INTERNATIONAL SUMMER SCHOOL
on Direct Application of Geothermal Energy
Under the auspice of the Division of Earth Sciences

BASIC FACTS ABOUT GEOTHERMAL ENERGY: ENERGY, CHARACTERISTICS AND ITS SPREADING AROUND THE WORLD AND GREECE

Michael Fytikas and Maria Papachristou
Aristotle University of Thessaloniki
Department of Geology

1. INTRODUCTION

The man's knowledge about Earth stems mainly from surface observations. The (indirect) information about the interior derives usually from the data of the deep wells constructed in areas that are explored for hydrocarbon and water deposits.

The Earth's interior is hot, which is proven by the presence of molted rocks (magma), the temperature of which is up to 1200°C when they reach the surface during the volcanic eruptions. Equally indicative of the high internal temperatures, are the "geysers", the overheated steam and gas (fumaroles), the hot grounds, hot springs, etc. The increase rate of the Earth's temperature is approximately 30°/km and is called *"geothermal gradient"*.

1.1 The Heat of Earth

The Earth spheroid consists of three main "layers":

- The **crust**, the average density of which is 2,7 gr/cm^3 and 3,3 gr/cm^3 at the continental and oceanic regions correspondingly. The composition of the continental parts is "granitic" and rich in light materials of big diameter and in radioactive isotopes. On the contrary, at the oceanic parts the heavier and of smaller diameter materials are in abundance (Ca, Mg, Fe).
- The **mantle**, which lies below the crust, is 2,9km thick and its average density is 5,7gr/cm^3. It mainly consists of silicate minerals (Mg and Fe) and its temperature ranges between 1000-3000°C. The upper part of the mantle is solid and the lower is liquid.
- The **core** is located at the center of the sphere and consists of an outer fluid "layer" of high density (11,5gr/cm^3) and temperature over 4000°C (outer core), and an inner solid layer (inner core). Both inner and outer core are mostly made by iron and nickel.

The rigid, rocky outer layer of Earth is called the lithosphere. The upper part of the lithosphere is very important for the geologic research because it is the only source of information we can have access to. The lithosphere consists of the crust and the solid outmost layer of the upper mantle. It extends to a depth of about 100km and it is broken into separate rigid zones (tectonic plates) that slide one towards the other and sit on the asthenosphere.

The heat of Earth's interior is most probably of sidereal origin and goes back to the period of Earth's formation. A large amount of heat also comes from the decay of the radioactive isotopes (mainly U^{238}, U^{235}, Th^{232} and K^{40}). The total amount of the Earth's heat is approximately 5,4x10^{21} MJ (*Armsted*, 1983). *White* calculated that the total heat contained in the first ten kilometers is equivalent to 2000 times the energy that can be produced by all the fossil fuels deposits of Earth.

1.2 *Transmission of Heat-Measurements*

The Earth's heat flows out continuously from the interior to the surface and is considered as stable and inexhaustible in human scale. Thus, it can contribute greatly to the covering of the global energy needs.

The total heat flow is approxi-mately $42x10^{12}$ W, but the cooling rate of Earth is very low, almost negligible, since it has been estimated that the mantle's temperature has been decreased merely 300-350°C during the past 3 billion years.

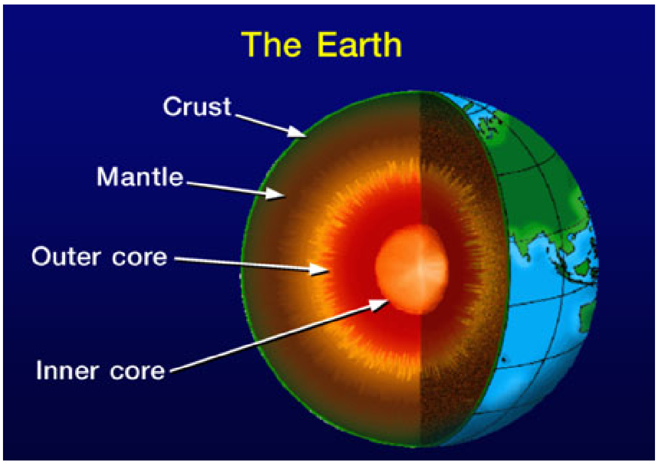
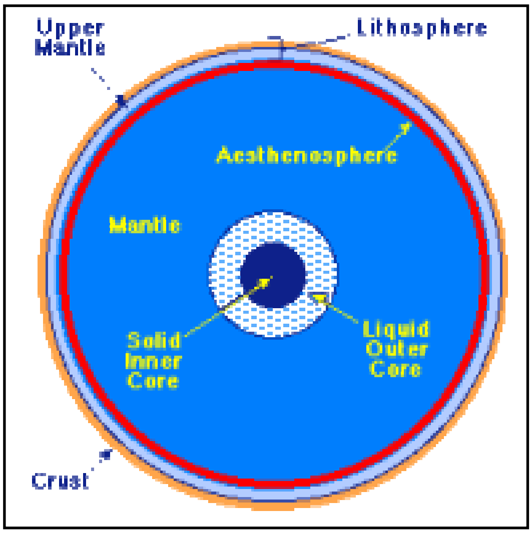


Figure 1: *Structure of the Earth*



The theoretical estimations of *Stacey & Loper (1988)* showed that $8x10^{12}$W of thermal energy come from the crust, which is relatively thin but rich in radioactive isotopes, and $1,7x10^{12}$W from the core, where these isotopes are absent.

The heat flow rate depends on the thermal conductivity of the rocks and the geothermal gradient, as it is the product of these two parameters. It is measured in Heat Flow Units (kcal/cm^2.sec or mW/m^2). For the determination of the heat flow value both parameters need to be calculated and proper conditions have to be provided.

The most reliable measurements of heat flow are those held inside deeps wells, constructed for example for hydrocarbon deposits exploration and exploitation. Unfortunately, when these wells are proved to be unproductive (95% of the cases) they are being sealed only a few hours after the end of drilling, therefore they can not be used for accurate measurements.

In addition to that, the geothermal gradient goes through several alterations during the drilling, since the circulation pulp cools the walls and the friction of the cutting edge heats them.

1.3 *Creation of favorable geothermal conditions*

As mentioned above, *White* has calculated the total heat amount that is contained in the first 10km of Earth's crust. This heat neither is concentrated in a single location nor has a unified form. The ideal conditions would be if the deposits, in the form of hot fluids, were located in small depths and had the highest possible temperatures. To accomplish that, permeable (reservoir rocks) and impermeable (cap rocks) formations and high geothermal gradients are necessary.

These conditions can be created by several geological and geodynamic procedures, by the means of which the heat can *flow* to the surface and accumulate near it. In such cases, heat can be effectively accessed and obtained in order to be exploited.

Huge amounts of heat are released along the **divergent plate boundaries**, where plates are moving apart and new crust is created by magma pushing up from the mantle. The heat flow at these zones can reach 1W/m^2 (*Waret, 1988*). The volcanic country of Iceland, which straddles the Mid-Atlantic Ridge, as well as the Afar region in East Africa, are two of the most noted places around the world where the spreading processes are evident.

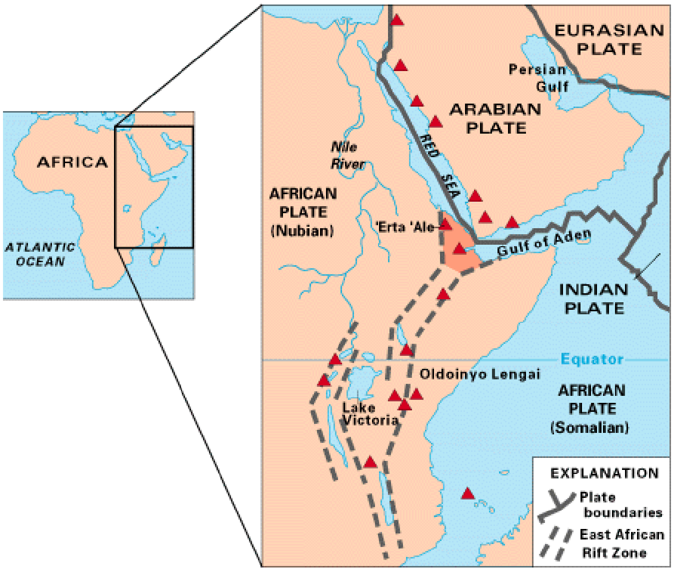


***Figure 3**: East African Rift Zone: Three plates are pulling away from one another (triple junction).*

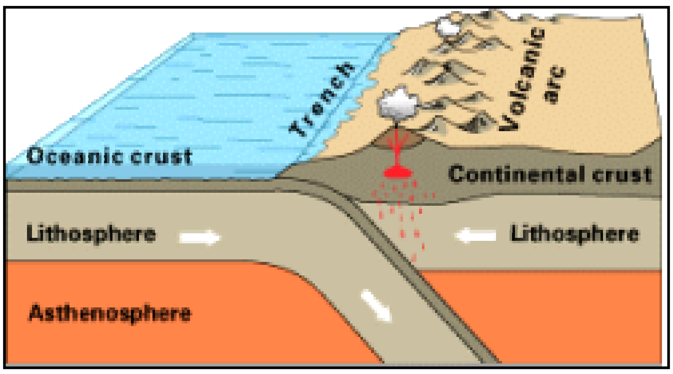


Figure 4: Oceanic-Oceanic convergence

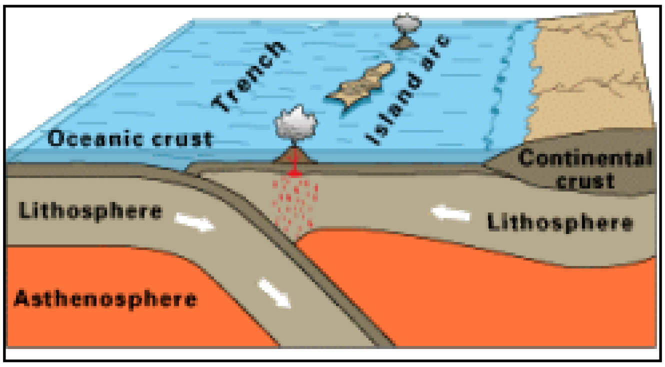


Figure 5: *Oceanic-continental convergence*

Favorable geothermal conditions can also be generated along the **convergent boundaries**, where tectonic plates dive one under another and crust is destroyed. The subducting plate slides and sinks with an angle of 30-35°, thus creating three different thermal zones, the most important of which is the third one, located 150-300km away from the oceanic trench which was created by the subduction. This zone is characterized by high rates of heat flow, since it occurs over melt zones, where the molten rocks (magma) move upwards. The ascent of the magma to the surface causes a significant heat transfer, the rate of which may be over 2,5kcal/cm^2.sec.

The type of the convergence that takes place between the tectonic plates depends on the kind of lithosphere involved. Convergence can occur between an oceanic and a continental plate, or between two oceanic plates or between two largely continental plates.

The convergence between two oceanic plates can result in the formation of volcanoes, which are typically strung out in chains called *island arcs* (e.g. Japanese arc, Philippine's arc, etc.)

The convergence between an oceanic and a continental plate cause the formation of long narrow, curving trenches which cut the ocean floor. Trenches are the deepest parts of the ocean floor, and in turn, the overriding continental plate is being lift up, creating towering mountains and continental volcanic mountain ranges (e.g. the cordilleras of Andes). The so-called "Ring of Fire" is a zone in the Pacific Ocean margins, where frequent volcanic eruptions take place. The volcanic island or cordilleras arcs in this zone are parallel to the trenches. The largest amounts of magma usually do not reach the surface but remain in relatively small depths, creating a positive thermal anomaly over the subduction zone.

The geodynamic processes that are associated with the plate motion may cause the thinning of the crust and therefore the presence of positive geothermal anomaly, since the temperatures are high in relatively small depths. Such areas are those of continental tectonic grabens, like the Rift Valley of Rhine, the Pannonic Plane, etc, as well as many places in Northern Greece (Thessaly, NW Macedonia, Almopia, Strymonas Basin, etc). The positive geothermal anomaly in areas like these is due to the rising of hot geothermal fluids towards or near the surface. In local scale, the presence of extensional tectonics and normal faults can also cause geothermal anomaly of small extend.

Other phenomena that affect the underground temperature distribution and its variation between different areas are also the age, nature and lithology of the geological formations of the crust. Conclusively, the high values of heat flow are mainly connected with the magmatism and the hydrothermal circulation, and secondly with the tectonic activity, the age and lithology of the rocks.

1.4 Heat Flow values

Since the practical interest for the exploitation of geothermal energy has to do mainly with the deposits located near the surface, additional local conditions play an important role and make the situation even more complex. These conditions are:

1. The "heat transfer" currents which are created by underground water and circulate inside large permeable formations, along big and open faults.
2. The massive introduction of cold surface water along fracture or carstic zones.
3. The creation of extended and relatively cold phreatic aquifers which "cover" and "hide" the warmer and deeper geothermal ones.
4. The intersection of impermeable geologic formations, which prevent the ascent of the hot fluids and make the heat conduct take place at a very slow rate.

2. EXPLORATION OF GEOTHERMAL ENERGY

The exploration of geothermal fields does not only depend on the favorable geologic situation but also on the relative economical-technical conditions. The cost of drilling works, in combination with the

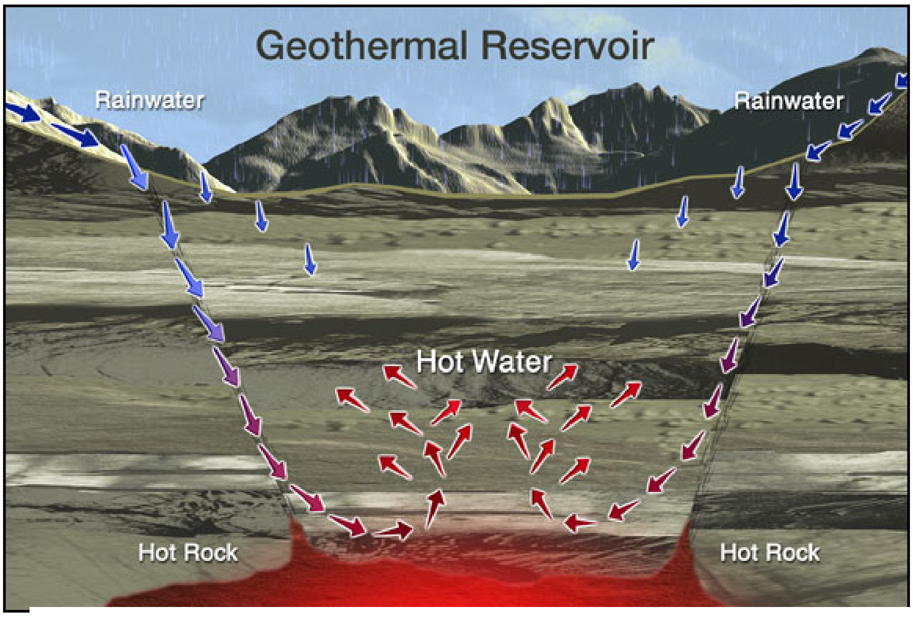


Figure 6: *Formation of a geothermal reservoir*

the quantity and quality of the produced fluids, is usually associated to the current energy unit price, which in turn depends on many imponderable factors that are imposed by the free market economy. Therefore, according to the present stan-dards, the exploration and exploitation of geothermal energy in depths bigger than 3.000m are practically disadvantageous.

In some case, even when the technology is available and the location of the deposits is favorable, the financial status may not allow the realization of an exploration project.

The most favorable circumstances are when the geothermal energy has the form of thermal fluids (mainly water with or without steam, with or without gases) which are trapped or circulate in permeable or porous rocks which are sufficiently supplied from the surface and are covered by impermeable ones.

The international experience shows that the most promising geothermal fields are those which have little or no evidence on the surface. However, the geothermal exploration must be held from the surface having the lowest possible budget. On the other hand, the most reli-able method, and the final stage of explo-ring a geothermal system, is the drilling of exploratory wells, which evidently increase significantly the overall cost of the exploration program. Therefore, before the sitting of the exploratory boreholes, a step by step program must be followed, which includes different phases of surface sur-vey. The multilateral exploration methods require the involvement of geo-scientists of different field of expertise. The proce-dure becomes progressively more and more sophisticated and detailed as the program develops. Its endmost purpose is to gradually eliminate the less interesting areas and concentrate on the most promising ones, and, finally, to decrease the risk of an error (false selection of the best drilling site) that might lead to the failure of the total project.

The systematic geothermal exploration provides the scientists with the necessary information about the underground conditions, which will lead to the construction of a realistic model of the geothermal system and the assessing of the resource potential.

2.1 Geothermal Exploration Phases

The geothermal exploration usually has the following four general phases:

1. Reconnaissance Study
2. Systematic and detailed exploration of the possible geothermal areas
3. Identification of the geothermal field, determination of its type, estimation of its extension and study of its characteristics
4. Construction of exploratory wells, Feasibility Studies

2.1.1 Reconnaissance Phase

Before drawing up a geothermal exploration program, all existing geological, geophysical and geochemical data must be collected and integrated with any other data available from previous studies in the area of interest and adjacent areas.

The purpose of this stage is to determine the most favorable areas, taking under consideration all the parameters: scientific, social and financial.

2.1.2 Systematic exploration

The systematic exploration is being held by the means of various methods, the most important of which are the geological and volcanological study, detailed mapping of the formations, tectonic analysis, hydrogeological study, detailed geochemical survey, geophysical prospecting and finally detailed heat-flow and temperature measurements.

2.1.2.1 Geological Study-Detailed mapping

The geological study of an area includes stratigraphic, lithological-petrological research and dating of the formations that dominate the geothermal field. The interpretation and evaluation of these data are essential for the understanding of the geothermal situation and the type (thickness, depth, porosity-permeability, etc) of the reservoir and the cover formations.

The most appropriate mapping scale for the systematic geothermal exploration is 1:10000 or 1:20000, which provides the necessary information for the determination of the geology, the geomorphology and the general tectonic status of the study area.

2.1.2.2 Volcanological Study

If the potential geothermal field lies in a volcanic area or if it is dominated by volcanic or magmatic formations, the volcanological study is obviously considered being indispensable.

The active or recent volcanism can sometime splay an important role to the formation of geothermal resources, since it may increase significantly the value of the geothermal gradient.

Where magma reaches the surface it can build volcanoes. But most magma stays well below ground, creating huge subterranean regions of hot rocks. These shallow regions of relatively elevated crustal heat have high temperature gradients. Consequently, the magmatic activity is important from the geothermal point of view; thus it must be studied in detail.

The aim of this study is the creation of a detailed volcanological –magmatological map, the clarification and determination of the volcanic and volcano-tectonic structures, the identification of the post-volcanic hydrothermal activity and its effects on the geological formations of the area, the dating of the volcanic rocks, the specification of the activity type, etc.

2.1.2.3 Tectonic and Neotectonic analysis

The tectonic structure can affect greatly the geothermal regime of an area, providing the necessary conditions for the circulation of deeper and therefore warmer fluids, which contribute to the convention of big amounts of thermal energy from the underground to the surface.

The normal faults are basically the main cause of the hot springs' creation, since they allow the ascent of the fluids. Consequently, the extensional tectonic activity can give rise to an extensive thermal anomaly. The latter, may have the form of a straight line or narrow zone along a fault, or a more complex shape when the underground route of the fluids is influenced by many aquifers and complicated geological structures.

The positive geothermal anomalies are always located in areas of very recent and active tectonic activity that sometimes creates recent or active magmatism and fractures and opens the “path” for the fluids to ascent to the surface.

2.1.2.4 Geothermal and Hydrogeological Studies

The underground circulation of water depends on the hydrogeological situation of the wider area. The inflow of meteoric water is determined by the lithology of the formations and the tectonic structure of the area. The underground horizontal circulation is affected by the sediments or other formations and particularly by the hydraulic characteristics.

Therefore, the available quantity of the geothermal fluids is directly related to the hydrogeological and hydrological conditions as well as on the energy characteristics of the fluids themselves.

The hydrothermal alteration of the formations, inside which the thermal fluids circulate, diminishes or even demolishes their permeability and storage capability.

On the contrary, the solubility of minerals (e.g. anhydrite) or limestones originates vacuities, which facilitate greatly the circulation and the storage of the geothermal fluids inside the secondary vacancies.

The differentiation of the *classical* hydrogeology and hydrology situation in a geothermal system is therefore evident, because the relation between the physical parameters of the “cold” underground water and “thermal” geothermal fluids is changed.

The geothermal fluids, which are heated by a magmatic source, pass to the gas phase, so their movement to the surface becomes easier and their pressure increases. Thus, they may come out to the surface having the form of fumaroles or geysers, usually following the tectonic lines.

2.1.2.5 Geochemical Survey

The identification of the deep geothermal reservoir characteristics can be achieved by the systematic study of the chemical properties of the fluids, which are met in surface or underground aquifers (*Henley & Ellis, 1983*). Therefore, the geochemical survey is a useful means of determining the type of a geothermal system (if it water or steam dominated) and the source of recharge water, of estimating the minimum temperature expected at depth, as well as the homogeneity of the water supply. Valuable information can also be obtained on what problems are likely to arise during the utilization phase (e.g. corrosion and scaling on pipes and plant installations, environmental impact) and how to avoid or combat them.

The geochemical survey includes sampling and chemical and/or isotope analyses of the water or gas from the geothermal manifestations (hot springs, fumaroles, etc) or wells in the study area. The chemical analyses of many and well-distributed samples makes the discovery of deep geothermal water much more statistically probable.

The geothermal fluids usually contain a large variety and big quantity of dissolved ingredients and elements, which constitute the *Total Dissolved Solids* factor (T.D.S.), and a small quantity of gases, the value of which is usually more than 5% of the TDS one.

The TDS factor actually indicates the salinity of a geothermal fluid. Its values range between a few hundreds and a few hundreds of thousands p.p.m. per Lt.

The most common, and often the sole, geothermal gas in low enthalpy fluids is CO_2, while in high enthalpy fluids other gases are contained as well. The “hydrothermal alteration» is a term used to indicate the mineralogical modifications caused to the rocks by their interaction with the fluids. Some of the reservoir’s minerals may be dissolved while others may be deposited. In addition, some elements from the fluid may substitute elements from the minerals or rocks.

The SiO_2 and $CaCO_3$ are the most common minerals that are deposited in a geothermal system. The solubility of SiO_2 decreases in proportion to the decrease of temperature, while pressure has a small impact. The deposits of SiO_2 (quartz), which are found on or below the surface, can sometimes constitute fossilized geothermal systems.

The calcite ($CaCO_3$) has a retrograde solubility, which means that it is more soluble in low temperature water, like other carbonate (dolomite, $MgCO_3$) or sulfureous minerals (anhydrite, $CaSO_4$).

Physico-chemical Characteristics of Geothermal Fluids

The chemical composition of the geothermal fluids is the product of their formation. The pH of the regular underground water is usually neutral and their character is bicarbonate. When they enter a geothermal system, they tend to be more of the chloride-sodium type, with their TDS values ranging from a few hundreds to 300.000 mg/lt. If the fluids' temperature is higher than the boiling point, the CO_2 or H_2S are being separated in the steam phase and move independently towards the surface.

Various systems (diagrams) of describing schematically the chemical character of the geothermal water have been invented (*Hem, 1970*). The most common method in geothermal research is the one designed by *Piper* (1944), which is based on the relative concentration of the ions Na^+, K^+, Mg^{++}, Cl^-, F, $SO_4^=$ and HCO_3^- + $CO_3^=$, that are contained in a geothermal fluid.

Chemical Geothermometry

The chemical analyses of the geothermal fluids can sometimes be used to estimate the initial temperature of the underground reservoir. This kind of information is obviously extremely valuable, especially when the temperature measurements inside the wells are not feasible. Thus, several different *geothermometers* have been successfully used for the estimation of the reservoir temperatures. These geothermometers are empirical and have been determined mainly by *Fournier (1981)* and *Henley et al. (1984)*.

The SiO_2 is an element the concentration of which is largely modificated in proportion to the temperature of the geothermal fluid. Thus, it is extensively used as a geothermometer.

Another system is based on the balance, which occurs between the elements Na, K, Ca & Mg, when the reservoir formations contain abundant quartz or feldspar minerals (*Fournier & Truesdell, 1973)*.

The use of different chemical geothermometers may have different results, even if they are implemented to the same geothermal fluids. Therefore, the usage of all the available geochemical and geological data can contribute to the evaluation of the credibility of each geothermometer for specific geologic conditions.

3. GEOTHERMAL ENERGY IN GREECE

Greece is a favored country from the geothermal point of view, since is very rich in geothermal waters and its potential has been characterized as significant. The origin of the geothermal fields is mainly associated to the wider area's geodynamic regime, with the active extensional tectonics affecting a wide area. In Greece there are two high enthalpy geothermal fields, in the islands Milos and Nisyros, where seven deep wells identified temperatures of 320°C and 350°C respectively. Low enthalpy fields abound in Greece, mainly in the east and north parts of the country, as well as in many Aegean islands. Present data yield a low enthalpy potential exceeding 400MWt proven and 800MWt probable (fig. 7).

Exploration

During the past years, the geothermal potential has markedly expanded through continuous research and production activities. The bulk of exploration projects were carried out mainly by the Institute of Geological and Mineral Exploration (IGME) and Universities.

The significant amount of new data and information that has been collected, revealed new low enthalpy fields, most of which are located in Northern Greece. Even in less favorable area, like Western Greece, new very promising data have been acquired.

The geothermal anomalies in Greece are mainly located in Tertiary-Quaternary basins with recent tectonic activity. Several exploratory wells have been constructed in these areas, some of which are already being used as productive ones, while others are planned to be utilized in the near future.

In some of the already identified geothermal areas, new, additional wells have been drilled, in order to better determine the extension of the field and the characteristics of the fluids.

Furthermore, in a number of cases (e.g. Sidirokastro and Therma Nigrita, *Strymon Basin*) complementary exploration indicated higher temperatures than the ones measured in the past.

In the following paragraphs a brief description of the most characteristic geothermal fields in Greece and the recent exploration activities is presented.

The *Strymon Basin* in East Macedonia is one of the most extensive geothermal areas in Greece, including several fields. During the past years, the Agistro geothermal field was studied, explored and delimited, the margins of the known fields of Therma, Nigrita and Sidirokastro were investigated resulting in the obtainment of new data. Recently, exploration projects were realized in the areas of **Achinos** and **Ivira**, which had shown evidence of great geothermal interest. Two, relatively deep (~500m) exploratory and one productive well (650m) were constructed there, establishing the great potential of the area. The geothermal reservoirs that were identified are remarkable, with temperatures that range between 40 and 75°C, while additional boreholes yields over 220kgr/sec. The production tests and the chemical analyses that took place determined the hydraulic characteristics of the aquifer and its behavior regarding the corrosion and scaling problems. The positive and stimulating new data has become the incentive for investments and further development in the area. The total extent of the geothermal area is estimated to be approximately 25km^2.

In the geothermal field of **Agistro**, the reservoir is located at the fractured metamorphic basement of the basin, which is covered by a weakly permeable cap. The exploratory and productive wells at 100-300m, showed temperatures of 40-47°C, while the exploitable flow rate was of the order of 30kg/sec. The geothermal water belongs to the group of carbonate-calcium-sodium type, with a T.D.S. of 0,26 gr/Lt, while no corrosion or scaling problems were encountered.

The geothermal reservoir of **Sidirokastro** is also located on the top of the metamorphic basement (marble) and in the basal conglomerates of Neogene. The geothermal water belongs to the group of carbonate-calcium-sodium type, with a T.D.S. just exceeding 1gr/Lt. The known extent of this field is about 14km^2.

During the past decade, additional exploration activities took place in the area of **Therma-Nigrita** area, with the construction of 9 new exploratory-productive wells at the depth of 80-370m, yielding more than 200kg/sec, 125 of which correspond to self-flowing wells. The fluids are rich in CO_2 and their temperature is 40-64°C. They belong to the group of acid carbonate-sodium-magnesium type with TDS ranging between 1,5-2,5 gr/Lt. The reservoir is located in the formation of the basal conglomerates.

Two new productive wells have been drilled in the area of **Eratino**, each 670m deep, yielding about 100kgr/sec artesian flow of 75°C water. The water originates from some permeable horizons at the dept of 550-650m, in the Miocene sediments.

In the area of *Mygdonia Basin*, three important fields were found in the past and have been further explored and exploited recently. A new productive well (120m deep) was drilled in the geothermal field of **Nymfopetra**, having water of 42°C, for the heating of asparagus cultivations. In the field of **Nea Apollonia**, two new productive wells (30m each) produce more than 100kgr/sec water of 56°C. The water is being transported to a nearby Spa complex for balneological and heating purposes. In the area of **Langadas** Spa, three new productive wells were constructed to cover the heating/cooling demands of several buildings of the town. The temperatures were 40, 29 and 20°C and the flow rate was 45, 120 and 80m^3/h respectively.

The geothermal field of **Neo Ryssio** is located close to the airport of Thessaloniki, where was constructed. An interesting geothermal gradient within the Quarternary-Miocene sediments was revealed, after the drilling of a 600m deep explo-ratory well. Important reservoirs are ex-pected inside the middle Miocene sedi-ments at the depth of approximately 800m with a temperature of 60°C. A new exploration-exploitation project is in prog-ress in this area, in order to use the geothermal potential for heating purposes.

In the new Campus of Aristotle University (**Thermi**, Thessaloniki) an interesting reservoir was identified, at the depth of

300m. The geothermal reservoir has artesian flow and its temperature is 24-29°C. The quality of the water is excellent. The construction of the well was financed by A.U.TH., in the frame of a geothermal exploration-exploitation project.

In Chalkidiki Peninsula, in **Sani** and **Afytos** areas, exploratory wells were drilled down to 600°C and revealed an artesian aquifer of bicarbonate fluid with 40°C temperature.

Two exploratory wells in **Irinoupoli** identified a 27°C fluid of high salinity at the depth of 400m.

Southwards of Irinoupoli, in the area of **Nissi**, two new exploratory wells were drilled, identifying a 35°C fluid of low salinity and high productivity at the depth of 500-580m.

Limnochori (NW Macedonia), is another interesting and promising geothermal area in Northern Greece, where the explorwtory wells yield more than 30kgr/sec water of 38°C. This reservoir is located at the top of the metamorphic basement of the basin at the depth of 200m.

In Western Macedonia, near the town of **Florina**, a new area of geothermal interest was accidentally found during the drilling of irrigation wells. The geothermal area seems to follow the important fault system of the area. Two 300m deep production wells yield 110 kgr/sec of water of 27°C and rich in CO_2.

In *Thrace*, the geothermal exploration expanded our knoweledge about the known geothermal areas, while two new geothermal fileds were identified (Sappes and Komotini).

The exploration that was carried out in the area of **Aristino-Aetochori**, resulted in the enlargement of the geothermal field known boundaries and the measured temperatures extended to 92°C. A new well yields more than 60kgr/sec of water from the depth of 300m.

In the area of **Neo Erasmio**, three new wells produce artesian water of significant flow rate, the temperature of which is 60°C.

Within the area of the **Traianoupolis** hot springs, two production wells were constructed for the heating system of the Spa complex. The wells yield about 30kgr/sec water of 52°C (Angelidis, 1999).

The geothermal field of **Nea Kessani** was extended towards the southeastern direction, after the information obtained by two new wells at the depth of 450 m, which produce water of 38°C that is used for anti-frost protection of the artificial ponds for fish-culture.

The geothermal field of **Sappes** was discovered recently after the drilling of four exploratory and three productive wells. A very important reservoir is located in the Tertiary volcanic formations and provides fresh water of artesian flow with 40°C temperature. The total extension of the field is estimated to be 25km^2.

Likewise, in **South Komotini** area, 5 exploratory wells indicated a new geothermal area of 30km^2, with temperatures approximately 40°C.

In the area of *Aegean*, the recently explored geothermal fields are in Lesvos, Chios Samothraki and Kimolos islands.

Lesvos Island: The Public Power Corporation (PPC) has financed an exploration program (Koutroupis, 1999), in the frame of which nine shallow wells were initially drilled (6 in Stipsi and 3 in Argennos area). Their temperatures were 92°C (Stipsi) and 86°C (Argennos) at a depth of 200m. At a second stage, three deeper wells (600m) were additionally constructed at the same areas, confirming the anticipated results. PPC plans to start a new drilling program for deeper wells (about 2km), in order to install a Rankine Cycle power production unit, in the area between Stipsi and Petra.

Chios Island: A new geothermal field was discovered in the area of Nenita. Its reservoir is located in the Mesozoic limestones, which are covered by impermeable sedimentary formations. Five exploratory boreholes were opened, which found the geothermal reservoir at the depth of 300-400m. The temperature of the fluids is 90°C and the extension of the field more than 5km^2. So far, a production well has been constructed for the evaluation of the reservoir's hydraulic parameters, the flow rate and the chemical composition of the fluids, which seem to belong to the group of sodium-chloride type with TDS>40gr/Lt.

Samothraki Island: Three new wells were drilled in the area of **Therma**, near the Spas, at the depth of 120m. The wells yield a high flow rate of high salinity fluids with 100°C temperature (Angelidis, 1999).

Kimolos Island: Two new wells were constructed in Kimolos isle, in the frame of a desalination project. The depth of the wells was 200m, the quantity of the fluids was large, while their temperature reach 60°C.

In *Western Greece*, (Epirus region) two new geothermal areas were discovered: the area of Sykies (Arta) and Konitsa (Ioannina).

Sykies: Two exploratory and one productive well at the depth of 300m were constructed, identifying a geothermal reservoir within the limestones at temperatures of 40-45°C, covering an area of more than $1km^2$. The geothermal water belongs to the group of $Na\text{-}Ca\text{-}Mg\text{-}HCO_3\text{-}Cl$ with TDS≈4gr/Lt, containing CH_4 and H_2S gas. The exploration program is still under progress.

Konitsa: During the exploration program that is being held in the area, a 300m deep exploratory well has been constructed, identifying a reservoir of 38°C within the limestones. The geothermal fluids most probably belong to the magnesium sulphate water group, with a TDS of 1,3 gr/Lt.

Some interesting geothermal fields have also been explored in the mainland of *Central Greece*. To start with, close to the city of Patra, in the area of **Antirrio**, an exploratory well encountered temperatures of 38°C at the depth of 150m. Secondly, in **Kavouri** (Athens), two wells have been constructed in the past years for production-injection purposes. Each of the wells yields more than 4kgr/sec water of high salinity and 36°C.

Exploitation

The exploitation of geothermal energy in Greece during the past decade is kept to direct uses. No electricity was produced for the sole geothermal power plant in Greece (2MWe in Milos Island).

The majority of the direct geothermal uses refer to greenhouse and soil heating, and secondly to space or district heating applications. The thermal capacity of the direct heat projects in operation (excluding Spas) is approximately 22MWt, representing an annual energy utilization of 221 TJ/yr.

The already constructed infrastructure in the fields of Nea Kessani, Thrace and Mygdonia Basin unfortunately remains unexploited due to managerial and financial problems. On the contrary, the new space heating project in Traianoupolis' Spa is successfully operating, while another project for heating the new spa complex of Nea Apollonia, has been already been completed but is not yet in operation. Two office buildings, in Neo Erasmio and Nea Apollonia, are being heated by geothermal energy, using floor radiant panels. Finally, Langadas district heating project, which is in its final stage, aims at heating a number of buildings in the nearby town of Langadas.

Nevertheless, the most significant development of geothermal direct uses refers to the agricultural sector, through the establishment of approximately 12ha of soil heating of asparagus cultivation in Macedonia and Thrace fields. The soil heating is accomplished by the direct flow of the geothermal water through corrugated polypropylene pipes placed underground. Despite the abundance of geothermal water with temperature over 100°C in Greece, the vast majority (~75%) of the greenhouse and soil heating applications use temperatures below 50°C.

Today, 56 Spas and Bathing Centers are in operation in Greece. During the past few years, many of them have been expanded or renovated. Most of them are open only during the balneological period (June-October), but lately, since the demand for nonstop service has increased, several spa resorts remain in operation all year long. One of the most known Spa Centers in Greece is the one of Therma Sylla (Edipsos), which has been recently restored and become a modern and luxurious place for balneo-therapy. Unfortunately, no systematic work has been carried out to estimate accurately the heat use in Spas. It can be roughly estimated that the total water flow exceeds 1000 kgr/sec, and the water temperature range between 18-90°C. Assuming that the temperature of the water after its utilization in the spas is 30°C, it can be calculated that the total thermal capacity of the Greek Spas is 35 MWt with a load factor of 0.15.

Figure 7: Greek geothermal fields