Geothermal Reservoirs in Volcanic Islands: The Example of Santorini, Greece

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ABSTRACT

Santorini is one of the most original, beautiful and impressive volcanic island complexes on this planet. At the same time, it is one of the most violent and destructive volcanoes on Earth. Approximately two million years ago, the volcanic activity in the area produced molten rock for the first time. It has taken thousands of eruptions since then to build up the present shape of Santorini. In the last 400,000 years there have been more than 100 eruptions slowly adding more rock and making the island bigger. Some of these eruptions were so violent that they demolished a large part of the volcano. The last catastrophic eruption occurred 3600 years ago, during the Late Bronze Age. It extinguished every trace of life and civilization that flourished in the Aegean area. The tremendous eruption of 1600 BC is known as the Minoan Eruption. It ejected into the air between 30 km^3 and 90 km^3 of magma in the form of pumice and volcanic ash. This material buried the island, plants, animals, people, and its culture. The most recent eruptions at Santorini occurred in 1939, 1941 and 1950.

This paper presents a brief description of the historical and recent volcanic activity at Santorini, the collapse of the original volcano and the formation of the present island complex, composed of the fragments that remained above the surface of the sea after the collapse. Several superficial evidences, like abnormal temperatures, a gas - leakage anomaly near one of the main island's cape, and a good fault-controlled vertical permeability, are probably related to the presence of a local hydrothermal submarine reservoir. We introduce a preliminary coarse evaluation of the geothermal potential of the zone, which can be considered as an example of the energy contained in volcanic islands.

1. INTRODUCTION

Approximately 62% of the active volcanoes on the planet lie along volcanic arcs near lithospheric subduction zones. This volcano-tectonic phenomenon is exemplified by dozens of island arcs around the world, such as the Antilles, the islands of Japan, the Aleutian Chain, and the South Aegean Volcanic Arc. Although the material erupted every year from these islands is small, heat flows related to these formations are considerable. According to Ungemach (2002), heat flow values as high as 600 mWm^{-2} have been registered at volcanic arcs, while the heat flows of the forearc and backarc regions register values of 30 and 90 mWm^2, respectively. In addition, the distinct physical settings that characterize these islands propitiate the formation of usable hydrothermal reservoirs (Ungemach, 2002). Most of these geothermal sources are related to quaternary volcanic systems, where calc-alkaline formations are present. Usually the fluids emanating from locations on volcanic arcs are a mixture consisting of fluvial, sea and connate water as well as magmatic gasses. Many times the geothermal reservoir is made up of a "*dual aquifer combining (i) a shallow hot water or even saturating steam-bearing horizon with predominantly meteoric recharge and (ii) a deeper seated, hotter, hydrothermal reservoir with likely seawater, connate/magmatic liquid and gas intakes.*" The tools provided by geochemistry can be useful in determining the origin and mixing of fluids in such systems.

With its whitewashed architecture and sun-bathed beaches, Santorini is perhaps best known as a popular tourist destination. Indeed, during the summer, the population increases up to one order of magnitude (Ungemach, 2002). Despite the serene aspect Santorini presents today, its history is replete with acts of destruction and violence. Circa 1600 BC, a huge plinian eruption shattered the island. Vast amounts of pumice, scoria, and ash were ejected into the atmosphere. After the volcanic edifice collapsed, gargantuan tsunamis reached the shores of Crete, triggering, some speculate, the eventual downfall of the Minoan Civilization. Although Santorini's last eruptive period ended during the mid - 20th Century, the presence of submarine thermal springs and sub-aerial fumaroles is reminder of the volcano's continuing activity. Yet, these characteristic also present a different prospect: the existence of an exploitable geothermal reservoir, which could prove quite beneficial to an island community that largely depends on imported energetic resources.

2. A BRIEF HISTORY OF THE SEISMIC ACTIVITY IN GREECE

Greece has a large concentration of earthquakes, exhibiting the highest seismicity in Europe and in the whole western Eurasia. The country itself is a natural laboratory, located in a region where the African plate is subducting under the Eurasian plate, accounting for over 50% of its seismic energy release per km^2. Greece also has a long cultural recorded history of damaging earthquakes. The first person to record a seismic event in Greece was Cicero, who wrote about a strong earthquake that ruined Sparta in 550 BC. Cicero also reported on the collapse of a portion of the Mt Taygetos's summit.

"*No historic information on the effects of earthquakes before the VI century BC exists. The ideas of people on the causes of earthquake generation for the fore-philosophical period had a mythological character. Thus, according to the tradition, Engelados, son of Tartaros and of Earth and leader of Giants, causes the earthquakes. Several myths are known for Engelados. According to the most known of them, he was killed by Athena who chased him, threw Sicily against him and completely covered him. Since then, Engelados moves and sighs in his grave and causes the*

earthquakes and the volcanic eruptions… Even up to the middle of the nineteenth century, information on the earthquakes is coming from no specialists on the subject (philosophers, historians, travelers, etc). For this reason, the information comes mainly from macroseismic effects of large shocks (destructions of buildings, ground changes, tsunamis, deaths, etc.) and only fragments of some ideas about the way and causes of earthquake generation are stated.", (Karakaisis & Papazachos, 2001).

The total number of known strong earthquakes occurred in Greece during the period 550 BC-1995 AD is about 600 (Karakaisis and Papazachos, 2001). These authors separate this chronology into three main intervals, according to the number of earthquakes that have been studied.

2.1 Period 550 BC - 1550 AD

About 150 strong earthquakes (M ≥ 6.0) occurred, with an average of about seven strong earthquakes per century.

2.2 Period 1550 - 1845 AD

The total number of earthquakes during this interval is about 170 and therefore their frequency is about 60 earthquakes per century.

2.3 Period 1845 –Present Day

The total number of strong earthquakes (M ≥ 6.0) studied during this period is 270; the present mean rate of strong earthquake generation in this area is about 200 earthquakes per century.

The tectonic movement in the region is also responsible for intense Tertiary and Quaternary volcanic activity in Greece. During the Oligocene, volcanism was mainly concentrated in northern Greece. Activity, however, slowly shifted southwest to the Aegean Sea, forming the present Aegean Volcanic Arc. Located on the southern edge of the Cyclades Plateau, the arc stretches 450 km from the islands of Nisyros and Kos, through Santorini and Milos, to Peloponnesian Peninsula. Volcanic products exhibit an evolution from basalts to rhyolites and demonstrate a calc-alkaline relationship characteristic of island arc formations (Panichi et al., 2000).

The high seismic activity of the zone is attributed to the convergence of the Aegean portion of the Eurasian lithospheric plate and the front part of the African plate. This region, called a Benioff zone for earthquakes, is found at an intermediate depth of 60-180 km beneath the volcanic arc (Papazachos and Papazachou, 1997).

Figure 1 illustrates the present day seismicity in Greece. Figure 2 shows the recent seismic activity in Santorini (Figure 3), which is permanently monitored by the Aristotle University of Thessaloniki and by the Institute for the Study and Monitoring of the Santorini Volcano (ISMOSAV).

2.4 The Geothermal Situation in the Aegean Arc Region

According to Fytikas *et al*. (2005), the interaction between the northeastward moving African plate and the Aegean microplate has produced heat flows higher than 80 mM/m^2 in the Hellenides and the Aegean sea. Furthermore, large amounts of gas are released from hydrothermal vents in shallow waters (less than 200 m) throughout the Aegean Volcanic Arc. This volume of gas, mostly CO_2, comes from degassing of the subducted plate and the mantle and from the decomposition of carbonates on the seabed. A few examples of these vents can be found on the islands of Milos, Santorini and Nysiros (Dando *et al*, 1999). Several such hydrothermal systems, resulting from intense volcanic and seismic activity, represent potential geothermal reservoirs. High enthalpy and several low-medium enthalpy geothermal fields (associated with graben structures) have been located within the southern and central portions of the Aegean (Fytikas *et al*, 2005). The rest of this paper will deal specifically with the island complex of Santorini in the central portion of the Aegean Volcanic Arc. The data presented in the following sections show that Santorini, an island arc volcano, harbors an important medium to high geothermal reservoir, which may be of great use in the coming decades.
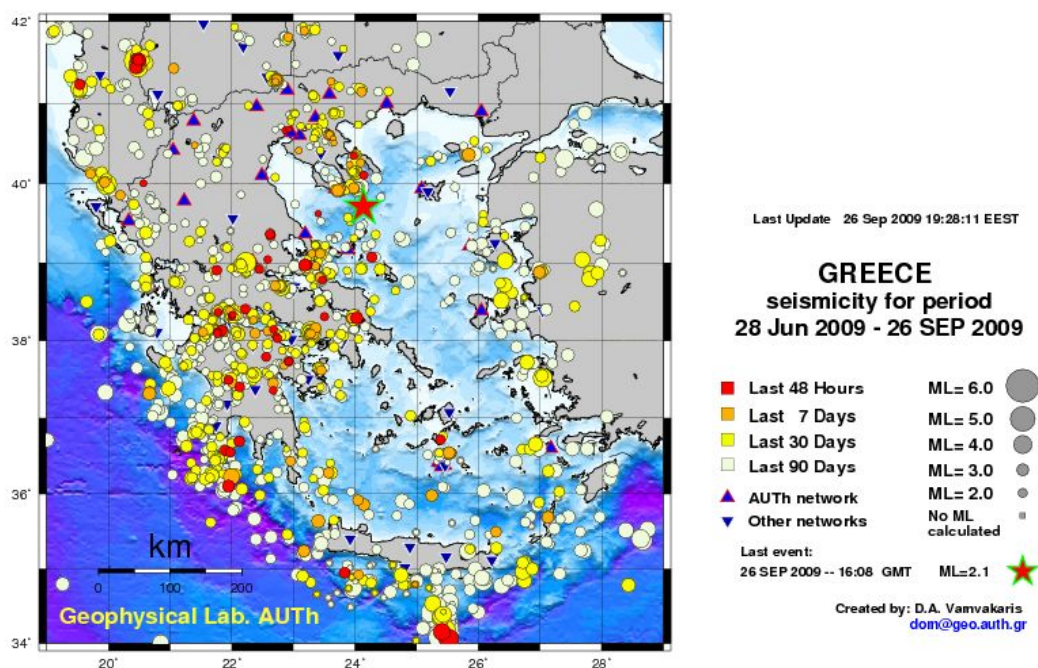

Figure 1: Present Greece seismicity. Measured and published by the Seismological Station of the Aristotle University of Thessaloniki (*http://lemnos.geo.auth.gr/the_seisnet/WEBSITE_2005/station_index.html*).
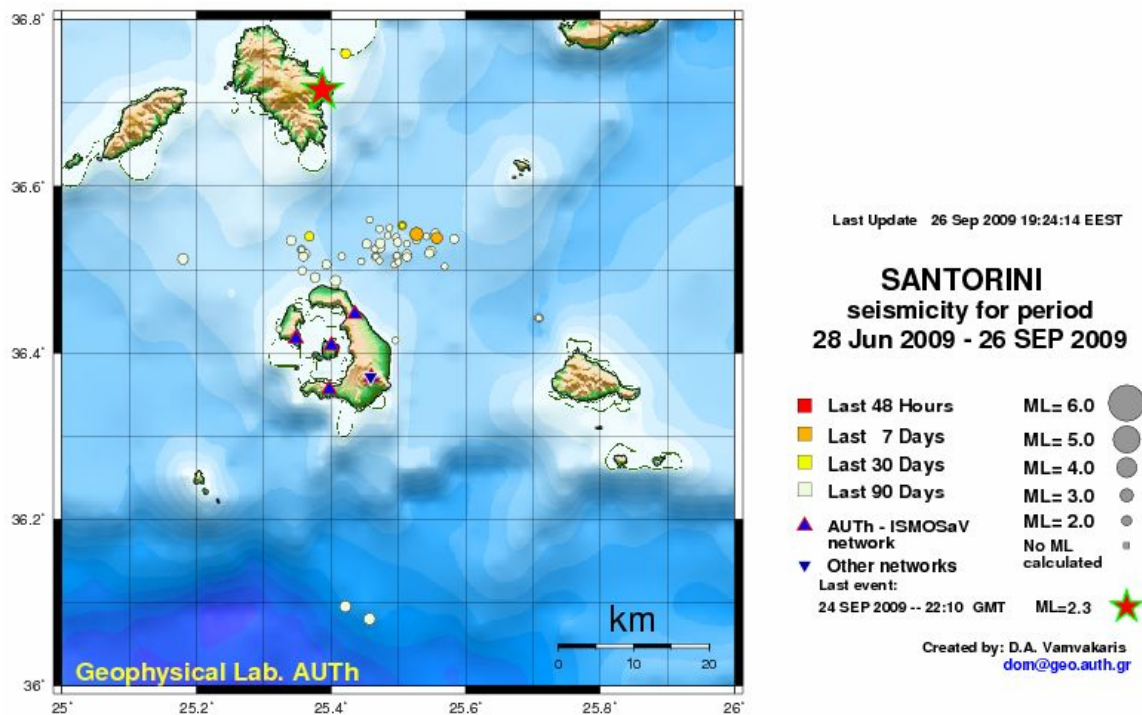
Figure 2: Location of the Santorini Caldera showing its present seismicity. The Seismological Station of the Aristotle University of Thessaloniki.
(*http://geophysics.geo.auth.gr/the_seisnet/WEBSITE_2005/REAL_TIME_MAPS/index.htm*).
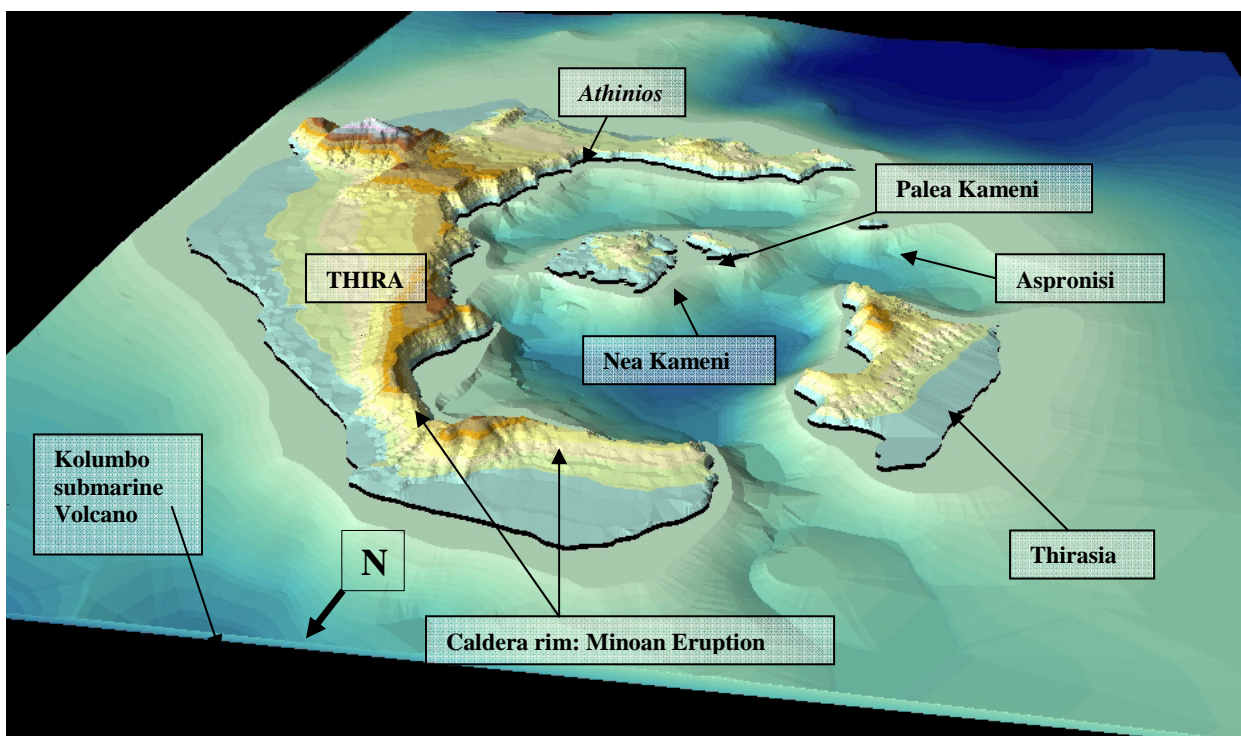

Figure 3: The Santorini Island Complex: Thira, Thirasia, Aspronisi, Palea Kameni and Nea Kameni.

3. THE CALDERA OF SANTORINI

The Santorini Caldera is the youngest active volcanic complex in Greece. It is located on the active front of the previously mentioned Aegean Arc and is formed by five islands of different characteristics (Figure 3). Three islands form the caldera rim, the largest of which is called Thira (E). To the NW of Thira lies Thirasia. The small Aspronisi

rises from the sea to the West. Two other small islands are in the center of the complex: the 2000-year-old Palea Kameni (Old Burnt Island), and Nea Kameni (Young Burnt Island), which has an approximate age of 425 years. Nea Kameni has a total surface area of 340 hectares, with its highest point at 127 masl. Palea Kameni has only 60 hectares and a maximum elevation of almost 100 masl (Vougioukalakis, 2007). Thirasia, Thira and Aspronisi are

the remnants of a series of volcanic collapses, the last of which was the terrible Minoan explosive eruption, which occurred 3600 years ago. During this paroxysmal event, the Strongili volcano collapsed, creating the grand cauldron of the Santorini caldera. About 30 km^3 of volcanic material were expelled during the eruption, much of which was deposited throughout the Mediterranean. The islands we see today are the fragments that prevail on the sea's surface after the catastrophic collapse (Vougioukalakis, 2007). Although no events similar to the Minoan eruption have occurred in recent times, the entire island complex is still exposed to a severe volcanic and seismic hazard (Figure 2).

Palea Kameni and Nea Kameni emerged from the sea in the centre of the Minoan caldera (Figure 3), by extrusion and effusion of dacitic domes and lava flows between 197 BC and 1950. Post-Minoan volcanic activity is almost entirely confined within the caldera. The only post-Minoan activity outside the caldera occurred in 1650 at the Kolumbo submarine volcano, 6.5 km offshore to the NE of Thira (Figure 3). An active fault system connects Thira and the Kolumbo volcano; it is marked on Thira by three NE-NNE-trending faults and by intense seismicity in the sector between Thira and Kolumbo. The historically eruptive vents of Palea Kameni and Nea Kameni are aligned in a NESW direction. The Kameni line and the Kolumbo line are the two tectono-volcanic systems with the most active tectonic features on Santorini, Both lines trace the sites where volcanic and seismic activities have the highest probability of occurring in the future (ISMOSAV, 2008).

A granite intrusion was encountered by a geothermal borehole, 250 m deep, drilled in the southeastern caldera rim near Athinios. A geothermal anomaly has been identified in the southern part of Thira, in a graben-like structure between Akrotiri and the prevolcanic basement outcrop (Barberi and Carapezza, 1994). Other recent faults have been mapped on Thira (Vougioukalakis, 2007). The most interesting is the NNE fault system of the southern part of the island. This fault system represents the eastern limit of the thermal area and is connected to the geothermal reservoir. This system feeds the most interesting thermal springs of Santorini (Vougioukalakis, 2007).

4. GEOTHERMAL SURVEYS ON SANTORINI

Several surveys were carried out on Santorini during the 1980s (Ungemach, 2002). The following section summarizes the finding of these early endeavors. The first two exploratory wells were drilled in northern Thira (near the Kolumbo peninsula). However, these 120 m-deep boreholes revealed that unconsolidated pyroclastic deposits permit an abundant intrusion of seawater (buffer effect) and no pronounced thermal gradient was detected (Fytikas et al., 1990).

A second location of geothermal interest during the initial exploratory period was the Akrotiri-Megalochori region, in southern Thira. Gravity and magnetic surveys presupposed the existence of a north-south Bouguer gravity anomaly between Emborio and Faros, a graben with a maximum depth of 1500 m (Mendrinos, Polyzou and Karytsas, 2007). The eastern edge of the depression produced the highest recorded temperature values. Since then, fieldwork in the area has confirmed the existence of such graben, which is composed of multiple faults and formations altered by hydrothermal activity.

After the gravity and magnetic surveys, nine slim boreholes were drilled in southern Thira reaching a depth of 200 m. Three of the boreholes, S-6, S-10 and S-11, showed that the stratigraphy and lithology of the formations regulated a noteworthy thermal gradient. Following the shallow boreholes, three deeper wells (S1, S2, S3) were drilled at the edge of the graben to better understand the origin of the fluids, gain insight on the thermal gradient within impermeable rock formations and study the structure of the basement (Fytikas et al., 1990).

Borehole S1 was drilled near Megalo Vouno. The first 200 m consisted mainly of pyroclastic deposits such as pumice, ash and scoria. Metamorphic formations were encountered between -210 and -255 m. The next 25 meters consisted of a granitic intrusion. S1 presented a maximum temperature of 64.7°C at - 240 m and a rather steep thermal gradient of 16°C/100 m (Fytikas et al, 1990).

Borehole S2 was drilled SSE of the S1. The drilling process encountered pyroclastic deposits down to a depth of 240 m. From -240 to -455 m, an Akrotiri series of andesitic-dactic lavas and tuffs were perforated. The final layer (between - 455 and – 460 m) consisted of metamorphic rock. The measured thermal gradient in this borehole fluctuated substantially before entering Akrotiri series. The estimated gradient in the impermeable structures was 13°C/100 m. Borehole S2 demonstrated a maximum temperature of 52.3°C at – 440 m (Fytikas et al., 1990).

Borehole S3, near Megalochori, perforated a layer of pyroclasts (down to -145 m) and metamorphic rock. At the bottom of the well (-260 m) a maximum temperature of 51.2°C was registered (Fytikas et al., 1984).

Furthermore, the geochemistry of some fault-controlled thermal springs indicates a temperature of 130-160°C in a relatively shallow reservoir in the basement at 800-1000 m depth (Barberi and Carapezza, 1994).

4.1 Current Monitoring of Santorini

In addition to the information gained through geophysical surveys, further data on the Santorini complex is obtained by the ISMOSAV (Institute for the Study and Monitoring of the Santorini Volcano, http://ismosav.santorini.net/) The ISMOSAV is a prestigious Greek non - profit organization founded in 1995. Under a research program funded by the European Union, the ISMOSAV operates a volcano observatory and several monitoring networks. Its objective is to promote volcanological research on the island, achieving the most accurate assessment of volcanic phenomena. The institute provides Santorini with an integral monitoring system, which guarantees the opportune prediction of a possible volcanic eruption. Most of the information we present in next section is a synthesis from its web page and from other publications of the same institution (ISMOSAV, 2008; Vougioukalakis, 2007).

4.2 Thermal Monitoring

The thermal monitoring on Santorini includes continuous registration of the Nea Kameni fumarolic temperature and the soil temperature on the CO_2 flux measurement area, as well as on the Palea Kameni hot spring (Figure 4). Periodic temperature registration (3 - 4 times per year) of the Nea Kameni and Thira hot springs, and of the deep well S2 on south Thira is regularly done. The thermal manifestations on Santorini are concentrated in two zones: the area near Kameni islands and on the western margin of the prevolcanic metamorphic basement of Thira. Fumarolic activity is manifested only on the top of Nea Kameni Island. The temperature of the fumarolic gasses, ranging from 60°C to 97°C, mainly depends on altitude (the highest

sites register the highest temperature values). The maximum registered temperature on Nea Kameni fumaroles present a fluctuation between 94°C and 97°C. The system is unstable, however, since fumarolic gasses outflow mainly through pyroclastic deposits.

Since 2002, a considerable diminution of the volume of the outflowing gasses from the Nea Kameni fumaroles was noted. This change was probably produced by a self-sealing process of the volcanic rocks altered by the circulating hot fluids in a period of low tectonic activity.

Along the coasts of Palea and Nea Kameni there are many warm water emanation sites. The most important are two hot springs on the eastern and western shores of the isthmus between Nea and Palea Kameni along the active tectonic "Kameni line". The hot springs at Afroessa Cove (Nea Kameni) registered a temperature of 34°C, while the springs at Agios Nikolaos Cove (Palea Kameni) registered 38°C. A deep exploratory well (-220 m) has been carried out on Palea Kameni close to the hot spring, aiming to study the hydrothermal system of the area. The maximum temperature registered in the borehole was 29°C at 10 m depth.

As mentioned previously, thermal manifestations on Thira are sited on the western edge of the outcropping prevolcanic basement. Three main hot springs are found here: the Plaka, Athermi Christu and Vlihada. The mean temperatures registered here are 33.6°C, 56°C and 32°C respectively. The three hot water vents outflow on the seashore. Also, a significant temperature gradient has been registered in the southern part of Thira Island. A deep borehole in this area has a constant maximum registered temperature of 52°C at 365 m depth below sea level (ISMOSAV, 2008).

4.3 Chemical Monitoring

The first survey of soil gas at Thira was done in June 1993. CO_2 flux and CO_2 and He concentrations were measured at 76 points covering the entire Thira Island (Barberi and Carapezza, 1994). The results confirmed that the main volcano-tectonic-geothermal lines are active fault systems leaking gas to the surface. During a volcano reactivation, the gas and liquid phase of the new magma drastically change the chemical composition of the fumaroles and hot springs. In Santorini the most abundant magmatic gas component is CO_2. High amounts of CO_2 are released to the atmosphere from active volcanic areas not only during eruptions but also during quiescent periods. This volcanic CO_2 discharge occurs from both active craters (Figure 4), as plumes and fumaroles, and the flanks of volcanic edifices, as diffuse soil emanations. The content of gaseous Radon (^{222}Rn) and the chemical composition of the fumarolic emissions as well as the hot springs are periodically monitored in the Thira-Thirasia soils. Radon is monitored with purpose of creating accurate earthquake prognosis (ISMOSAV, 2008). The main flux values per day range between 5 and 50 ppm/s, while the maximum registered values are lower than 150 ppm/s. 2008).

4.4 Monitoring of the Hot Fluid Composition

In volcanic areas the development of soil gas monitoring techniques is particularly important Periodic sampling and analysis of the major and some minor chemical species is carried out at the Santorini hot springs. Its thermal waters can be fed by: a) seawater that has undergone limited heating and mixes with groundwater or b) heated groundwater that mixes with seawater or c) heated

seawater-groundwater mixtures. Several of the above conditions are present at Santorini. On Palea Kameni, steam-heated seawater emanates from the thermal springs. The springs on Thira carry heated seawater as well; however, this liquid also carries some of the island's ground water. The high salinity measured at two springs indicates that the discharged fluid boils at its origin. These conditions might signify the existence of a medium enthalpy hydrothermal system (Mendrinos, Polyzou and Karytsas, 2007). In any case, all the thermal waters are connected with relatively shallow aquifers.
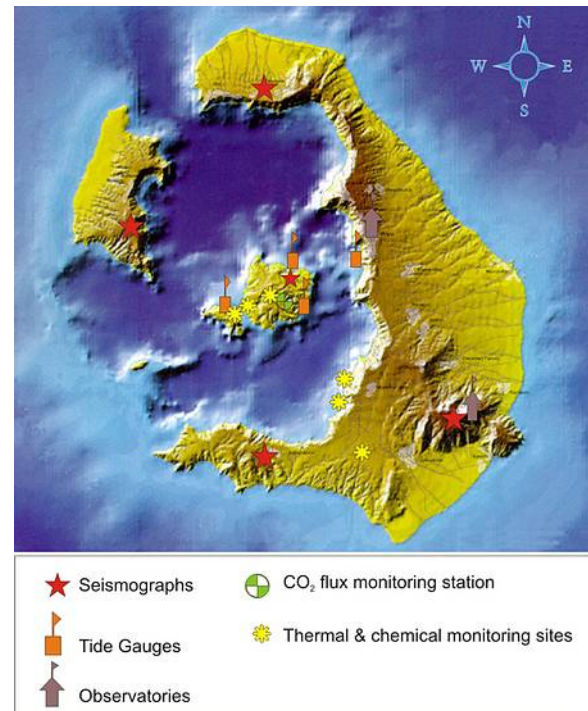

Figure 4: Sites of monitoring stations of the Santorini island complex (ISMOSAV, 2008).

Periodic sampling (2-3 times per year) and analysis of Santorini's hot gases are carried out with the purpose of determining their major and minor constituents (Figure 4). Nea Kameni fumaroles consist mainly of heated atmospheric air, and CO_2. Minor constituents (CH_4, H_2, CO) are present in variable proportions. Palea Kameni gases (Ag. Nikolaos cove bubbles) are essentially made up of CO_2 (99.9% in vol.), followed by N_2, and O_2. CH_4 and CO content are very low (< 10 ppm). During the monitored period, there were no significant changes in the chemical composition of both hot gasses and waters, which could have indicated some form of deep feeding process (ISMOSAV, 2008).

4.5 Seismic Monitoring

Every year an earthquake occurs with an average magnitude of 6.3 M in the broader Aegean area (Papazachos and Papazachou, 1997). The study of earthquakes is one of the most common methods to monitor volcanic activity. The method is based on the fact that magma causes small earthquakes as it escapes to the surface. The location and migration of the epicenters could describe the movement of magma as it makes its way toward the surface. With this data, it is also possible to estimate the velocity of magma and its place of exit on the surface, much before an eruption occurs. The Santorini Volcano is seismically monitored by a local network of five stations installed on the island by the Geodynamic Institute

of the National Observatory of Athens in co-operation with the Laboratories of Geophysics of the University of Thessaloniki and Athens.
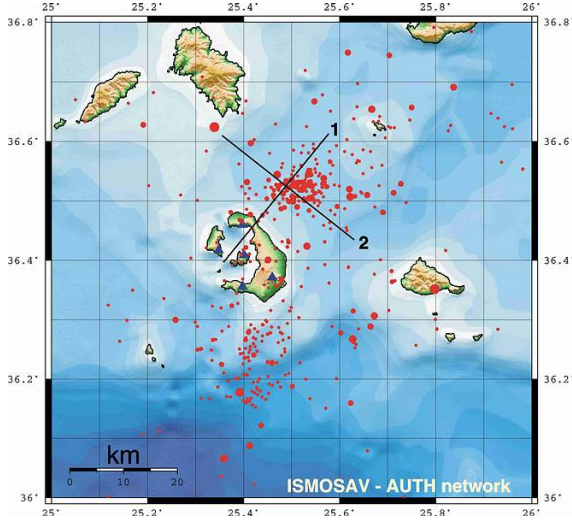
Figure 5: Map illustrating earthquake epicenters at Santorini (ISMOSAV, 02/ 2004 – 12/ 2007).

The central seismological station was installed on the highest place of the island on the top of the hill called Prifitis-Ilias. The stations were installed on Nea Kameni, Oia, Thirassia and Akrotiri. A number of earthquakes are recorded, of $0.5 \leq MD \leq 4.2$ (MD: Duration's Magnitude) and of focal depth varying between 1 km and 50 km. It is very clear that two clusters of epicenters are located in the area under study. The first cluster is located in the Caldera of Santorini and is associated with the volcanic process of the caldera. The second one is located near the northern edge of the Santorini at the Kolumbo Reef and is connected with the volcanic process at this reef. The seismic activity during this period remains in very low level in the caldera of Santorini and in a higher level at the Kolumbo Reef.

Since October 2007, a new service of real-time monitoring of seismic activity in Greece has been available on the web-page of the Seismological Station of The Aristotle University of Thessaloniki. Visiting this web-site, anyone can be informed about the seismic activity in Greece, but also in different specific areas of interest. A real-time seismicity map of Santorini is provided, because of the scientific interest for that area. This map is updated every 5 minutes and visitors can be informed about the earthquakes of the last 2, 7, 30 or more days. A catalogue with the whole data is also provided (ISMOSAV, 2008).

5. COARSE ESTIMATION OF THE GEOTHERMAL POTENTIAL OF THE SANTORINI CALDERA

Using the few data available and described in previous sections, is possible to estimate the thermal energy and the geothermal potential contained in the submarine reservoir of Santorini. Table 1 summarizes the available data, where C_W and C_R represent isobaric heat capacities for water and rock, respectively. Using average values of pressure, temperature, density, porosity, and enthalpy, we formulated a volumetric model to estimate Santorini's energy (Suárez *et al*., 2008). With the measured values of temperature (°C) at thermal springs obtained from geochemistry, a linear equation for temperature as function of depth (m) can be deduced:

$$T(z) = -10.0865 + 0.1701\, z \tag{1}$$

Table 1: Average thermodynamic data of the Santorini submarine reservoir.

Average Fluid Properties				
Pressure (bar)	Temp. (°C)	Density (kg/m^3)	Enthalpy (kJ/kg)	C_W (J/kg/°C)
50	160	910	678	4320
Thermodynamic Rock Properties				
Porosity (%)	Temp. (°C)	Density (kg/m^3)	Enthalpy (kJ/kg)	C_R (J/kg/°C)
10	160	2500	4046	1097

The thermal gradient around Santorini is estimated from the borehole drilled in southern Thira: $dT/dz = 0.1425$°C/m, then $\Delta T = 142.5$°C if $\Delta z = 1000$ m. Assuming a value for the volcanic rock thermal conductivity $k_T = 1.86$ W/m/°C, we obtain a heat flow $q_z = 0.265$ W/m^2. As comparative points, the estimated submarine heat flow in the Gulf of California is about 0.34 W/m^2 (Suárez, 2004). The average heat flow for the continents is about 0.06 W/m^2 and about 0.1 W/m^2 for the seas (Lautrup, 2005).

Let H_G/V_R [J/m^3] be the amount of geothermal energy per cubic meter transferred between two points of the vertical interval Δz:

$$\frac{H_G}{V_R} = C_R\, \rho_R\, \Delta T = \frac{Q_H}{V_R}\, \Delta t \tag{2}$$

where V_R is the reservoir volume and Q_H [W] is the power of the heat source producing a temperature growth of ΔT in the porous rock during a time Δt. Using the previous data of Table 1, we obtain an approximate value of the volumetric submarine geothermal energy contained in Santorini:

$$\frac{H_G}{V_R} \approx 411.4 \times 10^6 \quad \left[\frac{J}{m^3}\right] \tag{3}$$

An important practical application of the rock heat capacity is the estimation of the electric power generation potential from a geothermal reservoir. This potential depends on the stored geothermal energy of the system and on the efficiency factor with which the geothermal energy can be converted to electric power. The temperature change is defined as $\Delta T = T - T_0$, where T is the characteristic average reservoir temperature, and T_0 is the average ground surface reference temperature. It is reasonable to compute first the energy contained in every cubic meter of rock, especially if the total volume of the reservoir is unknown. This geothermal energy can be related to electric power production through the application of appropriate recovery and conversion factors. We define the electric geothermal power as:

$$G_P = \eta_G\, \frac{H_G}{t_E} = \eta_G\, \frac{\rho_R\, c_R\, V_R\left(\overline{T} - T_0\right)}{t_E} \quad \text{[MW]} \tag{4}$$

where t_E represents a period of commercial exploitation of the reservoir, usually taken as 30 years (transformed to seconds) and η_G is the geothermal - electricity conversion factor. Assuming a global $\eta_G \sim 2\%$ for volcanic submarine geothermal fields (Suárez and Viggiano, 1992), a reservoir

volume of hot rock of approximately 100 km³ (Figure 3), and assuming $\Delta T = 150°C$, the electric geothermal power at Santorini could be:

$$G_P = \frac{0.02 \times \rho_R \, c_R \, V_R \left(T - T_0 \right)}{30 \times 365.25 \times 86400} \approx 869 \text{ MW}_e \quad (5)$$

6. ADDITIONAL EXAMPLES OF VOLCANIC ISLANDS WITH GEOTHERMAL RESOURCES

Besides the island complex of Santorini, other islands throughout the Aegean and in the world have local important geothermal potentials. The Pacific Ocean alone contains more than 25,000 islands, including partially submerged islands, most or all of them are from volcanic origin. The Ring of Fire is an area where large numbers of volcanic eruptions occur in the basin of the Pacific Ocean. In a 40,000 km horseshoe shape, the Ring is associated with a nearly continuous series of oceanic trenches, volcanic arcs, and volcanic belts and/or plate movements. With 452 volcanoes, the Ring of Fire is home to over 75% of the world's active and dormant volcanoes. The Pacific Ocean also contains several long seamount chains, formed by hotspot volcanism. These include the Emperor Seamounts chain, the Louisville seamount chain, and the Hawaiian Islands (Wikipedia, 2009). The countries in the world that are geothermal powers, Philippines (1980 MW$_e$), Indonesia (1058 MW$_e$), New Zealand (550 MW$_e$) and Japan (535 MW$_e$) are also very well known volcanic islands located in the Pacific Ocean.

This section will briefly describe geothermal power developments on the islands of Milos (Aegean) and Guadaloupe (Antilles).

6.1 Milos

The island of Milos is located west of Santorini in the Southern Aegean. The island is composed of a metamorphic basement topped by several layers of highly permeable sedimentary rock and several layers of as altered tuffs, lahars and lava domes. According to Fytikas (1989), Milos displays some of the most important volcanism in the Aegean. Although the last major eruption is believed to have occurred 500,000 years ago, the presence of fumaroles, hot springs and altered formations are evidence of continuing magmatic activity (Ungemach, 2002*).

The geoelectrical soundings and gravity surveys carried out during the early 1970s marked the beginning of the geothermal exploration on Milos. Two deep wells encountered a high enthalpy, water dominated system. In 1987, the Greek Public Power Company put a 2MW$_e$ pilot plant on line. The project, however, encountered scaling problems and soil pollution related to the plant caused adversity among the population. Presently, the utilization of geothermal resources is limited to a handful of houses and one hotel [which] use shallow groundwater of 45-60 °C temperature for space heating and for a swimming pool (Mendrinos, Polyzou & Karytsas, 2007). Despite the negative view of geothermal energy on the island, Milos, with water demands on the rise, would indubitably benefit greatly from this energy source in a near future (Ungemach, 2002).

6.2 Guadeloupe

The subduction of the Atlantic Plate beneath the Caribbean Plate has produced two island arcs in the Caribbean Sea. While the easternmost arc is composed of extinct cones, the islands in the western arc are active or dormant volcanoes. Many of the islands present opportunities for geothermal development (Hunter, 2000).

Among these islands is Guadeloupe, belonging to the Lesser Antilles. During the 1969-1970, four wells were drilled on the coast of Basse-Terre by EURAFREP. Only one of these, however, BO-2 (-350 m), proved to be productive with a vapor flow of 33 T/h and 5.3 bar/g separation pressure. The vapor flow of well BO-4 (10 T/h) was considered too low for power generation. In 1987, well BO-2 was integrated into the 5 MW$_e$ Bouillante plant. Further consideration was given to well BO-4 in 1997 when studies showed that this well could be stimulated with the injection of cold sea water (Sanjuan *et al*, 2000). Two additional, producing wells were drilled in 2001 at the same time that BO-2 was taken off the grid. As of 2003 Bouillante's generation capacity is 15 MW$_e$ (8% of the island's electrical demand). Guadalupe plans to extend its exploitation to 20-30 MW$_e$ by 2010 (Low-Bin, 2007).

7. CONCLUSIONS

Santorini being one of the most original and impressive volcanic islands complex, it has been at the same time one of the most violent and destructive volcanoes on Earth.

The huge Minoan Eruption of 1600 BC ejected into the air 30 km³ of magma in the form of pumice and volcanic ash. This eruption devastated the island, its people and civilization. The most recent eruptions at Santorini occurred in 1939, 1941 and 1950.

Various anomalous soil degassing sites have been detected at the caldera. The sudden appearance of soil gas anomalies are precursors of earthquakes and volcanic eruptions. The main anomalies detected correspond to the Kolumbo line and to the Kameni line, two fault systems that controlled all the historic volcanic activity of Santorini. Soil gas data and seismological evidence, indicate that the Kolumbo and Kameni lines are the most probable sites for future volcanic or seismic reactivation.

Several superficial evidences demonstrate the existence of a local geothermal submarine reservoir in Santorini. We presented herein a preliminary, coarse evaluation of the geothermal submarine potential of the zone, which could be around 869 MW$_e$. Many other volcanic islands throughout the oceans have important geothermal possibilities. If the partially and totally submerged islands are included, the total potential represented by this type of geothermal reservoirs, for direct uses and to generate electricity, will be substantially higher.

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