New thermometric data from shallow aquifers in Santorini: Possibilities for geothermal exploitation

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ABSTRACT

The geothermal exploration in Santorini island (Greece), conducted by IGME in the mid '80s, identified a low enthalpy geothermal system in the southern part of the island (Megalochori-Emporio area). The geothermal reservoir was found at a depth of around 300m with temperatures up to 65°C. Medium-enthalpy fluids most probably exist in south Santorini, at a depth of less than 1000 m, whereas higher temperatures could obviously be found inside the caldera. During the years 2014-2015, a new geothermal project was carried out in Santorini, financed by the Municipality of Thera, aiming at evaluating the geothermal resources of the island with a particular emphasis on the shallow ones, recommending the most appropriate ways to use the confirmed geothermal potential, as well as suggesting further research/development activities. The detailed and extensive field work included temperature and electrical conductivity measurements in the relatively shallow aquifers around the island (in 141 wells), selective sampling, and chemical analyses. The thermometric research revealed a very interesting zone of geothermal anomaly in the central part of Santorini, with temperatures exceeding 26-27°C at very shallow (40-190m) depths. The proposed applications (heating/cooling, desalination, bathing, agricultural drying etc.) are considered suitable to the unique character of the place, with emphasis to the touristic and rural activities in the island.

1. INTRODUCTION

The island of Santorini (or Thera) is located approximately 120km northwards of Crete, constituting the southernmost part of the South Aegean Volcanic Arc (SAAVA). It belongs to the island volcanic group of Thera, Therasia, Aspronissi, Palea Kameni and Nea Kameni. Santorini is considered as the most active volcanic centre of SAAVA and one of the most violent caldera-forming volcanoes worldwide, during the recent and historical time periods.

The favourable geothermal conditions in Santorini are associated with the active volcanic and tectonic activity of the broader area and the presence of shallow magma chambers under the two calderas (Santorini and Kolumbo) (Fytikas et al., 1990a).

So far, the island is relying on imported fossil fuels to cover its energy needs, which increase dramatically during the high touristic period (April to October). The Institute of Geologic and Mineral Exploration (IGME) carried out an extensive programme of geothermal exploration in Santorini during the 1980s, which revealed the existence of a low enthalpy system in the southern part of the island with temperatures as high as 65°C (Fytikas et al., 1990a). According to the geologic, geophysical and geochemical research, the existence of medium enthalpy reservoirs (T=90-150°C) at greater, yet economic, depths (800-1000m) is very probable in this specific region.

Almost three decades after the work of IGME, no further activities for the exploitation of the explored geothermal potential have been taken place. In 2014, the Municipal Authority of Thera financed a new geothermal project focusing mostly on the investigation and evaluation of the shallow geothermal potential of the island. The thermometric survey showed that very shallow aquifers with temperatures above 21-22°C exist all around the island. Moreover, temperatures of 26-27°C were recorded in the central part of Santorini, establishing a new geothermal region that needs to be further explored.

2. GEOLOGICAL AND TECTONIC SETTING

Santorini is almost entirely made up of Pliocene to recent pyroclastics and lavas (Skarpelis & Liati, 1990), as a result of many successive volcanic eruptions in a period that lasted approximately 0.7 Ma.

The pre-volcanic basement belongs to the Attico-Cycladic Massif (Fytikas et al., 1990a; 1990b). It outcrops only in the SE part of the island (Profitis Helias, Pyrgos, Gavrilos) and in the area of Athinios (Figure 1).

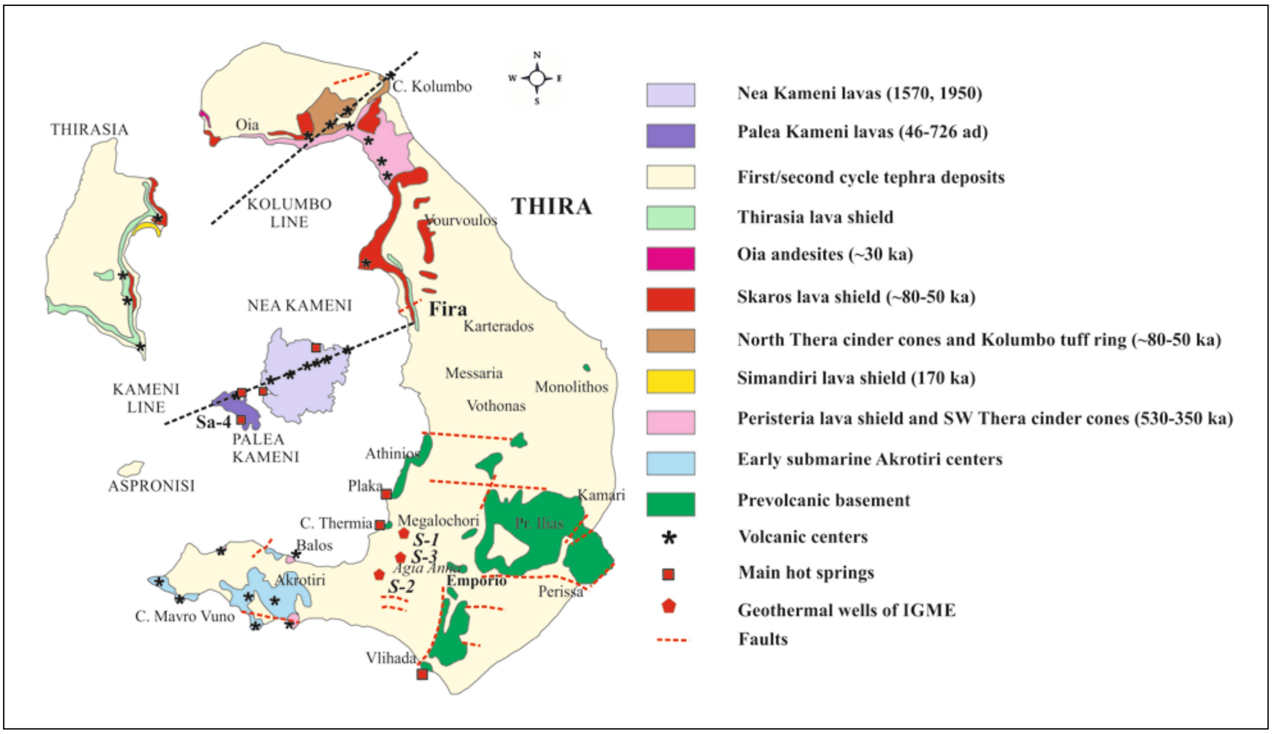

Figure 1: Geologic map of Santorini (sources: Pavlides et al., 1997; Druit et al., 1999; Francalanci et al., 2005).

These formations consist of epimetamorphic phyllitic series of Upper Jurassic-Lower Cretaceous age (Tataris, 1964; Fytikas et al., 1990b), Upper Triassic-Upper Cretaceous re-crystallized limestones of large thickness (Papastamatiou, 1958; Blake et al., 1981; Fytikas et al., 1990b), as well as of glaucophanitic schists. The latter outcrop at the walls of the caldera, in the areas of Athinios and Thermia (Figure 1) and have been party affected by contact metamorphism due to a more recent (7 Ma) granitic intrusion (Skarpelis & Liati, 1990), intersected by exploration boreholes.

The post-alpine volcanism is dated from the Early Quaternary (1.6-2.0 Ma ago). It started in the Christiana islands (20km SW of Santorini) and continued to the north. Druitt et al. (1989) have divided the volcanic activity into six main stages, the most recent of which begun in the later Copper Age and is still in progress. The products of the oldest activity outcrop at the south-western part of the island and were produced by sub-marine volcanic centers (Fytikas et al., 1990b). The most recent large explosion in Santorini is the so-called “Minoan”, which took place about 3600 years ago (~1613 B.C.). The last caldera collapse and the formation of Therasia, Aspronissi and Santorini (in its present form) islands, are related to the catastrophic Minoan explosion. The islets of Palea Kameni and Nea Kameni were created during the post-calderic activity that started in 197 B.C. (Francalanci et al., 2007). The last paroxysmal event covered the entire island with pumice, flows and surge deposits (Fytikas et al., 1990b). The most recent volcano eruption happened in 1950.

The complicated tectonic setting of Santorini reflects the several phases of caldera collapse and the active extensional regime of the central-south Aegean. The main faults trend NE-SW and have reactivated the E-W and N-E pre-existing faults (Perissoratis, 1995). An N-S tectonic graben in the area between Meglochori and Vlychada, revealed by the geophysical exploration in southern Santorini, has affected the older basement formations and is directly related to the significant geothermal anomaly in this part of the island.

The caldera of Santorini with the Palea and Nea Kameni islets, as well as the active Kolumbo crater and the Christiana islands are aligned in a NE-SW direction, following two fracture zones, known as “Kameni” and “Kolumbo” lines, respectively (Figure 1). These lines are characterized by seismic and intense tectonic and volcanic activity. In fact, the volcano-tectonic system of Kolumbo is considered as the most active tectonic feature of Santorini (Arriaga et al., 2008).

3. GEOTHERMAL REGIME

The geotectonic regime and the magmatic conditions are responsible for the development of important geothermal and hydrothermal activity in the broader area of Santorini. This is evidenced by the presence of several terrestrial and submarine thermal springs and fumaroles on Santorini, Nea Kameni, Palea Kameni and Kolumbo. The temperature of the fluids outflowing from the Kolumbo caldera bottom reaches

224°C (NOAA Ocean Explorer, Thera 2006 Expedition Summary) whereas it does not exceed 97°C on the Palea Kameni and Nea Kameni islets.

The majority of the hot springs on Santorini spout from the internal walls of the caldera or can be found at the external south-eastern part of the island, along faults, fractures and fissures of the pre-volcanic basement. The most important hot springs are located in Plaka (33.6°C), Thermia (56°C) and Vlychada (32°C) (Figure 1). The absence of more spectacular surface geothermal features (such as hydrothermal craters) can be attributed to the existence of very "young" and very permeable volcanic layers, which allow the massive intrusion of sea-water that, in turn, affects significantly the temperature and the chemical composition of the uprising hot fluids.

The preliminary geothermal survey during the early 1980's, identified a significant geothermal anomaly in the southern part of the island, located inside or near the metamorphic basement. The subsequent drilling exploration included eleven (11) exploration boreholes, nine (9) of which in the region of Akrotiri-Megalochori-Perissa-Vlychada (Figure 2), at depths between 138 and 182m (Fytikas et al., 1990a). The stratigraphy, the temperature profiles and the chemical analyses indicated the area near G-8 and G-9 boreholes (Figure 2) as the most promising location for further drilling operations.

In 1985, IGME drilled three (3) deeper geothermal wells, labeled as S-1, S-2 and S-3 on the map of Figure 2. The maximum recorded temperatures, the corresponding depths and the geothermal gradients are presented in Table 1.

Table 1: Geothermal production wells in Santorini

Well	Total depth (m)	Temperature (corr. depth)	Gradient (°C/100m)
S-1	270	64.7°C (240m)	16
S-2	460	52.3°C (440m)	13
S-3	260	51.2°C (260m)	10.5

The investigation of IGME confirmed the existence of an important low enthalpy system in southern Santorini and led to the delimitation of the probable low temperature geothermal field that covers an area of 25km^2 (Figure 2) with temperatures 30-65°C in relatively shallow depths (100-250m).

The chemical analyses of 117 groundwater samples collected by IGME (Kavouridis et al., 1982) showed that all samples with temperatures up to 65°C belong to the sodium-chloride type. Their salt content is high, even higher, in a few cases, than the sea-water, with TDS (Total Dissolved Salts) reaching 54.223 meq/l The Cl/Na molar ratio was approximately equal to 1 for the shallow waters, whereas it became higher with temperature increase (deeper water).

The chemical geothermometers of SiO_2 (Fournier, 1977), Na-K-Ca (Fournier and Truesdell, 1973) and Na/K (Fournier, 1979) showed initial reservoir temperatures of 160-190°C, 130°C and 140°C, respectively (Fytikas et al., 1990a). Mendrinos et al. (2010) applied the K-Na-Mg geothermometer (Giggenbach, 1988) to the water of the well S-3, which suggested deep equilibrium temperatures in the 110-175°C range. Taking into account the mean geothermal gradient in the area, fluids of approximately 140°C are expected to be found at an estimated depth of 800-1000m, inside the intensively fractured zones of the limestones or the calc-schists of the basement.

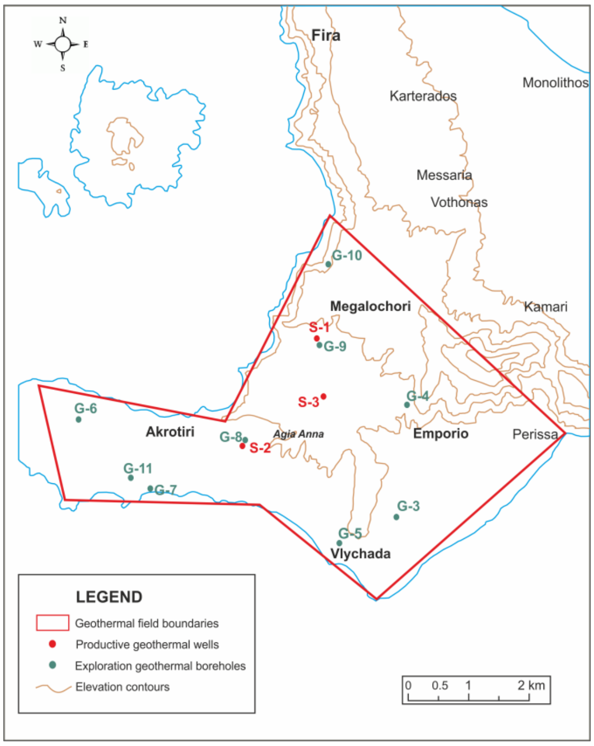

Figure 2. Low enthalpy geothermal field of Santorini

4. RECENT (2014-2015) GEOTHERMAL DATA

The surface investigation concerned in-situ well-head measurements of the temperature and Electrical Conductivity (EC) in 141 shallow irrigation and water-supply wells (Figure 3), downhole temperature measurements in six (6) non-operating wells, as well as water sampling and chemical analyses from eight (8) selected sites (Figure 4).

The water table was found, almost everywhere on the island, at the sea-water level, i.e. approximately 25-200m below the ground surface. The wells in Santorini are relatively shallow (max depth~200m), since the drilling was concluded once the aquifer was encountered. No new measurements were performed at the geothermal wells drilled by IGME in the southern part of Santorini (S-1, S-2, and S-3) because they are severely damaged.

3.1 Thermometric survey

Figure 3 illustrates the distribution of the wellhead temperatures in Santorini. As expected, the most interesting area with the higher measured temperatures (45-65°C), is close to *Megalochori*, where the major geothermal anomaly had been identified. The depth of the wells in this region ranges from 80 to 240m.

In contrast, the lowest temperatures were recorded at the northern part of Santorini, in the area of *Oia*. In majority, the depth of the wells in this area is less than 40m, with well-head temperatures up to 22°C. Nonetheless, the temperature of the only relatively deep (182m) well used for desalination, exceeded 24°C.

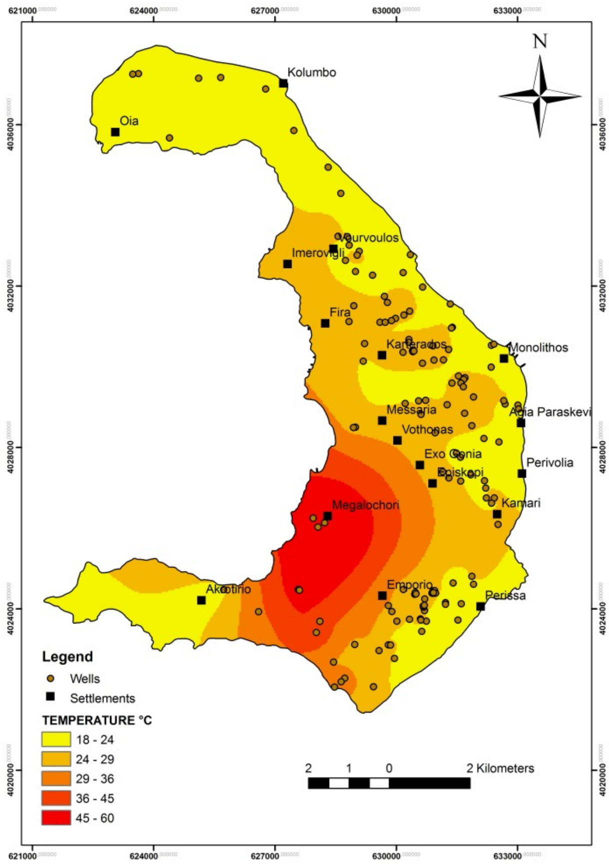

Figure 3. Wellhead temperature distribution

Due to the increased energy demands in the broader region of Fira, which is the capital and the main tourist destination of the island, the field-work focused particularly on investigating the geothermal situation in the central part of Santorini (Vourvoulos-Fira-Messaria-Monolithos-Vothonas-Kamari), for which no previous temperature data existed.

In *Vourvoulos* (north of Fira), the well depth and the well-head temperatures vary from 90 to 120m and from 23.6 to 26.3°C, respectively. Near the town of *Fira*, the temperatures at fourteen (14) measured wells with depths 40-190m ranged from 23.4 to 27.7°C In the area of *Messaria*, the recorded temperatures were 24°C to 27.6°C at wells with depths varying from 60 to 200m. The maximum temperatures in the area of *Monolithos*, very close to the airport of the island, reached 25.8°C at very shallow wells (less than 75m). Similarly, the temperatures in *Kamari* area exceeded 26°C. By moving to the south and closer to the geothermal field, the recorded well-head temperatures became higher. In the area of *Vothonas* they varied from 23.4 to 28°C at wells with depths ranging from 55 to 105m.

All forty (40) wells measured in the areas of *Emporio* and *Vlychada*, i.e. inside the geothermal field, are very shallow (25-50m). The well-head temperatures in *Emporio* were about 24-27°C, except one case where it exceeded 29°C at a 27m deep well. The temperatures in *Vlychada* are higher, ranging from 27 to 32°C.

Despite the large number of private and municipal wells in Santorini, the downhole measurements proved a difficult task. The majority of the wells were productive during the period of the field survey, therefore it was impossible to conduct any measurements in their interior. In many other cases, the non-operating wells were damaged, or inaccessible or even not available by the owner. Eventually, only six (6) wells (Figure 4) were suitable for temperature measurement as a function of depth, four (4) of which are located north to the geothermal field.

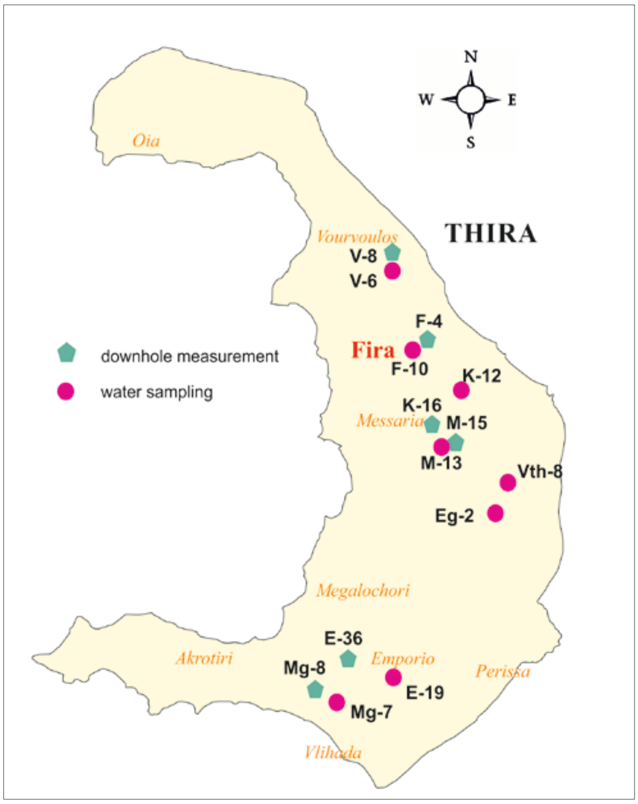

Figure 4. Downhole measurements and water sampling sites

The maximum temperatures and the corresponding depths, as well as the calculated geothermal gradient are presented in Table 2. The temperature profiles are illustrated in Figure 5. The geothermal gradients have been calculated taking into account the temperature variation below the depth of 20m. However, the results are biased by the fact that all these wells are shallow, since there was no point on continuing the drilling once the uppermost aquifer was encountered. For that reason, there is no information for the temperature distribution below this depth. In addition, the water flow at the bottom of the wellbores has certainly affected the temperature regime inside the wells.

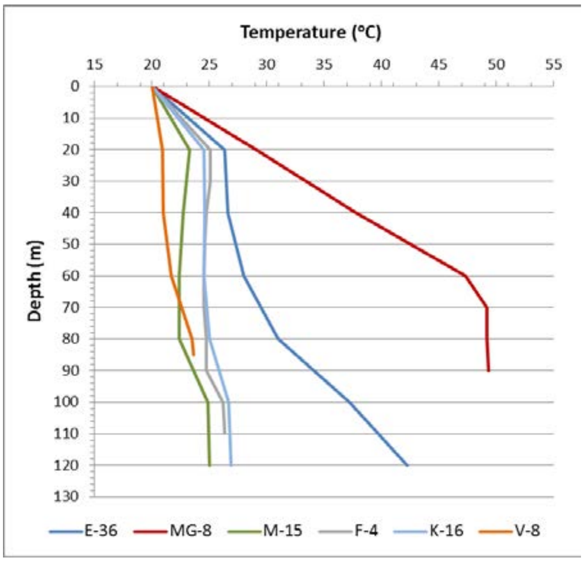

Figure 5: Temperature profile of six selected wells in Santorini

As shown in Table 2, the bottom-hole temperatures of E-36 and Mg-8 are consistent with the temperatures that were anticipated inside the area of the proven geothermal anomaly. The calculated gradient for the well E-36 is similar to the gradients derived from the measurements in the geothermal wells of IGME (see Table 1). The well Mg-8 is characterized by rapid increase of temperature with depth, resulting in a very high gradient, i.e. 28.8°C/100m. However, this value cannot be considered as reliable, due to the small well-depth.

Table 2: Downhole temperature measurements

Well	Locality	Maximum Temperature (°C)	Gradient (°C/100m)
E-36	Emporio	42.2°C (120m)	15.9
Mg-8	Megalochori	49.2°C (70m)	28.8
M-15	Monolithos	25.0°C (120m)	2.42
F-4	Fira	26.2 °C (100m)	1.30
K-16	Karterados	26.7°C (100m)	2.40
V-8	Vourvoulos	23.5°C (85m)	4.15

The downhole temperatures of the wells M-15, F-4, K-16 and V-8, all located northwards of the geothermal field, are typical of shallow or low enthalpy geothermal anomaly. The calculated geothermal gradients are generally low, but, as discussed above, they are not reliable. The calculation of the true gradient in these unexplored areas would require measurements in deeper wells, which, for the time being, do not exist.

5. WATER SAMPLING AND ANALYSES

During the thermometric survey of June-July 2014, the electrical conductivity (EC) of the water was in-situ measured at the head of 141 measured wells. The EC values in two wells of the desalination plants in Fira and Oia exceeded 20.000μS/cm. The EC was above 10.000μS/cm in three wells located close to Perissa, Monolithos and Emporio, whereas for the rest of the samples it ranged from 900 to 6700μS/cm.

In October 2014, samples from eight (8) selected sites were collected from the central and southern part of Santorini (Figure 4). Three samples were collected from each site and were analyzed at the Analytical Chemistry Laboratory of the Chemical Engineering School (AUTH) for determining their physicochemical characteristics (Table 3), the main ions and trace elements.

Table 3: Physicochemical parameters of the water samples

Well	Locality	Temp. (°C)	pH	EC (μS/cm)	TDS (mg/l)
Mg-7	Megalochori	44	7.5	7460	4076
F-10	Fira	25	7.7	3810	2206
V-6	Vourvoulos	26	7.6	5280	2886
K-12	Karterados	27	7.8	2490	1440
M-13	Messaria	25	8.1	930	644
Vth-8	Vothonas	29	7.8	3650	2256
E-19	Emporio	29	7.7	3380	1987
Eg-2	Exo Gonia	25	7.8	3220	1713

With the exception of M-13 sample, the TDS values in all the samples exceed 1000 mg/l, which classifies the samples as brackish waters. In addition, all samples except M-13 are rich in Na^+ and Cl^-; the concentration of these two ions varied from 111 to 1150 mg/l and from 135 to 2080 mg/l, respectively.

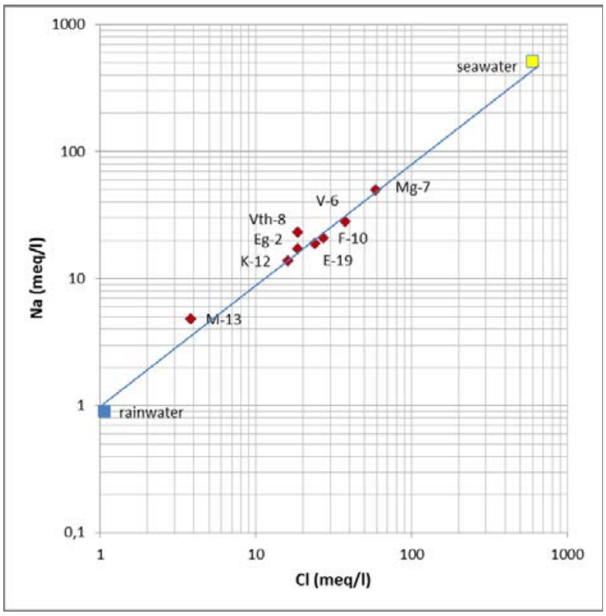

Figure 6. Molar ratio of Na^+ and Cl^- in Santorini samples

The molar ratio of Na^+ to Cl^- (plotted in Figure 6) shows that six (6) samples lie along the seawater–rainwater mixing line. In these samples the Na/Cl ratio is less than 1, denoting seawater intrusion in the aquifers. On the other hand, the Na/Cl ratio for the M-13 and Vth-8 is above 1, suggesting that these waters originate from aquifers inside alkaline magmatic formations.

The applied Revelle index clearly shows seawater intrusion in the wells Mg-7 and V-6, probable intrusion for the F-10, E-19 and Eg-2 samples and no intrusion for the K-12, Vth-8 and M-13 wells.

According to the Piper diagram (Piper, 1944), all the water samples except M-13 are classified in the Cl-SO_4 water type (Figure 7).

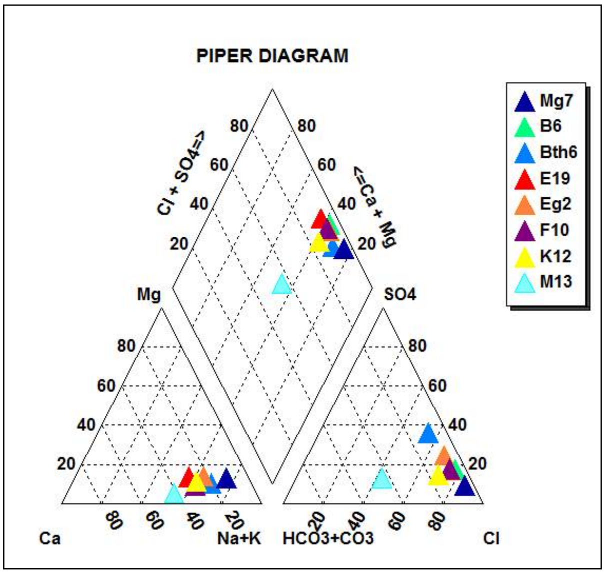

Figure 7. Piper classification of Santorini samples

Toxic trace elements, such as Pb, Cu, Cr, Sb, Zn and Cd were not detected; however, As concentrations higher than the guidelines for drinking water (10 μg/l) were measured in 5 samples (F-10, V-6, K-12, M-13 and Vth-8). The increased content of As in thermal waters is generally attributed to volcanic rock leaching (Valentino & Stanzione, 2003).

The scaling potential of the water samples was determined by using the Supersaturation ratio (S), the Langelier Saturation Index (LSI) and the Ryznar Stability Index (RI). The supersaturation ratio of $CaCO_3$ for six samples ranges from 1.19 to 2.65 at 25°C and from 1.57 to 2.57 at 45°C. The S value for the sample M-13 was 3.46. The experience from low enthalpy wells in Greece has shown that scaling occurs when the critical value of S=3 is exceeded. Therefore, serious scaling problems are not likely to be encountered, at least for the majority of the cases and for temperatures below 65°C. On the contrary, the LSI and RI values indicate that scale forming is probable, whereas corrosion is less possible.

6. GEOTHERMOMETERS

In order to estimate the subsurface temperature in the studied areas, the geothermometers of SiO_2 and Na-K-Ca were applied at the eight (8) water samples. The results are presented in Table 4.

The Na-K-Ca geothermometer, which provided temperatures around 140-150°C, is considered as the most reliable for Santorini, due to the specific lithology of the studied areas. According to the geothermal gradients, the above temperatures are expected at depths around 800-1000m. The latter is consistent with the geoelectrical findings, i.e. very low (1.5 Ohm·m) electrical resistances near the depth of 800m, inside the pre-volcanic basement of the broader Megalochori area (Budetta et al., 1984). It should be mentioned that such low resistivity values (0.5-5 Ohm.m) measured in Milos Island were indeed associated to the high enthalpy reservoir in Zephyria (Fytikas et al., 1989).

Table 4: Temperature estimation based on the Silica and Na-K-Ca geothermometers

Sample	SiO_2	Na/K/Ca
Mg-8	129	153
F-10	103	148
V-6	98	134
K-12	104	141
M-13	109	153
Vth-8	105	142
E-19	92	139
Eg-2	91	143

7. DISCUSSION-PROPOSED ACTIVITIES

Santorini Island is currently strongly depending on fossil fuels in order to cover its energy requirements. According to the “Sustainable Energy Action Plan” for Santorini island (www.islepact.eu), elaborated in 2012 by DAFNI (Network of Aegean Islands for Sustainability) in collaboration with the local and regional authorities, the largest energy consumers are the residential (~40%) and the tertiary (~50%) sectors. The total final energy demand in the island exceeded 178 GWh in 2005, while the estimated annual increase rate of electricity demand is 9%. Heating/cooling in the residential sector and accommodation/food service activities in the tertiary sector represent more than 60% of the final annual energy demand. These requirements are mostly covered by electricity (up to 80%) and fossil fuels (up to 40%). The Renewable Energy Sources (RES) cover only a very small fraction (<10%) of the primary energy demand, which, unfortunately, does not include geothermal energy. Fuel combustion for heating and cooling contributes the largest share of the CO_2 emissions, i.e. 54% according to the most recent available data (for the year 2012). Between the years 2005 and 2020 the total increase of emissions is estimated to be 60%.

The Municipality of Thera has set ambitious targets concerning its energy policy by the year 2020. This includes cutting the CO_2 emissions by 5444 tn/year, reducing energy supply by 15329 MWh/year and increasing the renewable energy production by 1669 MWh/year. The measures to make this policy successful involve, among others, the use of geothermal heat pumps for heating and cooling in public and private buildings and residences. No provision had been made until recently for the use of the confirmed or the possible, and so far unexplored, low-enthalpy geothermal potential of the island.

The recent thermometric survey (2014-2015) proved that most of the areas to the north of the identified low enthalpy geothermal field, i.e the region between Vourvoulos, Fira, Messaria and Kamari (see Figure 3), are geothermally interesting and promising. The recorded temperatures (22-28°C) were significantly higher than it was anticipated beforehand in such shallow depths (40-120m below ground surface). The stable and extended geothermal anomaly in this part of Santorini can only be associated to a deeper geothermal system with temperatures at least up to 90°C that can be found in depths from 500 to 900m. Similarly to the situation in southern Santorini, this anomaly could be attributed to the intense and extensional tectonic activity that has affected the crystalline pre-volcanic basement of the island.

The exploration activities to confirm the resource and estimate its likely potential must include geophysical surveying and temperature gradient drilling in selected areas, so that additional and critical subsurface information can be obtained.

This exploration phase should initially focus on the areas of *Fira*, *Monolithos* and *Vothonas-Messaria*, for reasons related to the availability of energy users and to the higher recorded temperatures. *Fira* is the administration and tourist center of the island, with several public buildings, hotels, museums, as well as health and sports centers that could cover their energy requirements for heating/cooling and hot water by using geothermal energy. The same stands for the civil/military airport of Santorini, which is located in *Monolithos* and is soon expected to expand. On the other hand, the highest temperatures outside the low enthalpy geothermal field were measured in the areas of Vothonas and Messaria, reaching approximately 28°C. The latter, makes this area a very promising new geothermal region that needs to be one of the primary exploration sites.

The re-evaluation of the data from the past geothermal exploration in southern Santorini suggests the construction of three (3) new exploration/production wells in the areas of *Megalochori*, *Vlychada* and *Emporio*. Their depth should exceed 600m (up to 800m), targeting the pre-volcanic metamorphic basement, where temperatures above 65°C are expected to be found. The total cost of these three wells is roughly estimated to approximately €450,000. These wells will allow the investigation of the deeper aquifers as well as the production of low to medium enthalpy geothermal fluids that could be used in several direct applications, as it will be discusses in the following paragraphs.

To start with, the easiest, simplest and directly applicable scenario regards the exploitation of the shallow geothermal resources for the heating/cooling of buildings (schools, office buildings, hospitals, hotels, etc.) and residences by using the available low temperature (20-25°C) waters from existing wells. A GSHP system for a 2000 m^2 building would reduce the heating/cooling cost up to 1/5 of the corresponding cost for a conventional system.

The GSHPs could also be used for greenhouse heating. It is estimated that the heating of a 0.4 ha greenhouse in Santorini would require approximately 480 MWh/year. The annual cost using conventional fuels would reach almost €50,000, whereas the relative cost with GHSPs should not exceed €10,000, making the latter a very attractive option.

Santorini is a well-known wine producing region with ten major wine producing facilities. GSHPs could be used for the heat, cool and chill that is required for the treatment and decantation of must, the alcoholic fermentation and the temperature maintenance at desired levels. A GSHP system was installed a few years ago in a small winery in Peloponnese, which annually produces 500 tons of wine. A pair of geothermal heat pumps provides 57 kW for heating and 53 kW for cooling. The installation of the system cost €60,000 and the payback time is estimated to 4-5 years.

The confirmed or probable low enthalpy geothermal resources of the island (T>25°C) could be exploited for space or district heating purposes. For a 2000m^2 area, the use of geothermal fluids with an average temperature of 70°C would reduce the heating cost by 55% compared to a GSHP system and by 84% in comparison to a conventional oil boiler.

Another interesting use of geothermal energy could be the dehydration of agricultural products. “Sun-dried” tomatoes are one of the most famous products of the island. On the other hand, geothermal dehydration constitutes an interesting and successful alternative option for tomato drying. The first project of using low enthalpy geothermal fluids for tomato drying was realized in Neo Erasmio (Xanthi, Northern Greece). The dehydration plant operates since 2001 during the period August-September and has produced, so far, more than 150tn of excellent quality dried tomatoes. The unit uses geothermal fluids of 59°C, temperatures that have already been found in southern Santorini.

Moreover, a hot aquifer with temperature above 40°C that has been encountered by a water supply well drilled in Megalochori settlement could be partly utilized for heating an olympic-size swimming pool which is planned to be constructed. The total heating cost is estimated to €10,000/year, whereas part of the geothermal water could be further used in the spa facilities of the nearby hotels. The combined use of thermal water for both heating and therapeutic purposes has proved to be a very cost-effective mode of exploiting geothermal energy in the balneotherapy/spa sector, also contributing to the extension of the traditional balneotherapy/tourism period.

In case fluids with temperatures between 60 and 80°C are discovered, they could be used for the desalination of seawater. It has been well established by the international experience that the most economic desalination method is the use of geothermal heat in multiple effect distillation (MED) plants. So far, five reverse osmosis desalination units are in operation in Santorini, but none of them is using any kind of renewable energy sources.

The most compelling, yet ambitious and certainly optimistic, exploitation scenario involves the use of high temperature geothermal fluids (100-150°C) for the power generation or/and seawater desalination. As discussed in the previous chapters, such resources are to be expected in depths greater than 800m in the area of the confirmed geothermal field.

8. CONCLUSIONS

The geothermal exploration has shown that:

- *High enthalpy* geothermal resources (T>150°C) probably exist inside the calderas of Santorini and Kolumbo, along the homonymous tectonic lines. These resources are practically inaccessible and are not considered as exploitable, due to environmental and economic reasons.
- *Medium enthalpy* resources (90-150°C) are expected to be found in southern Santorini, in depths around 800-1000m. The latter is based on the existing thermometric, geochemical, geophysical and drilling data from this area.
- *Low enthalpy* resources are confirmed in the area between Megalochori-Perissa-Vlychada-Akrotiri. The geothermal field covers 25km^2, with reservoir temperatures 30-65°C, in depths 50-250m. Furthermore, the recent thermometric survey strongly indicated the existence of a low enthalpy geothermal anomaly in central Santorini. The mean wellhead temperature in this area exceeds 25°C, whereas the maximum values reach 28°C.
- *Shallow geothermal* resources with temperatures between 20 and 25°C were recorded in almost all measured wells on the island.

The area between Vourvoulos, Fira, Monolithos and Kamari needs to be further and thoroughly explored in order to locate the hot reservoirs and establish the boundaries of the thermal anomaly.

Moreover, new and deeper (600-800m) exploration/production wells should be drilled near Megalochori, in the area of the highest confirmed geothermal anomaly, targeting temperatures of at least 90°C inside the metamorphic basement.

Given the major economic activities of the island, the rapid growth of the touristic sector, the unique physiognomy of the place and the energy policy that the local authorities are determined to apply, the following direct geothermal applications are proposed:

- Use of GHHP's for the heating and cooling of public buildings and accommodation facilities.
- Exploitation of the confirmed low enthalpy potential of southern Santorini for heating/ cooling applications (buildings, greenhouses, swimming pools), dehydration of agricultural products and seawater desalination.
- Combined use of low enthalpy geothermal fluids for heating and recreation (balneotherapy) in spa facilities.

Depending on the findings of the future geothermal exploration, geothermal heat could be used for a number of direct applications in central Santorini, as well as for binary cycle power generation.

Despite the high initial cost of investment, geothermal energy would result, in the long run, in huge cost savings and significant economic development. Therefore, the local authorities should (i) encourage the citizens to adapt the technology of GSHPs and convert their heating systems from oil to geothermal, (ii) support and promote the use of geothermal heat in various sectors (agricultural, industrial, recreational, etc) and (iii) set a specific agenda for further geothermal exploration activities.

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