ~65°C at 240m. Well S2 was located south-southeast of S1 and reached a depth of 460m, with measured temperatures at 39°C at 120m, 35°C at 220m and 52°C at 440m. Well S3 was located at the south part of the island near Megalochori, with maximum measured temperature of 51°C at well bottom (260m).

From the above we conclude that an active hydrothermal system is present in the area, with high enthalpy fluids present within the fracture zones of the metamorphic basement at depths below 1 km.

4. Nisyros island

4.1 Geological setting of geothermal relevant structures

Geology and tectonic setting

In Nisyros the volcanic sequence lies on top of the basement comprising Mesozoic limestones and Neogene sediments, as indicated by the two deep geothermal wells Nis-1 and Nis-2 and by the presence of xenoliths within the pyroclastics deposits. The first volcanic activity was submarine. Subsequent volcanic activity resulted in the genesis of a composite volcano, which underwent several caldera collapses during relatively large pyroclastic eruptions. Later on, several dacitic domes popped up in the western part of the caldera. In historical times, only hydrothermal eruptions took place in the south-eastern part of the caldera generating a handful of hydrothermal craters, some of which are still well preserved, with the last hydrothermal events occurring in 1871-1873 and in 1888.

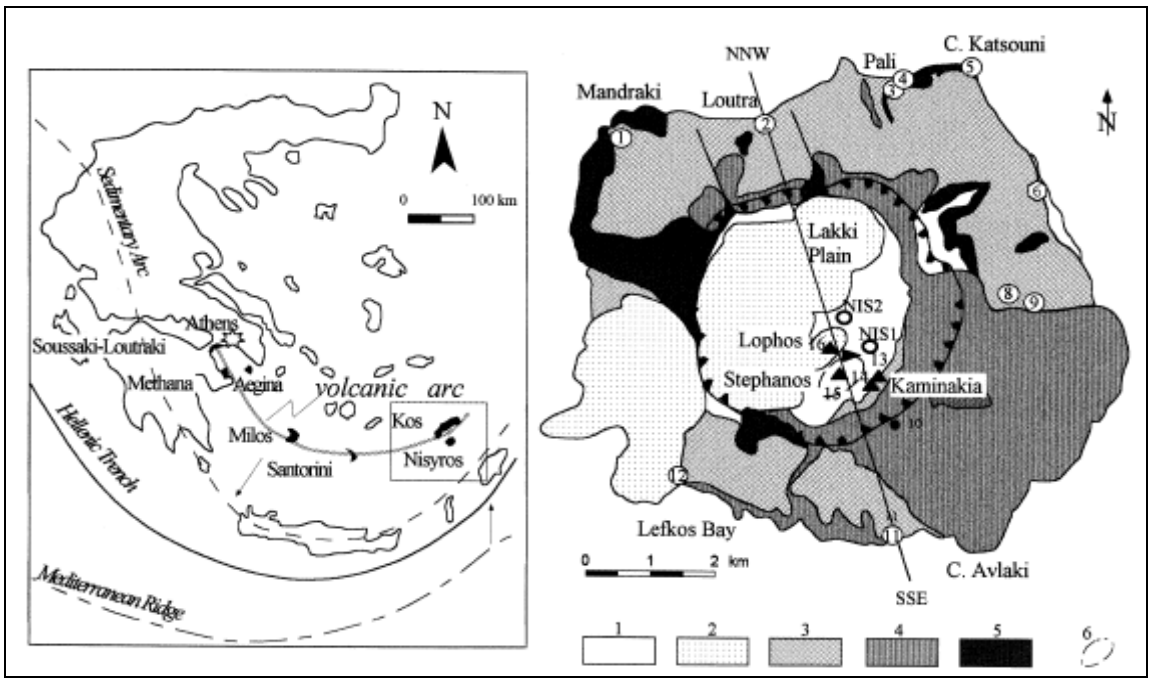


Fig. 4: *Schematic geological map of Nisyros island: (1) alluvia deposits, (2) post caldera dacitic lava domes and flows, (3) various pyroclastics "pumice, scoriae, cinder", (4) andesitic-dacitic lava flows and dykes, (5) andesitic, basaltic-andesitic pillow lavas, hyaloclastites, (6) phreatic explosion craters. Numbers refer to different types of wells and spring waters "hexagon: bicarbonate water, circle: chloride water" (Kavouridis et al., 1999)*

Today fumarolic fields are present in the hydrothermal crater area. Major fumarolic vents are located in the craters of Stephanos, Polybotes Micros, Polybotes, and Phlegethon, which partially destroyed the Lofos dome. Minor fumarolic vents occur in the Kaminakia craters area. All these vents have outlet temperatures close to 100°C and pH~1,5. Several thermal springs with temperatures up to 54°C, discharging steam-heated seawater, are located along the northern and southern coasts of the island *(Marini et al., 2002).*

The geology of the island and main geothermal features are presented in figure 4, while The conceptual model of the field is shown in figure 5. The tectonic setting of the island is characterized by NE-SW and NW-SE faults, which serve as flow paths to the surface manifestations *(Kavouridis et al., 1999).*

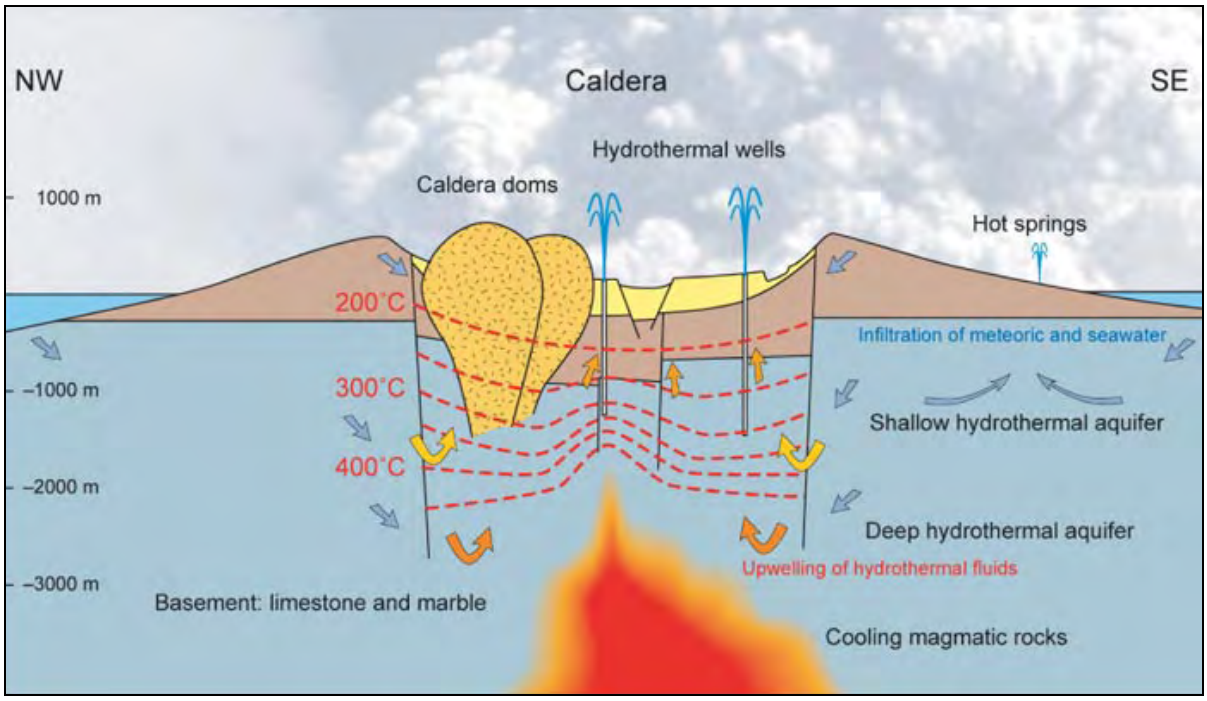


Fig. 5: Nisyros conceptual model by Swiss Federal Institute of Technology (ETHZ)

Temperature and transmissivity range

Deep well Nis-2 encountered a deep liquid dominated reservoir containing water of 250°C (well Nis-2) within two fractured zones of limestones intercalated with sub-intrusive quartz-dioritic rocks, encountered at depths 1100-1300m and 1500-1550m (well bottom). At shallower depths between 370-470m an aquifer of hot water around 150°C was encountered within the andesitic lavas and breccias.

Deep well Nis-1 encountered a series of productive fractures at depths below 1450m till well bottom (1800m – diorite intrusive body) within the metamorphic marble and schists containing intercalations of hydrothermally altered volcanics. These fractures contain liquid water of 300-350°C temperature. In addition, well Nis-1 encountered a shallow aquifer of temperature around 100°C at depths 400-1000m within fractured altered volcanics (andesitic lavas, breccias and tuffs) and the upper part of the limestones.

4.2 Assessment of reservoir

Geothermal Exploration Methodology

On Nisyros island the following surveys have been carried out:

- Geochemical investigation of the hot springs encountered at the north and south coast of the island, which yield warm water of 40-50°C, as well as of the fumaroles encountered in and around the phreatic craters and lava domes of the caldera. Isotopic and chemical analysis of the fluids were carried out and chalcedony and K/Mg geothermometers were applied.
- Earlier DC resistivity and gravity surveys by IGME.
- The two deep wells Nis-1 and Nis-2 have been drilled in the caldera by PPC.
- Audiomagnetotelluric (AMT) surveys.
- Additional geophysical surveys have been carried out at the southern part of the island, which included MT, gravity, VLF and SP.

Results and experience gained

The geochemical investigation of Nisyros geothermal field indicated the presence of two distinct types of fluids. One shallow of temperature 120-170°C probably present beneath the entire island, and another deep of temperature 275-350°C beneath the caldera *(Kavouridis et al., 1999).*

The DC resistivity survey identified a near surface low resistivity zones of 1 Ohm.m beneath the caldera plateau.

Well Nis-1 produced geothermal fluid from two deep zones. The deeper one contains fluid of very high salinity estimated at 100.000 ppm TDS, which was completely plugged by scale deposits during the first production test. Subsequent production was only from upper production zones (less than 1600m depth) which yielded 3,24 kg/s of two phase steam condensate comprising 2,80 kg/s vapour and 0,44 kg/s liquid at 10 bars well head pressure.

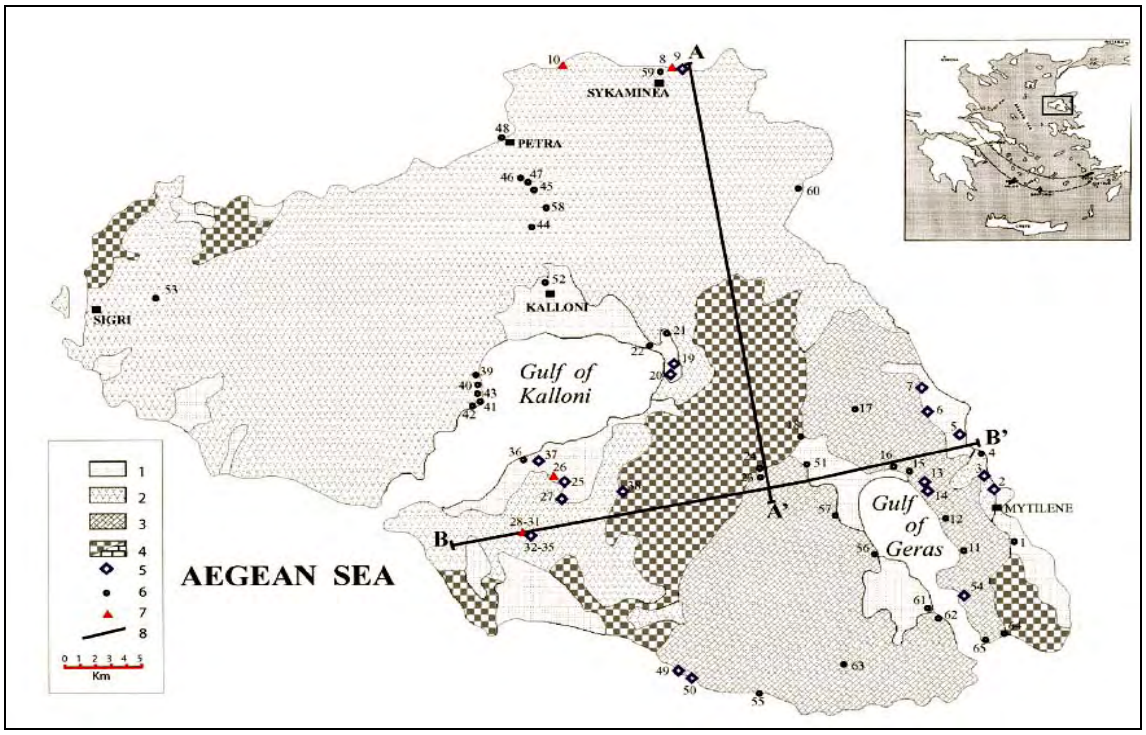
Well Nis-2 yielded 14 kg/s two phase fluid of high salinity (34.000 ppm chloride) of 50% brine and 50% steam mass flow at 11 bar well head pressure.

The 1-D inverted audiomagnetotellurics provided an image of the subsurface structure inside and outside the caldera. Subsurface resistivity ranged from 1-12 Ohm.m inside the caldera and 3-10 Ohm.m at the south part of the island.

5. Lesvos island

5.1 Geology

Lesvos is located at the north east part of the Aegean sea and is characterized by Miocene volcanism. Its geological setting is summarized in figure 6. The south-east part of the island near Geras Gulf, is characterized by the outcrops of an ophiolite basement alternating to carbonate-phylite with embedded marble lenses at the central part of the island. Towards the north, the metamorphic basement is covered by either high-K, calc-alkaline ignimbrite or shoshonitic Miocene volcanic formations.



(1) Pliocene-Quaternary marine and continental sediments, (2) Miocene volcanic rocks, (3)ophiolitic basement, (4) carbonate-phyllite basement, (5) cold water, (6) thermal water, (7) thermal water with associated gas phase, and (8) trace of idealized sections.

Fig. 6: Geological and geochemical map of Lesvos island (A. Bencini et al., 2004).

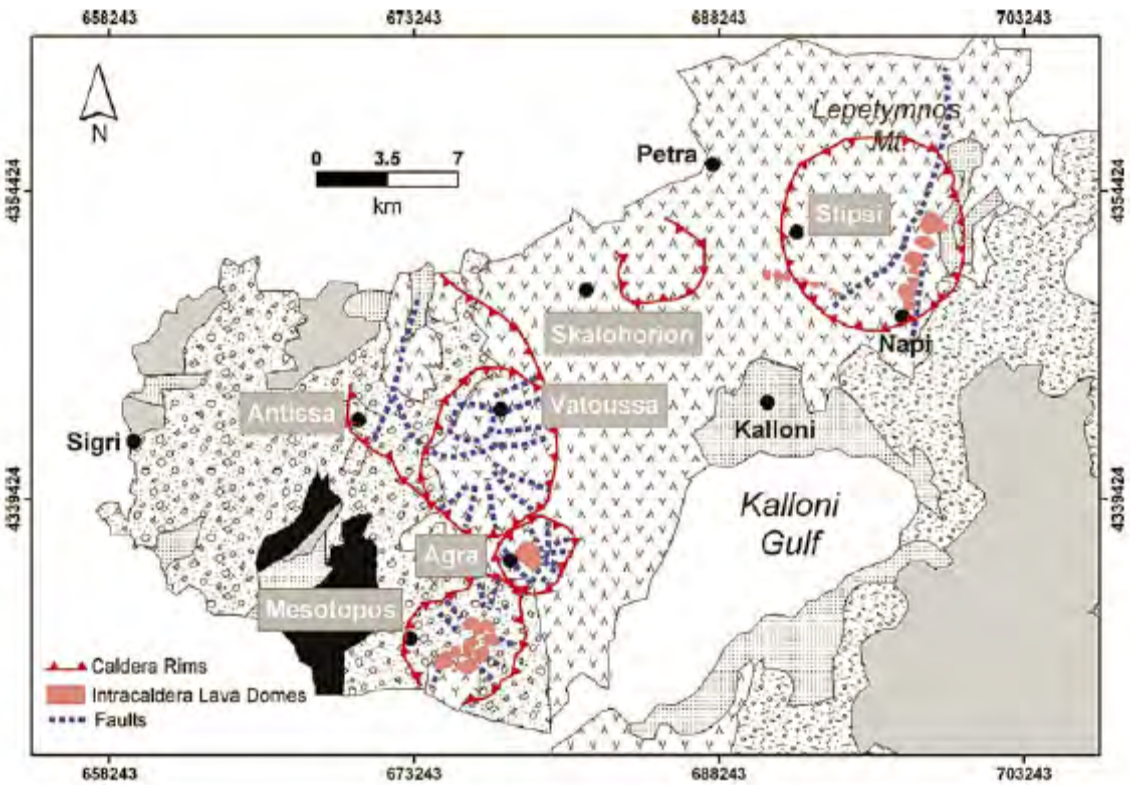


Fig. 7: Identification of caldera structures in north Lesvos by satellite remote sensing techniques (Kouli and Seymour, 2006).

The north-west part of the island is characterized by the presence of acid pyroclastic rocks and the well known fossil forest. Alluvia deposits have been formed at the inner gulfs of Kalloni and Geras.

Remote sensing methods associated with satellite imaging have identified the structure of 6 calderas, which may be excellent targets for deep geothermal exploitation (see figure 7).

5.2 Geothermal Exploration Methodology

Geothermal exploration on Lesvos included geological mapping, mapping of thermal manifestations, geochemical investigation, thermal gradient mapping from temperature measurements in shallow wells, and deep exploration drilling. At present the Public Power Corporation of Greece is performing drilling exploration at aiming in investigating medium enthalpy resources sufficient for a 8 MWe power plant. Geochemical investigation has indicated the presence of CO_2 rich geothermal fluids rising through the main faults with temperatures of 50-120°C as estimated by geothermometers. Drilling exploration so far indicated maximum measured temperatures at depths down to 1000m do not exceed 100°C.

5.3 Utilisation

At present geothermal utilization involves thermal spas and heating of greenhouses at the following locations: Geras gulf using ~40°C geothermal water, Thermi using ~60°C geo water, Polichnitos and Lisvori using 65-80°C geothermal water and Argenos using 80-90°C geothermal water.

6. Chios island

6.1 Geology
(Dotsika at al., 2006)

The geology of Chios island is summarized in figure 8. Three main rock groups are encountered on the surface. They are: (a) Neocene fluvial-lacustrine deposits encountered at the southeast part of the island, the thickness of which exceeds 250m; (b) Triassic-Jurassic limestones and dolomites covering the central part of the island and (c) Paleozoic clastic rocks outcropping at the northwest part of the island.

Regarding stratigraphy, the Paleozoic formations are 3-4 km thick and comprise greywacke and shale intercalated by conglomerates, quartzite and limestone lenses, with intrusions from volcanic rocks of lower carboniferous. At the central part of the island, the limestones and dolomites are 300m thick and are interlayered by Bauxites. Below, dominant formations are red conglomeratic sandstones. At the southeast part of the island, the Neocene fluvial-lacustrine deposits are more than 250m thick, and overlay older Neocene sediments comprising tuffs, green sands,

gravels and ferrous sandstones. Towards west, these sediments overlay deeper Triassic limestones and dolomites.

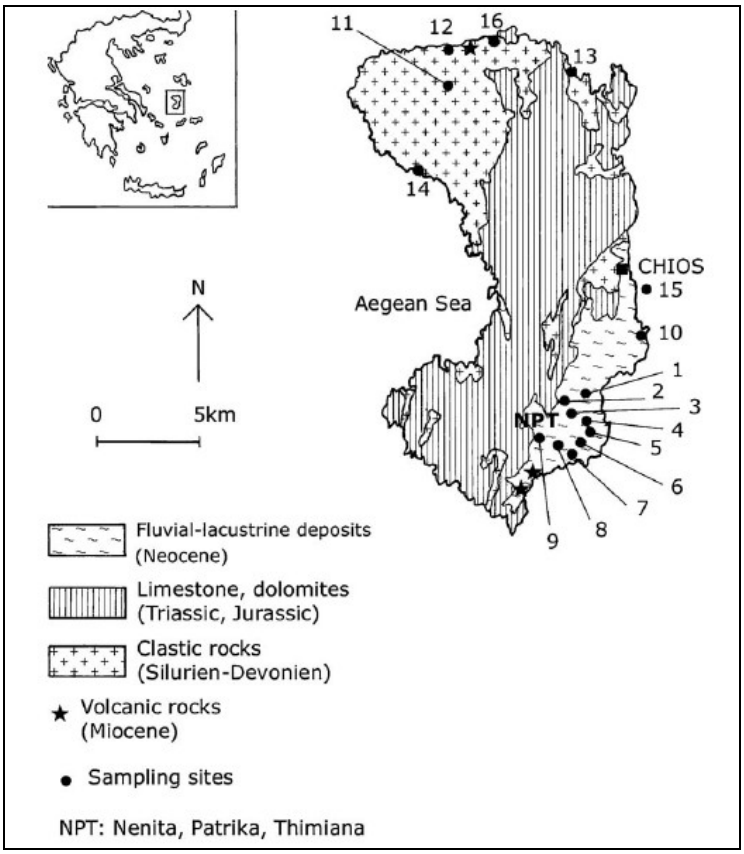


Figure 8: *Geology of Chios island and sampling points for geochemical analysis (Dotsika at al., 2006).*

6.2 Geothermal Exploration Methodology

Geothermal exploration on the island included geological mapping, geochemical investigation of waters from springs and shallow boreholes, mapping of mercury concentration of surface rocks and shallow drilling. With the exception of geochemical investigation of Chios waters, which was carried out by Dotsika et al. 2006, all other geothermal exploration activities were undertaken by the Institute of Geological and Mineral Exploration of Greece (IGME). The geochemical investigation of Dotsika et all 2006 indicated the presence of two deep aquifers, one at northwest (sample points 12 and 14 of figure 8) with 220°C temperature and one at southeast (sampling site NPT of figure 8) with 80°C temperature.

The distribution of mercury within the surface rocks of the island is presented in figure 9. It is known that areas of high mercury content in the soil are associated with the upflow zone of deeper low, medium or high enthalpy hydrothermal systems. Such areas are dark coloured in figure 9, and indicate the presence of either a fossil or an active hydrothermal system there.

Two hot springs are encountered at the northwest part of Chios, spring 12 with 54°C temperature and 4100 ppm chloride and spring 14 with 35°C temperature and 22.250 ppm chloride (see figure 8). Another warm spring, marked as No 10 in figure 8, is located approximately 4 km south of Chios town the temperature of which is 26°C and its chloride content 19.000 ppm. Three cold springs are encountered at the north part of island, points 11, 13 and 16 of figure 8, which have temperatures 15-17°C and salinity 300-600 ppm. Points 1-9 of figure 8 correspond to shallow boreholes, the temperature of which varies from ~20°C of boreholes 1-5, to 25-30°C of boreholes 6-9.

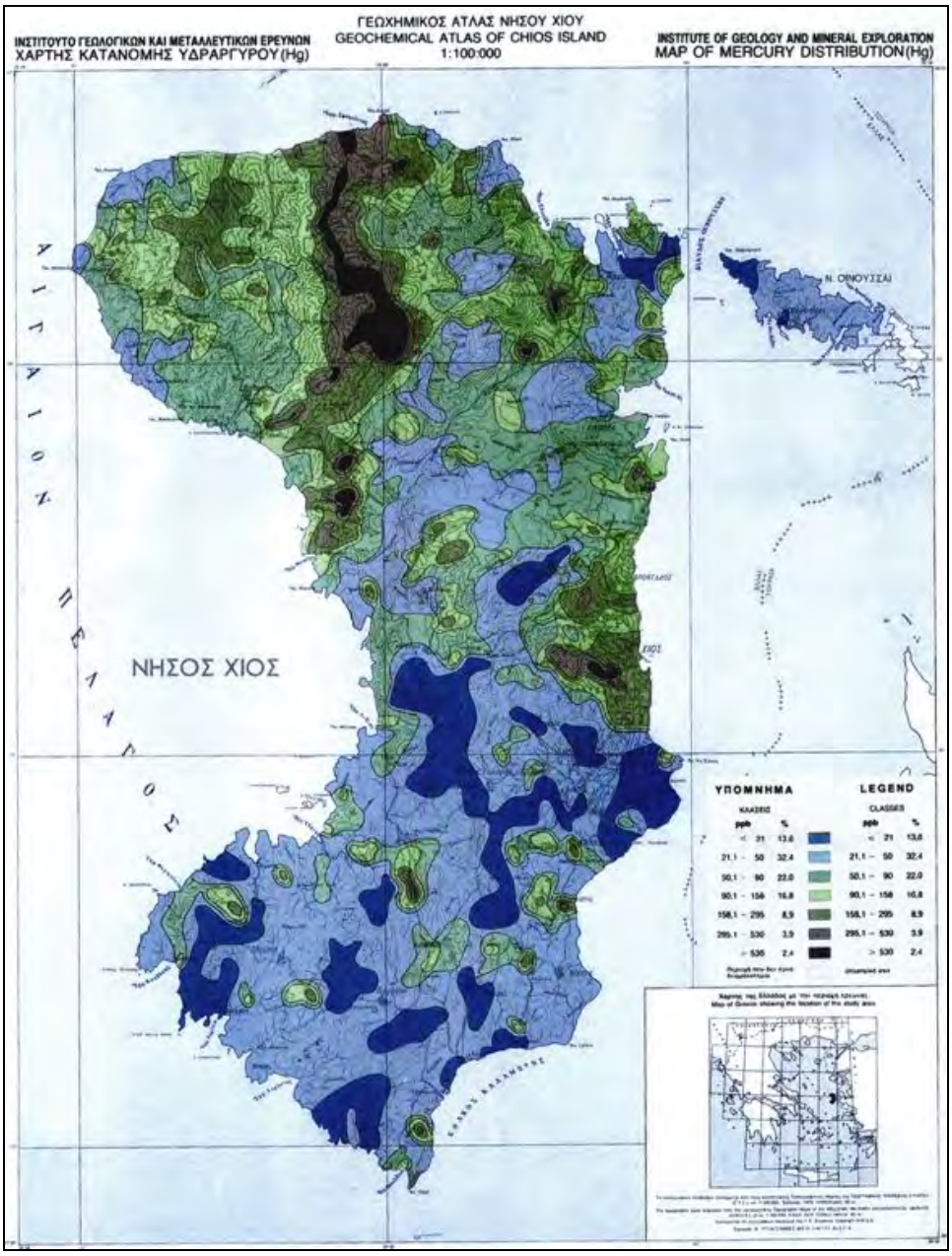


Fig. 9: Mercury distribution on Chios island (IGME)

Our opinion is that hot spring 14, which has the highest salinity with chloride content exceeding the one of local seawater, is an evidence of deeper hydrothermal fluids, probably of acid sulphate dilute chloride type, comprising a mixture of local

groundwater, seawater and deeper boiled seawater with 140°C origin temperature as indicated by the K-Mg geothermometer, which is most credible for seawater systems. Hot spring 12 water seems to be of dilute chloride type and a mixture of deep boiled seawater with local groundwater with 150°C origin temperature as indicated by the K-Mg geothermometer.

Geochemical investigation therefore, has provided strong evidence of the presence of a medium and probably high enthalpy active hydrothermal system beneath the northwest part of the island, probably delineated by the mercury distribution of surface rocks. Further geophysical investigation is necessary comprising MT resistivity and active seismic surveys followed by deep drilling exploration.

6.3. Utilisation

No utilization of geothermal energy takes place on Chios island at present.

7. Samothraki island

7.1 Geology and tectonic setting

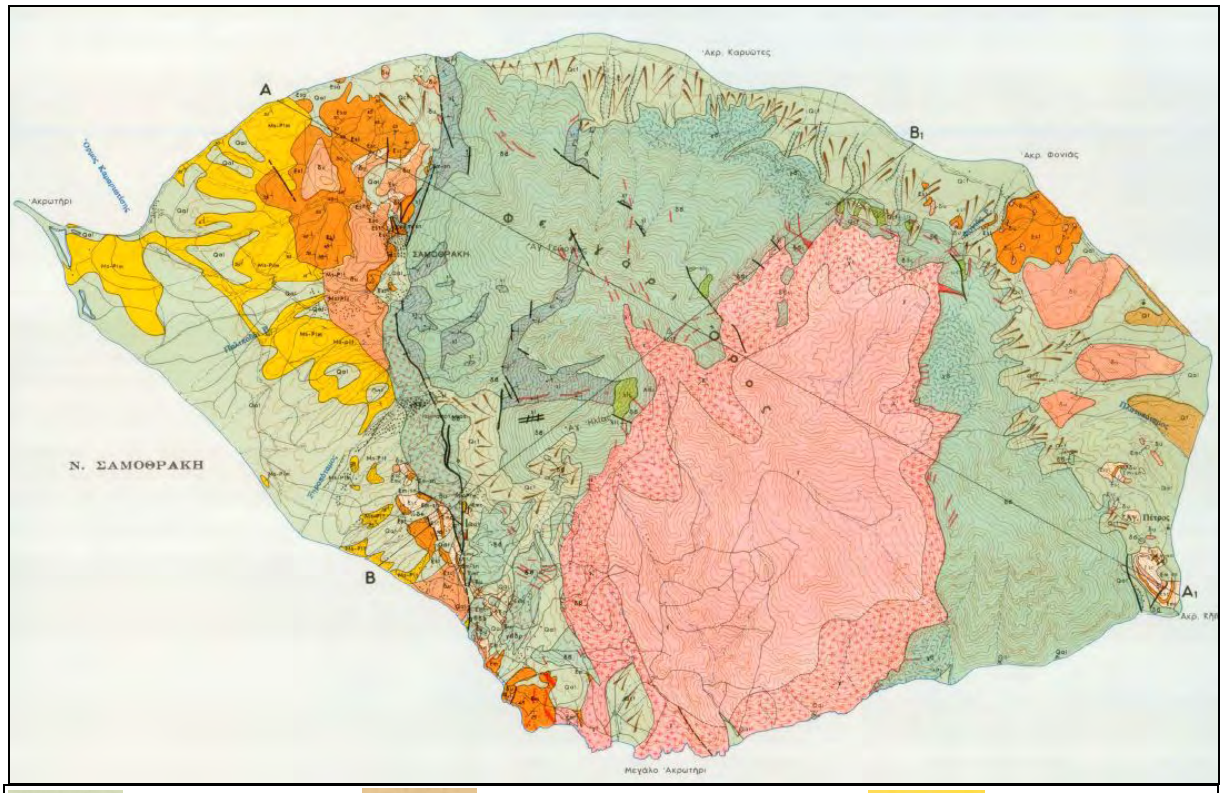
(*Kotopouli et al., 1989; Tsikouras and Hatzipanagiotou, 1995; Fytikas et al., 2007*)

The island of Samothrace located 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 Serbo-macedonian and Rhodope Massifs. The geologic map of the island is presented in figure 10.

The main geological units of the island are as follows: (a) The “Basement Unit” which is the stratigraphically lowest formation [a diversity 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]. Doleritic intrusions cut locally all these rock-types. In several places the contact between the ophiolites and the basement appears to be normal with steeply dipping intrusive contacts suggesting an autochthonous or at least parautochthonous origin. (c) Clastic series. Neritic, clastic sedimentary rocks of Eocene age (sandstones, shales) cover uncomformably the “Ophiolitic Unit”. (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 lie in the peripherical regions 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 in the 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 to thermal manifestations.



Alluvia deposits, Pleistocene fan sediments, Neogene sediments, Rhyo-dacite porphyrites, Porphyritic granites, Upper Eocene andesites Upper clastic sequence (sandstones),, Numulitic limestones, Middle Eocene basal clastic sequence, Cretaceous basalts and gabbros, Shale series

<u>Fig. 10:</u> Geological map of the Samothraki island. (Institute for Geology and Mineral Exploration of Greece)

7.2 Geothermal Exploration Methodology

At present, geothermal exploration consists of only geological mapping and drilling of three shallow boreholes (S-1, S-2 and S-3 at depths of 120, 120 and 40 m respectively) in order to supply the thermal spas operating near the hot springs at Therma village.

7.3 Utilisation

Apart from the spas, no other use of geothermal energy takes place on the island.

8. Continental Basins, massifs

8.1 Geology

The geology of areas of geothermal interest of North Sterea, Thessalia, Macedonia and Thrace is presented in figure 11. The geology of the basins of Nestos, Xanthi-Komotini and Alexandroupolis is presented in more detail in figure 12.

The Nestos Delta Basin

The Nestos Delta basin occurs 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. Two major faults in the N70º and N160º directions enclose the basin.

Metamorphic rocks of the Rhodope massif (mainly gneisses, amphibolites and marbles comprise the basement of the area, which it has been deformed and metamorphosed during several tectonic episodes. Unconformable sediments of Miocene (marls, sandstones, siltstones, lignites, clays, conglomerates and anhydrites) lagoon facies (*Lalechos, 1986*) exist on the metamorphic basement of this region. 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 deltaic deposits lying unconformably over the previous series characterize the Plio-Quaternary sediments. The loose sandstones and clays at the basin margins and marine and lacustrine sediments in the central part of the basin compose these formations. 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°. This structure was dissected by successive extensional faults about N120-140° (*Lyberis, 1985; Mercier et 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.

The Xanthi - Komotini Basin

The Xanthi – Komotini basin occurs 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 consist of clastic sediments of Eocene – Quaternary age and it extends 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 placed.

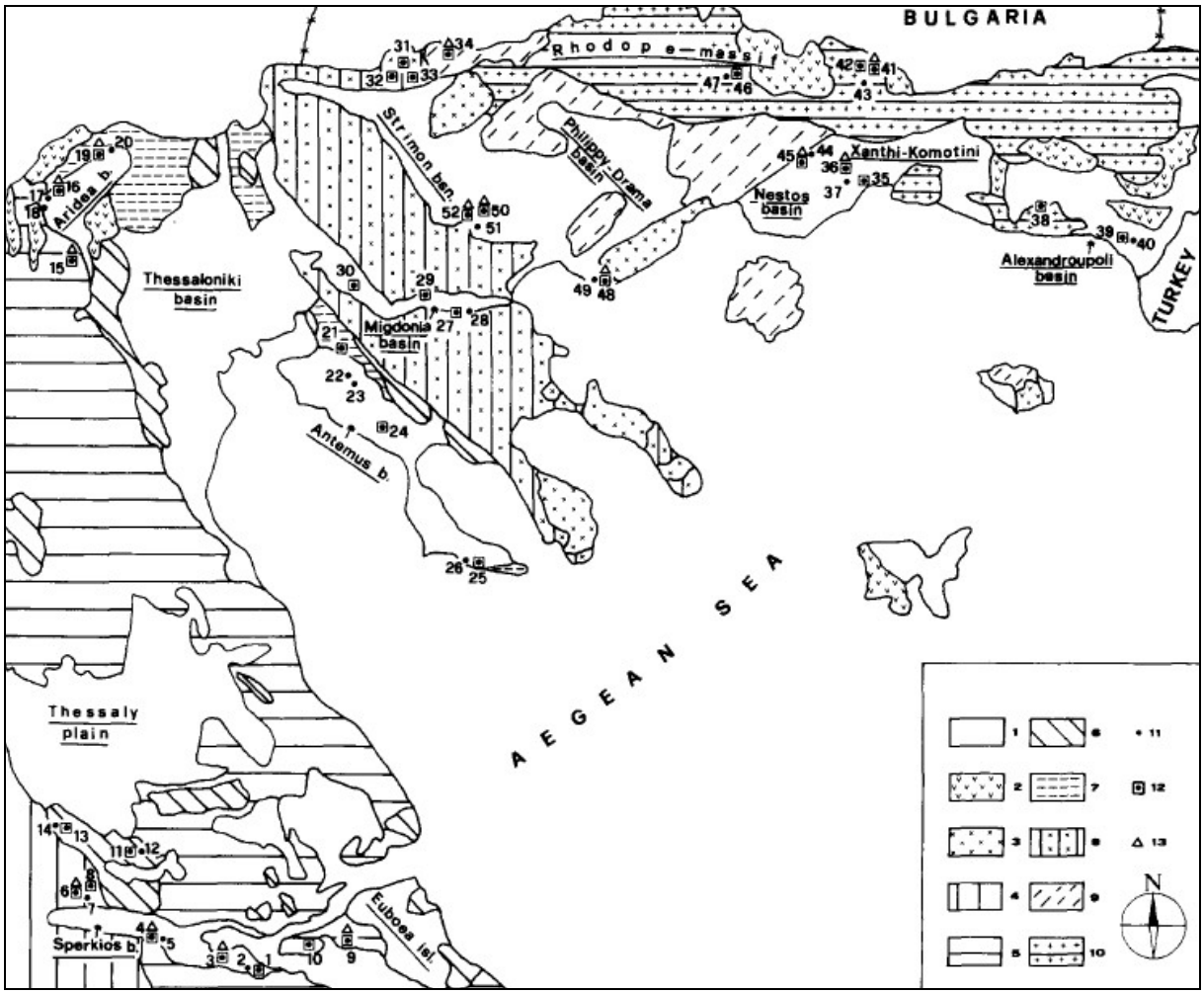


Fig. 11: *Geology of areas of geothermal interest of central and north mainland Greece: 1. Oligocene and more recent basins; 2. tertiary volcanics; 3. Tertiary granites; 4. Pindos nappe; 5. Pelagonian nappes; 6. Ophiolites; 7. Vardar zone; 8. Serbo-Macedone massif ; 9. Mesozoic Rhodope metamorphic belt ; 10. Palaeozoic Rhodope metamorphic belt ; 11. cold springs ; 12. warm springs ; 13. gas vents. (Minissale et al., 1989).*

Geologically the region belongs to the Rhodope massif. The gneisses, mica schists, marbles and amphibolites comprise the crystalline basement (*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/microconglomerates), 700-900 m Miocene sediments (alternations of clays, marls and siltstones) and 500-600 m Eocene-Oligocene formations at the deeper parts.

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 a region of approximately 2000 km^2 all within the Western Thrace territory (*P.P.C., 1988*).

Major faults enclose the basin occasionally which is reached at depths of 3500 to 4000 m. The Palaeogene – 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 sandstones, marls, limestones, polygenic volcanic breccias, tuffs and siltstones constitute the marine Palaeogene sediments (average thickness of about 2000 m). 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).

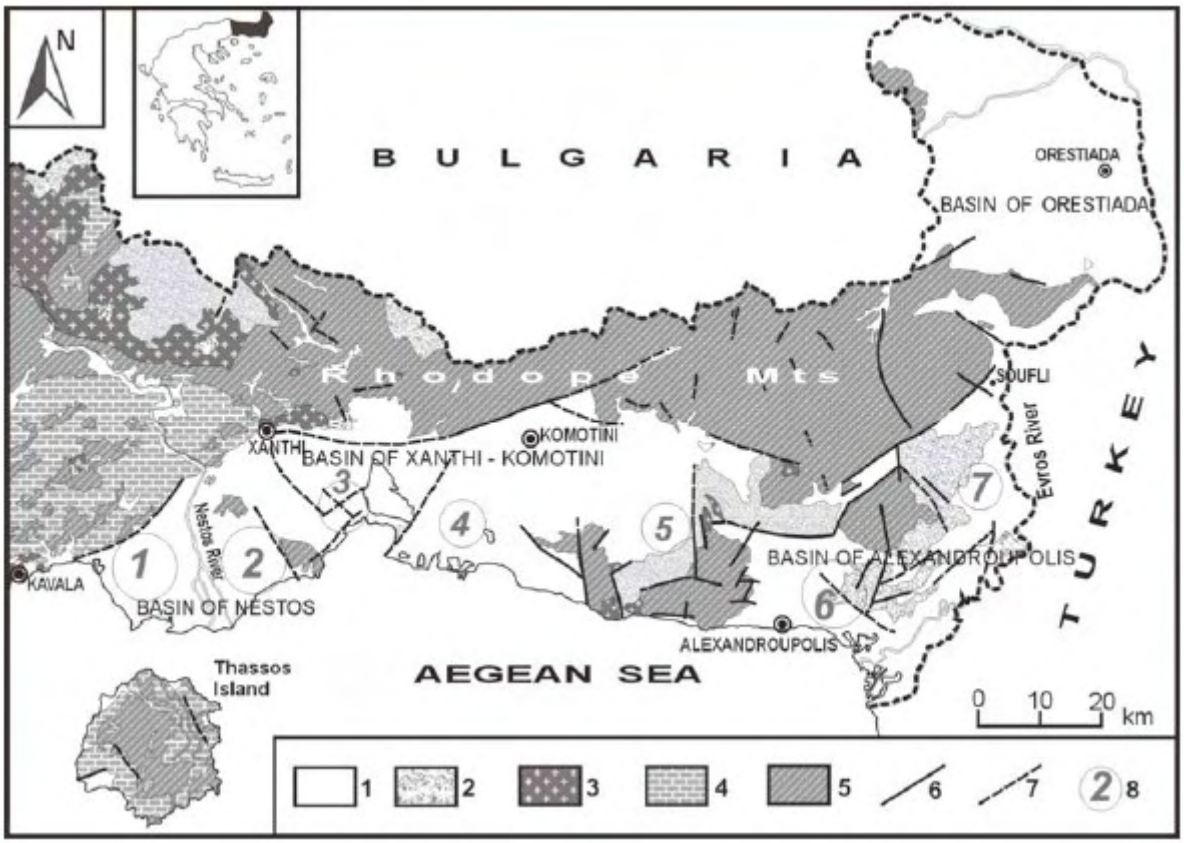


Fig. 12: Geology of basins and massifs of East Macedonia and Thrace region.
[1:Tertiary and Quaternary sediments, 2: Tertiary volcanic rocks, 3: Granites and granodiorites, 4: Marbles and limestones of the Rhodope massif, 5: Metamorphosed rocks, 6: Faults, 7: Probable faults, 8: Geothermal fields (the numeration of the fields is as follows: 1:Eratino, 2: Magana – Neo Erasmio, 3: Nea Kessani, 4: Mitrikou Lake, 5: Sappes, 6: Aristino – Alexandroupolis, 7: Tychero)]
(Kolios et al., 2005).

Volcanic activity developed in the wider region during the Oligocene – Lower Miocene (33 to 23 Ma). In the territory of Alexandroupolis and Soufli, the volcanic products mainly appear 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. Pyroclastics, tuffs and tuffites alternated with sediments of

Priabonian and Oligocene age comprise the volcanic products. Ignimbrites occur in the Dadia area. Domes and lava flows outcrop in the external part of the basin. Alteration processes affected the volcanic products. The spatial evolution of sedimentation and volcanism is controlled by two main fault systems in NNW-SSE and NNE-SSW directions.

The Strymon Basin

The basin of Strymon is a typical post-orogenic graben, which is still active. It has been shaped between the Serbomacedonian massif (SRB) on the West and the Rhodope massif on the East. Marbles, gneisses and mica schists constitute the eastern margin of this basin. The Vrondou granitic complex dated between 28 and 32 Ma (*Marakis, 1969; Durr et al., 1978; Kolocotroni, 1992*) breaking through these metamorphic rocks of the Rhodope massif. Schists, leucocratic, augen and migmatic gneisses, amphibolites and marbles (lower unit) comprise the SRB massif (on the West). Late Paleozoic, Cretaceous and Palaeogene granitoid bodies intruded into the SRB massif (*Kilias et al., 1999*). The total thickness of the Neogene and Quaternary sediments at the centre of the basin is evaluated to be close to 4000 m. Various depositional palaoenvironments (continental, fluvial, fluviolacustrine, lacustrine-marshy, marine, brackish, deltaic) were produced during the Neogene – Quaternary and their succession make the stratigraphy very complicated (*Syrides, 2000*).

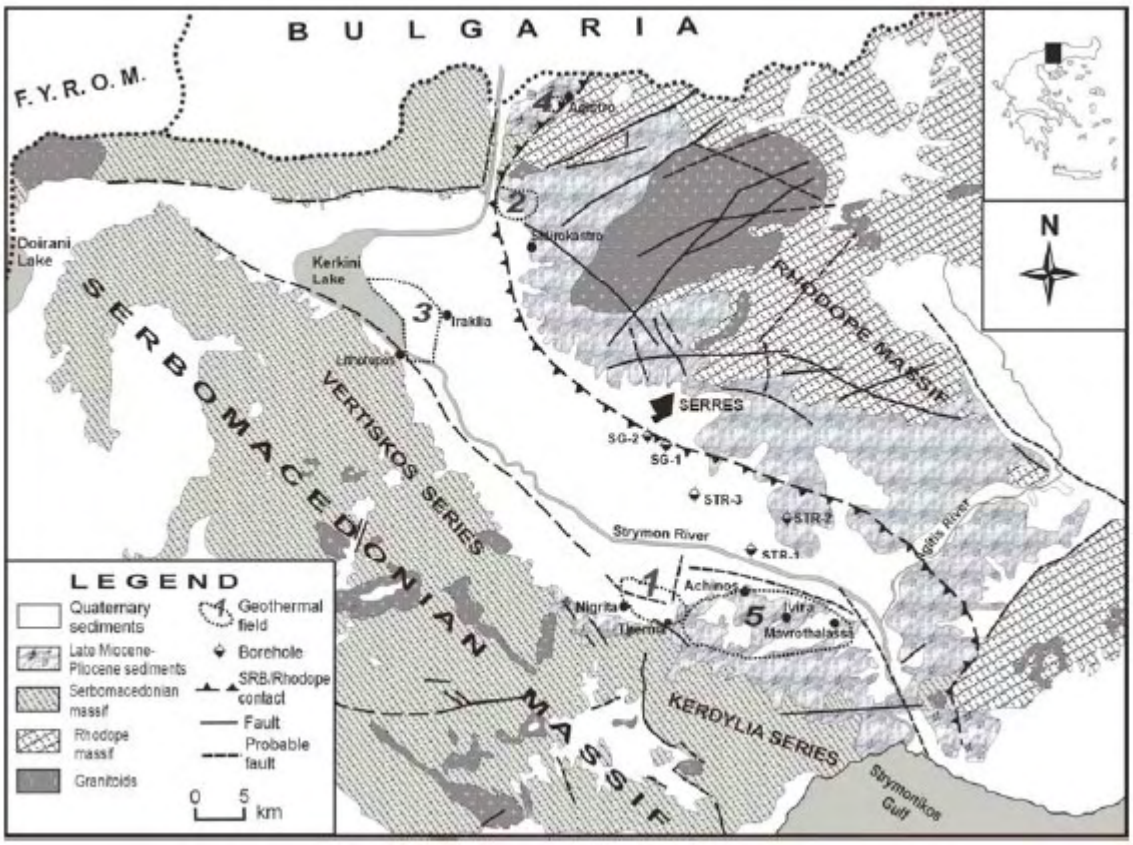


Fig. 13: Geology of Strymon basin. *(geothermal fields 1: Therma-Nigrita, 2: Sidirokastro, 3: Lithotopos - Iraklia, 4: Agistro, 5: Achinos – Ivira – Mavrothalassa; STR: deep well drilled for oil exploration, SG: cold water well).* (Karydakis et al., 2005)

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) constitute the typical stratigraphic column of the basin (*Lalechos, 1986; P.P.C., 1988*). In the wider region of the Strymon basin the principal faults are oriented in NNW-SSE, NNE-SSW to NE-SW and WNW-ESE to W-E directions. At the margins of the Strymon basin (Strymoniko, Sitsi-Kamen) small volcanic edifices appear (probably altered rhyolites) which are related to the extension tectonics of the area. The geology of the Strymon basin is presented in figure 13.

The geothermal conditions in the Strymon basin are favourable 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 favourable for the uprising of the geothermal fluids at relatively shallow and exploitable depths or at surface. The general geological settings are favourable 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*).

8.2 Geothermal Exploration Methodology

Geothermal exploration in the above areas comprised geological mapping and geochemical investigation of surface or near surface waters, accompanied by drilling targeting the upper thermal aquifers in the vicinity of hot springs, which are used for spas. Geochemical study of hot springs and borehole waters carried out by Minissale et al. 1989 indicated the main areas of geothermal interest, which are analyzed in table 1 together with a summary of drilling exploration results.

Of the areas listed in table 1, the one with the highest interest in terms of geothermal development for power generation is the Eratino field of delta Nestos river[1], where the maximum measured temperature of 178°C has been measured at 4km depth, and where geothermometers indicate the presence of deep reservoirs of 120-150°C temperature. The conceptual model of this field, as derived from geochemical and drilling exploration is presented in figure 14.

In addition to the geochemical and drilling exploration, a DC resistivity survey has been carried out by the Aristotle University of Thessaloniki in Mygdonia basin, which delineated a deep reservoir in Langadas *(Thanassoulas, 1983)*. Moreover, SP, gravity and VES resistivity surveys have been carried out by IGME in Delta Nestos

[1] 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 geothermal anomalous area (*Fytikas et al., 2007*).

(Eratino) area, which revealed the basement depth and main deep fractured zones and faults *(Thanassoulas and Lazou, 1993)*.

Table 1: Areas of geothermal interest of central and north Greece

Area of geothermal interest	Water sampling No of figure 11	Sampling temperature °C	SiO_2 and/or K/Mg geothermometer °C	Drilling exploration	
				Depth, m	°C
Alexandroupolis basin	38-40	15-50	120-140	Aristino : 200-465 Tychero : 400	30-92 38
Nestos and Xanthi-Komotini basins	35-37, 44-45	15-70	120-150	N.Kessani : 300-400 Sappes : 250-400 L.Mitrikou : 450 Magana : 200-400 Eratino : 550-650 1700 3000-4000	75-80 38-40 40 40-65 65-75 115 127-178
Central Rhodope massif	41-43, 46-47	10-55	120-150	-	-
Strymon basin	31-34, 50-52, 48-49	40-60	100-140	Agistro : 70-130 Sidirokastro: 10-450 Iraklia : 300-450 Nigrita : 100-400 Ivira : 450-550 SG-1&2 : 500 STR-2&3: 2678-3144 STR-1: 2884-3651	40-47 40-65 40-62 40-65 40-50 20 89-96 106-135
Mygdonia basin	27-30	39-44	80-100	Nymfopetra : 60-110 N.Apollonia : 30-110 Langadas :100-200	45 56 30-38
Anthemous basin	21-26	19-40	100-130	N.Ryssio : 500 Sani : 500-600	40 30-40
Aridea basin	15-20	15-37	60-85	300-780	30-38
Sperchios basin incl. Smokovo & Aidipsos	1-14	18-80	80-120	Thermopyles: 50-200 Aidipsos : 0-100	35-46 50-78

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 (*Fytikas et al., 2007*).

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 (*Fytikas et al., 2007*).

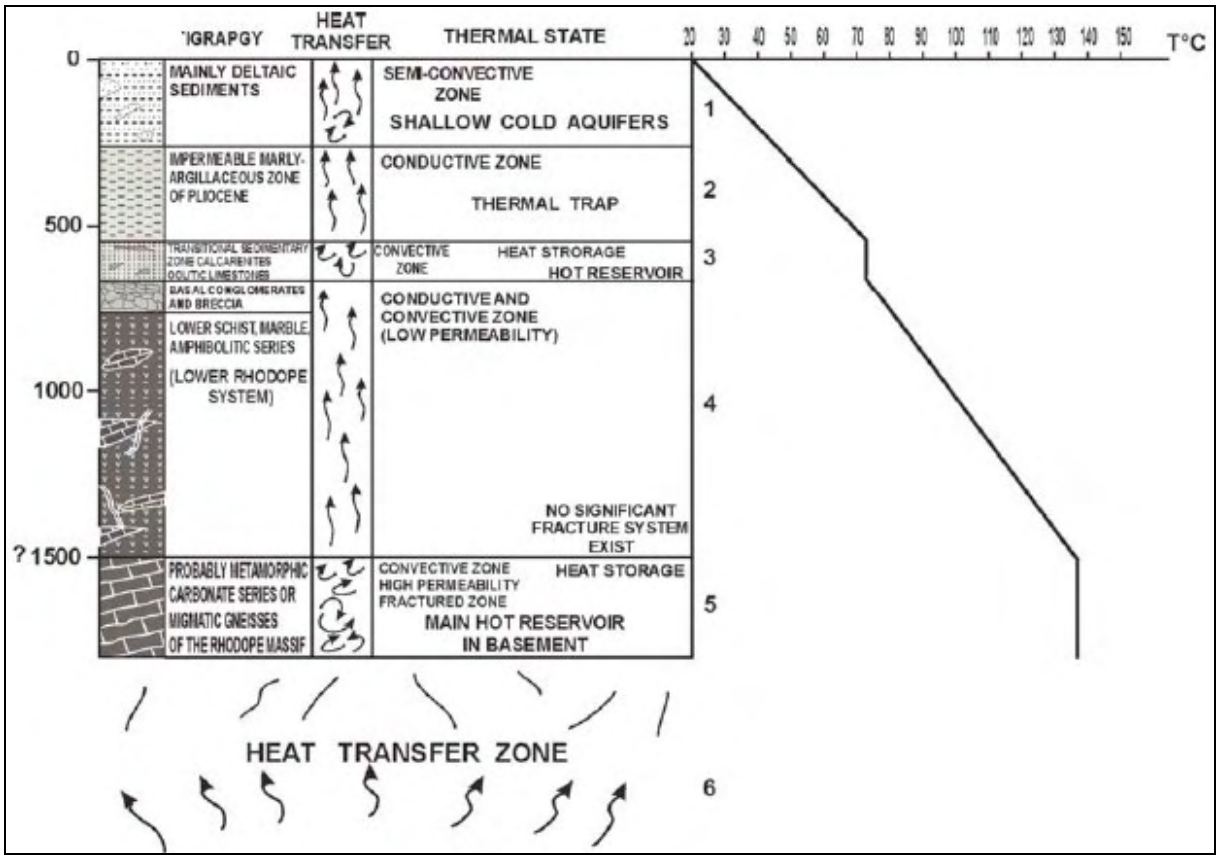


Fig. 14: Conceptual model including expected stratigraphy and temperature profiles in Delta Nestos (Eratino), where a deep reservoir of ~140°C is probably encountered within the basement at depths beneath 1500m. (Fytikas and Kolios, 1992)

8.3 Utilisation

At present low enthalpy geothermal fluids of temperatures 27-60°C are utilized for greenhouse heating, space heating, fish farming and drying of vegetables in the basins of Mygdonia, Strymon, Nestos, Xanthi-Komotini and Alexandroupolis. In addition, in many more places the geothermal fluids are used for spas and bathing.

9. Conclusions

The deep tectonic structures and the young to recent volcanism in Greece have created high heat flow, which resulted in a large number of geothermal fields of both low and high enthalpy.

After thirty years of extensive exploration activities (geological mapping, geochemical investigation, thermal gradient mapping, geophysical surveys, etc) as well as drilling a considerable number of shallow and a few deep wells, the rich

geothermal potential of Greece was confirmed as low, middle and high enthalpy fields and new areas of geothermal interest were identified.

High enthalpy geothermal resources have been identified in the islands of the Aegean volcanic arc Milos, Nisyros and Santorini. Low enthalpy fields indicating deeper medium enthalpy geothermal resources are located in the islands of Miocene volcanism Chios, Lesvos and Samothraki.

In the basins of North Greece there is a large number of low enthalpy geothermal fields (water temperatures of 30-100°C). These fields are located at very shallow depths in the post-orogenic basins of the area (basins of Strymon, Nestos Delta, Xanthi-Komotini, Evros). The geological and tectonic conditions are favourable for the presence of medium enthalpy (T=100-150°C) geothermal resources at greater but exploitable depths (down to 2-3 km), which are suitable for geothermal power generation.

Other areas with low enthalpy geothermal resources, but with promising medium enthalpy resources at deeper levels include the basins of Anthemous, Mygdonia and Sperchios.

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