PROCEEDINGS, Thirty-Third Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 28-30, 2008
SGP-TR-185

GEOTHERMAL MANIFESTATIONS AND EARTHQUAKES IN THE CALDERA OF SANTORINI, GREECE: AN HISTORICAL PERSPECTIVE

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ABSTRACT

Santorini is one of the most original, beautiful and impressive volcanic islands complex in this planet. At the same time it was one of the most violent and destructive volcanoes on Earth. Approximately two million years ago the volcanic activity in the area produced the first molten rock. 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. This activity shaped the civilization which developed on the island. The last catastrophic eruption occurred 3600 years ago, during the Late Bronze Age. It extinguished every trace of life and civilization which flourished in the Aegean. The tremendous eruption of 1600 B.C., known as the Minoan Eruption, ejected into the air 30 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. In this paper we present a brief description of the historical and recent volcanic activity in Santorini, the collapse of the original volcano and the formation of the present island complex, composed with 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 geothermal submarine reservoir. We introduce a preliminary evaluation of the geothermal submarine potential of the zone.

INTRODUCTION

Greece has the largest concentration of earthquakes, exhibiting the highest seismicity in Europe and in the whole western Eurasia. This country is a natural laboratory by itself, 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 past damaging earthquakes. The first person to record a seismic event in Greece was Cicero, who wrote that a strong earthquake occurred in 550 BC that ruined Sparta. Cicero also reported the collapse of a portion of the summit of Mt Taygetos.

"*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*". (Karakaisis & Papazachos, 2001). "*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*.", (*ibid*.).

Greece always exhibited high seismic activity. The total number of known strong earthquakes 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 which have been studied:

Period 550 BC - 1550 AD.
About 150 strong earthquakes ($M \geq 6.0$) occurred, for an average of about 7 strong earthquakes per century.

Period 1550 - 1845.
The total number of earthquakes of this interval is about 170 and therefore their frequency is about 60 earthquakes per century.

Period 1845 - present day.
The total number of strong earthquakes ($M \geq 6.0$) studied during this period is 270; the present mean rate of strong earthquake generation in this area is about 200 earthquakes per century.

The 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, also called a Benioff zone for earth-quakes of intermediate depth 60-180 km (Papazachos and Papazachou, 1997). An illustration of present day seismicity in Greece is shown in Figure 1.

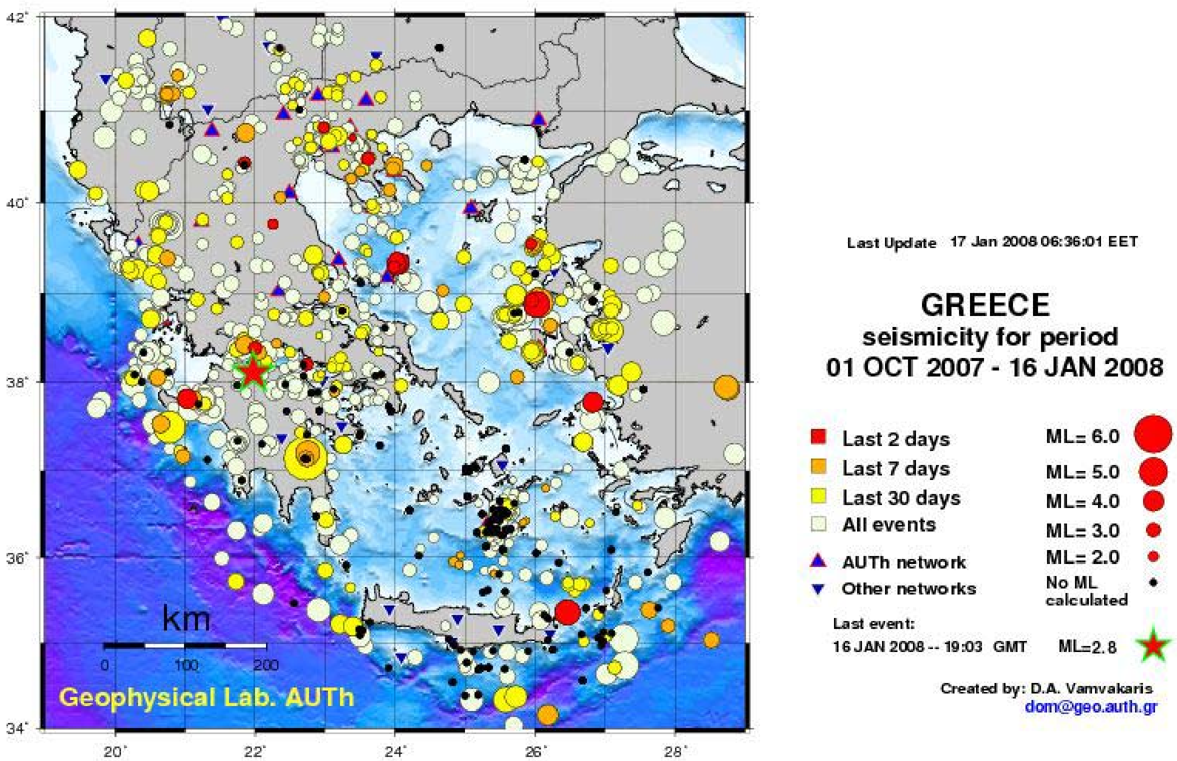

Figure. 1. Present Greece seismicity. Measured and published by the Seismological Station of the Aristotle University of Thessaloniki (http://lemnos.geo.auth.gr/the_seisnet/WEBSITE_2005/station_index.html).

THE SANTORINI CALDERA

The Santorini Caldera is the youngest active volcanic complex in Greece. It is located on the active front of the Aegean arc (Fig. 2) and is formed by five islands of different characteristics. The main island is called Thira (E), Thirasia at the NW and the small Aspronisi at the West. Other two small islands are in the center of the complex (Figure 3): Palea Kameni (Old Burnt Island), of about 2000 years old and Nea Kameni (Young Burnt Island), of about 425 years old. 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). The entire complex is exposed to a severe volcanic and seismic hazard (see Fig. 6). The island of Thira is densely inhabited and visited by many people, especially during the main tourist summer season. Thirasia, Thira and Aspronisi are the remnants of a series of volcanic collapses, the last of which was the terrible Minoan explosive eruption, occurred 3600 years, producing about 30 km^3 of erupted material (*ibid*).

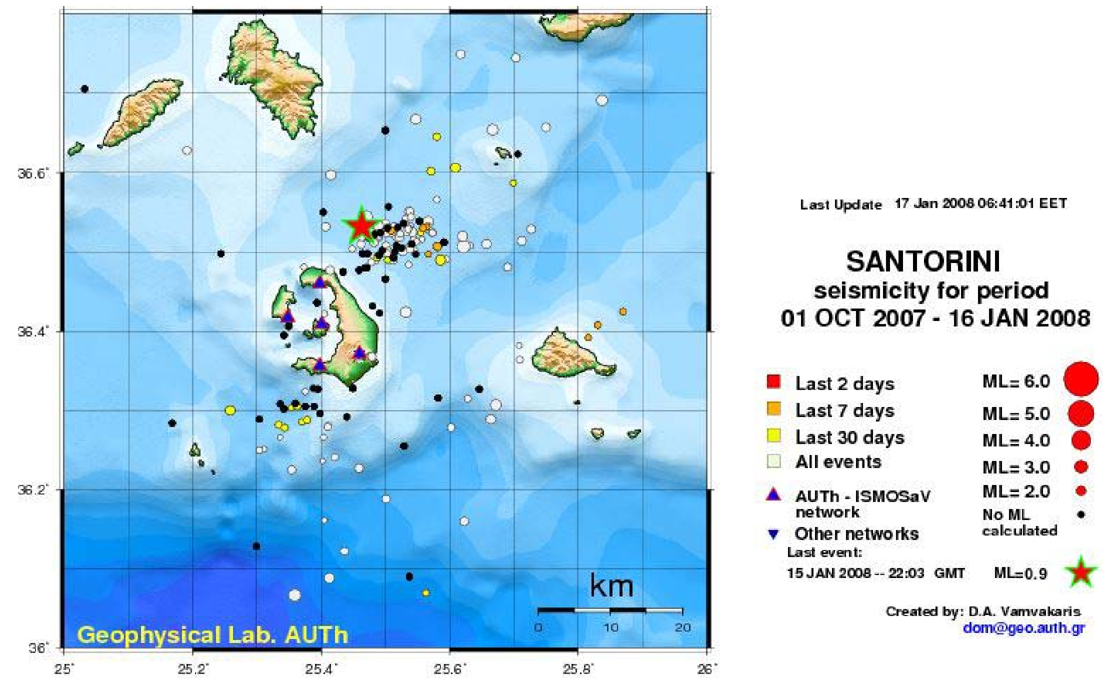

Figure. 2. Location of the Santorini Caldera showing its present seismicity. (The Seismological Station of the Aristotle University of Thessaloniki).

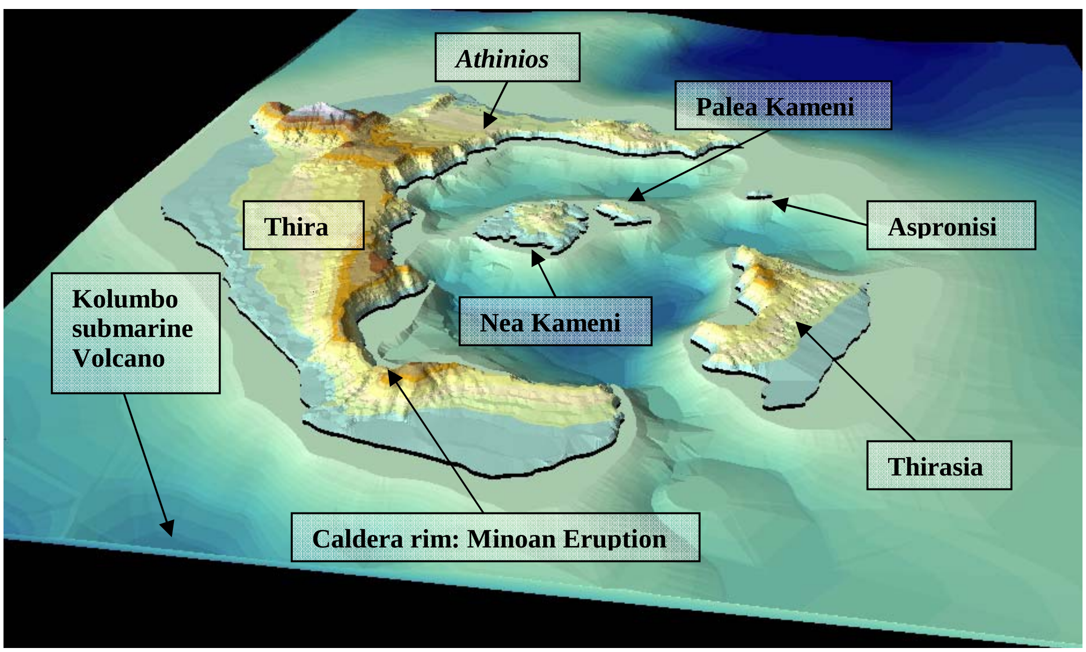

Figure. 3. The Santorini Island Complex: Thira, Thirasia, Aspronisi, Palea Kameni and Nea Kameni.

The huge cauldron of the Santorini caldera was created during the huge Minoan eruption, when the Strongili volcano collapsed. The islands we see today are the fragments that prevail on the sea surface after the catastrophic collapse (*ibid*). Palea Kameni and Nea Kameni emerged from the sea in the centre of the Minoan caldera (Fig. 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 (Fig. 3). Another 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 historical 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 of Santorini, Both lines are the trace of sites where volcanic and seismic activities have the highest probability of occurring in the future (ISMOSAV, 2007). A granite intrusion was encountered by a geothermal borehole, 250 m depth, 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. The geochemistry of some fault-controlled thermal springs indicates a temperature of 130-160°C in a relatively shallow reservoir in the basement (800-1000 m depth)*", (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, feeding the most interesting thermal springs of Santorini (*ibid*).

MONITORING OF SANTORINI

The Institute for the Study and Monitoring of the Santorini Volcano (http://ismosav.santorini.net/), (ISMOSAV) is a prestigious Greek non - profit organization founded in 1995, whose primary aim is to maintain the operation of the Volcano Observatory and the monitoring networks, established under a research program funded by the European Union. Its objective is the promotion of 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 sections is a synthesis from its web page and from other publications of the same institution (ISMOSAV, 2008; Vougioukalakis, 2007).

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 (Fig. 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. The thermal manifestations on Santorini are concentrated in two areas: the Kamenis area and in the western margin of the prevolcanic metamorphic basement of Thira. Fumarolic activity is manifested only on the top of Nea Kameni Island. Fumarolic gasses have a temperature ranging from 60°C to 97°C, depending mainly from the altitude (the highest sites in altitude register the highest temperature values). The system is unstable, as fumarolic gasses outflow mainly through pyroclastic deposits. The maximum registered temperature on Nea Kameni fumaroles present a fluctuation between 94°C and 97°C. Since 2002, is noted a considerable diminution of the volume of the out flowing gasses from the Nea Kameni fumaroles. This change is 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 a lot of warm water emanations. The most important are two hot springs in the east and west shores of the isthmus between Nea and Palea Kameni, along the active tectonic "Kameni line".The temperatures registered here are 34°C for the hot springs of Nea Kameni Afroessa cove and of 38°C for that of Palea Kameni Agios Nikolaos cove. 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. On Thira thermal manifestations are sited in 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. Both three hot waters outflow on the seashore. 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).

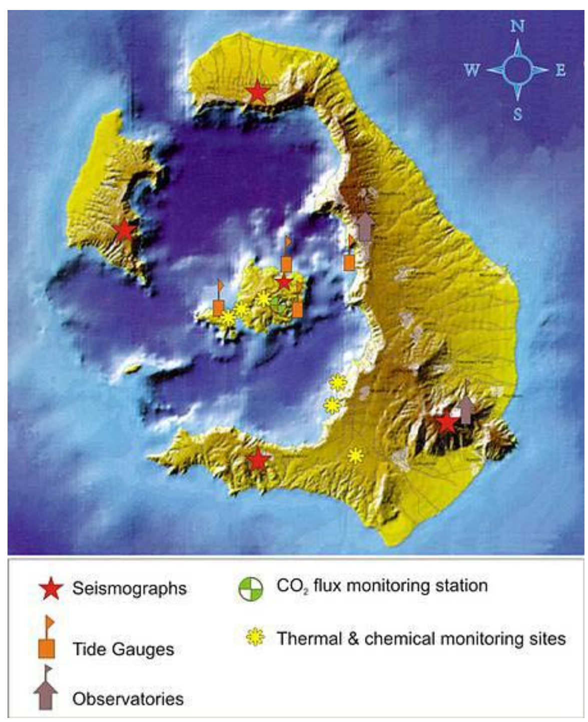

Figure. 4. Monitoring the Santorini island complex.

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 in 76 points covering the entire Thira Island (Barberi & 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 change drastically 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 (Fig. 4), as plumes and fumaroles, and the flanks of volcanic edifices, as diffuse soil emanations. The gas Radon (^{222}Rn) content and the chemical composition of the fumarolic gasses and the hot springs are periodically monitored in the Thira-Thirasia soils. The main flux values per day, range between 5 and 50 ppm/s, while the maximum registered values are lower than 150 ppm/s. Radon is the most studied gas, for the purpose of earthquake prognosis. (ISMOSAV, 2008).

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 carrying 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 ground-water that mixes with seawater or c) heated seawater-groundwater mixtures. In any case all the thermal waters are connected with relatively shallow aquifers. Periodic sampling (2-3 times per year) and analysis of the main and minor constituents is also carrying out for the Santorini hot gasses (Fig. 4, Nea Kameni fumaroles and Ag. Nikolaos bubbles). Nea Kameni fumaroles consist of a strong portion of heated atmospheric air, and CO_2. Minor constituents (CH_4, H_2, CO) are present in variable proportions. Palea Kameni gasses (Ag. Nikolaos cove bubbles) are essentially made up of CO_2 (99.9 % vol.), followed by N_2, and O_2. CH_4 and CO content are very low (< 10 ppm). In all the monitored period, there are no significant changes in the chemical composition of both hot gasses and waters, which could indicate any deep feeding process (ISMOSAV, 2008).

Seismic Monitoring

Every year an earthquake occurs of 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 a volcanic activity. The method is based on the fact that magma causes small earthquakes during its escape to the surface. The epicenters location and their possible migration could describe in any time the movement of magma, in the way to the surface. It is also possible to estimate the velocity of magma and its place of exit in the surface, much time before the eruption. The Santorini Volcano is seismically monitored by a local network of 5 stations installed in 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. The central seismological station was installed in the highest place of the island in the top of the hill called Prifitis-Ilias. The stations were installed in 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 1km 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 is available in 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 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).

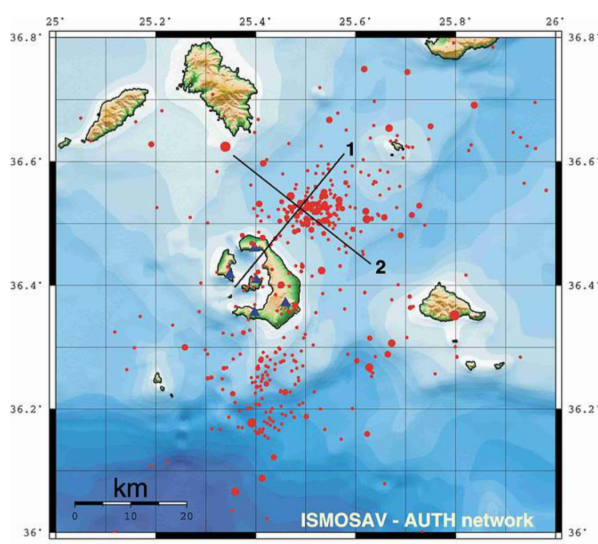

Figure. 5. Map illustrating earthquake epicenters in Santorini (02/ 2004 – 12/ 2007).

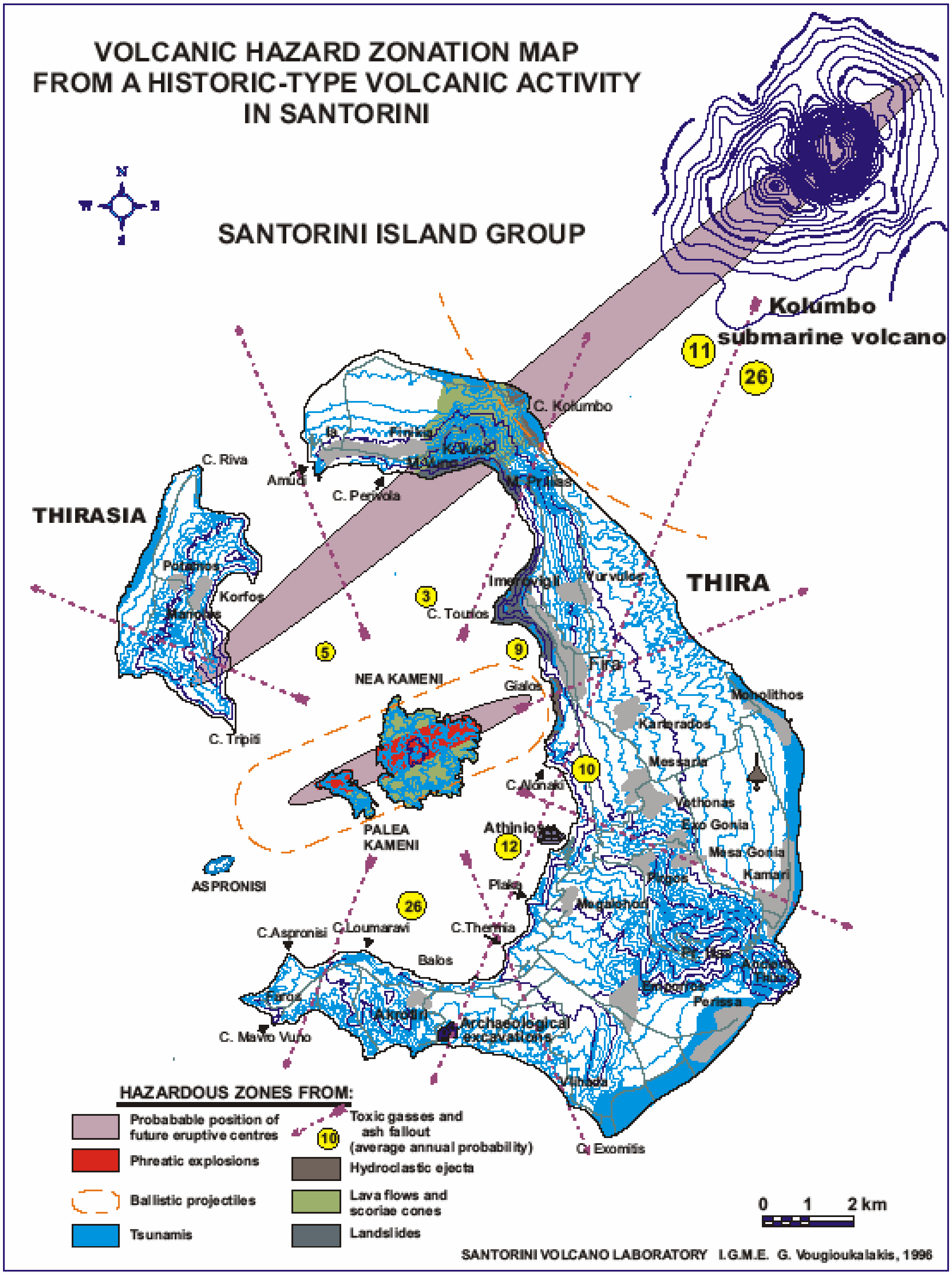

Figure. 6. Map of volcanic hazard zones of Santorini (created by G. Vougioukalakis, 1996).

ESTIMATION OF THE THERMAL ENERGY AVAILABLE IN THE SANTORINI CALDERA

Using the few data available, described in previous sections, it is possible to estimate the thermal energy accessible in the submarine reservoir at Santorini. Table 1 summarizes the available data.

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

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

Where the parameters C_W and C_R are water and rock isobaric heat capacities respectively. With the measured values of temperature at thermal springs obtained from geochemistry, a linear equation for temperature as function of depth (m) can be deduced:

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

The thermal gradient around Santorini can be estimated from the borehole drilled in southern Thira: dT/dz = 0.1425°C/m, then ΔT = 142.5°C if Δz = 1000 m. Assuming a value of k_T =1.86 W/m/°C for the volcanic rock thermal conductivity, 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. The average heat flow for the continents is about 0.06 W/m^2 and about 0.1 W/m^2 for the seas (Suárez, 2004).

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:

$$\frac{H_G}{V_R} = C_R\,\rho_R\,\Delta T = \frac{Q_H}{V_R}\Delta t \;,\quad \left[\frac{\text{J}}{m^3}\right] \qquad \textbf{(2)}$$

Where V_R is the reservoir volume and Q_H [W/m^3] 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 we obtain an approximate value of $H_G \sim 4 \times 10^5$ kJ/m^3.

A practical important 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. For this computation $\Delta T = T - T_0$, where T is the characteristic average reservoir temperature, and T_0 is a reference value close to the average ground surface 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. Taking ΔT = 150°C and with the previous data, the volumetric submarine geothermal energy in Sanorini is:

$$\frac{H_G}{V_B} = \rho\, c_p\, \Delta T \approx 411.4 \left[\frac{\text{MJ}}{\text{m}^3}\right] \qquad \textbf{(3)}$$

This thermal energy can be related to electric power production through the application of appropriate recovery and conversion factors. The electric geothermal power is defined as:

$$G_P = \eta_G \frac{H_G}{t_E} = \eta_G \frac{\rho\, c_p\, V_B\left(\bar{T} - T_0\right)}{t_E} \;\text{[MW]} \qquad \textbf{(4)}$$

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 submarine geothermal fields (Suárez & Viggiano, 1992) and a reservoir volume of hot rock of approximately 100 km^3, (Fig. 5) the electric geothermal power at Santorini could be:

$$G_P = \frac{0.02 \times \rho\, c_p\, V_R\left(T - T_0\right)}{30 \times 365.25 \times 86400} \approx 869 \text{ MW}_e \qquad \textbf{(5)}$$

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 km^3 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.

- Several 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.

- Many superficial evidences demonstrate the existence of a local geothermal submarine reservoir in Santorini. We presented a preliminary, coarse evaluation of the geothermal submarine potential of the zone.

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