Santorini Volcano: The intra-caldera unrest of the period of 2011 - 2012, as revealed by seismicity, temperature, sea-level, geochemical and GPS data

D.G. Panagiotopoulos[1], C. Papazachos[1], G. Vougioukalakis[2], S.C. Stiros[3], Th. Laopoulos[4], M. Fytikas[5], E. Karagianni[6], D. Vamvakaris[7], F. Moschas[7], V. Saltogianni[8], K. Albanakis[8]

1 Καθηγητής ΑΠΘ , 2 Δρ ερευνητής ΙΓΜΕ, 3 Καθηγητής Πανεπιστημίου Πάτρας,
4 Αναπλ. Καθηγητής ΑΠΘ, 5 ομότιμος καθηγητής ΑΠΘ, 6 ΕΔΙΠ ΑΠΘ,
7 Phd Πανεπιστήμιο Πάτρας, 8 Msc Πανεπιστήμιο Πάτρας
panagiot@geo.auth.gr

Abstract: During the period 2011-2012 an unrest of the Santorini volcano (Thera island) in central Aegean Sea (Greece) was associated with a well-defined microseismic activity in the center of Santorini caldera. This microseismicity was spread out along the Kameni island line (a tectonovolcanic linear structure extending from the Kameni Isl. to the city of Fira - Thera). In this paper the results of the recordings of the volcano's monitoring networks for the period 2011-2012 are briefly described. All these data have been produced under the responsibility or with the cooperation and assistance of ISMOSAV (Institute for the Study and Monitoring of Santorini Volcano). The Institute's (ISMOSAV) activities are intended to coordinate all the individual research efforts for the management of the volcanic risk. This seismovolcanic activity has provided a great opportunity for the Institute and the island's local authorities to test the efficiency of the existing monitoring networks. Moreover, it was a great opportunity, to start the procedures for the preparation of appropriate emergency plans for future needs.

1. Introduction – Geological settings

The Greek region is located on the Mediterranean-Melanesian zone of the continental rupture system, exhibiting intense volcano-tectonic activity throughout its history. Typical features of this major geological structure are the strong megadomes of ruptures - folds, the strong geophysical anomalies of the main potential fields, the high seismicity of the broader Aegean area and the volcanic and geothermal phenomena of the volcanic arc of the southern Aegean Sea. All these phenomena are encountered in typical subduction areas all over the world, well explained by the plate tectonics' theory.

Figure (1) shows the major features of the lithospheric microplates in this area and their main motions, which define the principal geodynamic and geophysical characteristics of the Aegean sea and its neighboring regions. A schematic model of the main features of the deep active tectonics and structure was proposed by Papazachos et al. (2005) for the Greek subduction system (Figure 2). In this study an attempt was made to present information about the converging lithospheric plates in the Greek area, in combination with information about the location and size of the primary magma zone beneath the central Aegean Sea.

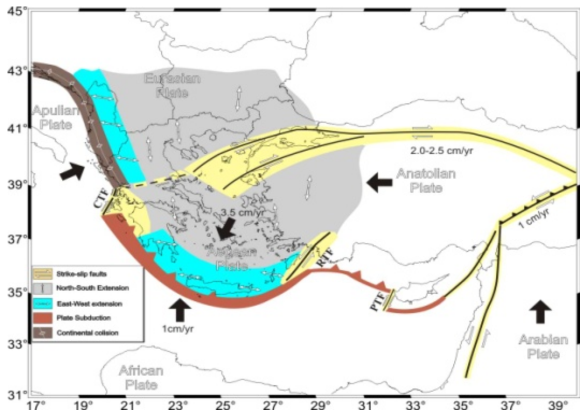

Figure 1: *Main motions of the tectonic microplates which define the main geodynamic and geophysical characteristics of the Aegean Sea and neighboring regions (Papazachos et al., 1998).*

Figure (2) (Papazachos et al., 2005) presents a vertical profile of the deep geological structure (Greek subduction zone) of the Hellenic arc in an approximately SSW to NNE direction, up to the depth of 200km. The main idea is that the zone of the primary magma genesis is located just above the section of the subducted oceanic plate with low seismicity, around the depth of 110-140 km. The authors suggested that on the basis of this observation, the segment of the subducted oceanic plate with low seismicity is dehydrated at depths less than 110km. Following this proc-

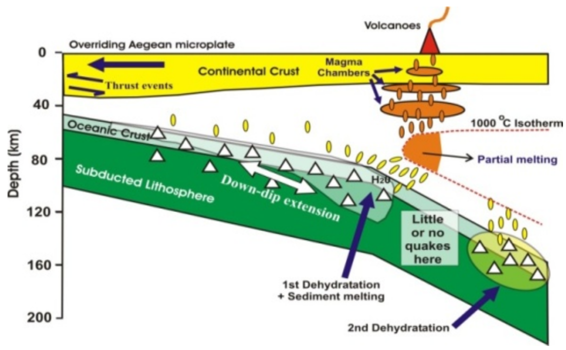

Figure 2: *A synthetic model of the converging lithospheric plate system and the geotectonic structure of the Southern Aegean region, resulting in the genesis of the primary magma zone under the Central Aegean Sea (Papazachos et al., 2005).*

ess, the water which has been released contributes to the procedure of the formation of the primary magma after entering the isotherm of 1000^0 C in the upper mantle under the central Aegean crust. Additional information (Zellmer et al., 2000) on trace element and isotopic data which are observed in the Santorini's volcano support the model i.e. that the sources of the primary magma in the Hellenic volcanic arc is the subducted oceanic crust in the area, in combination with the mantle wedge which is established above this oceanic crust and the Aegean slab.

As a result of the intense seismic deformation field in the area of the southern Aegean, distinct clusters of large fractures are observed. The volcanic centers and the epicenters of strong earthquakes (of shallow and intermediate depth) in the region of the volcanic arc in the southern Aegean form five (5) very well defined linear groups (seismovolcanic clusters) in direction N600E (Papazachos and Panagiotopoulos, 1993). Figure (3) shows all (complete data set) shallow and intermediate depth earthquakes, as well as the volcanic centers (volcanoes and solfatara fields), as depicted by Papazachos and Panagiotopoulos (1993). In the central Aegean Sea, the crust is characterized by an extensional stress field, with a roughly NNW-SSE direction.

Since the occurrence of both shallow and intermediate depth shocks and volcanic activity indicate the mode of rupture of the crust in this area, it is safe to assume that these seismovolcanic clusters are due to the presence of the corresponding five (5) rupture zones (faults), with a typical strike of N600E. We have to note that the shallow seismic activity in the eastern and central region of the volcanic arc is higher than in the western region, with the same being valid for the volcanic activity. This is also supported by the fact that the largest earthquakes in the western part do not exceed the magnitude of 6.5, while in the central-eastern part of the volcanic arc they reach the magnitude of 7.5 (e.g. Amorgos 1956 event).

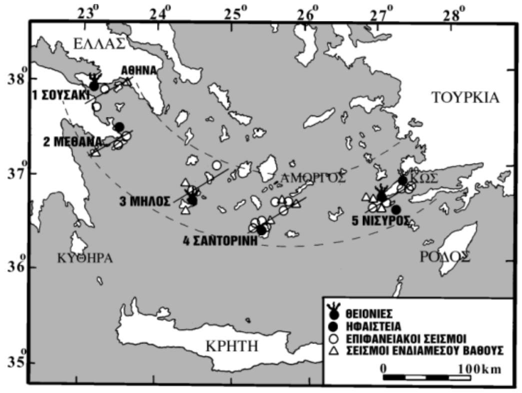

Figure 3: *The main five (5) linear seismovolcanic clusters in the volcanic arc of the Southern Aegean Sea (Papazachos and Papagiotopoulos, 1993).*

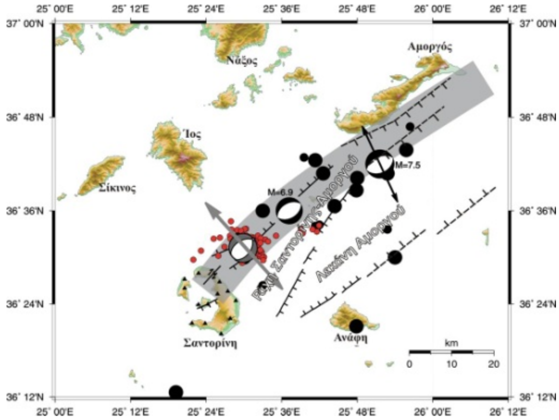

Figure 4: *The Amorgos-Santorini main rupture zone (Dimitriadis et al., 2009) .*

The seismo-tectonic rupture zone of the Columbos-Santorini volcanic system is presented schematically in Figure (4) (center of Figure 3), corresponding to a continuation of the active normal fault of Amorgos, which generated two of the largest shallow earthquakes observed during the 20th century in the Greek area.

These two earthquakes have occurred with a time difference of 13 minutes on July 9, 1956, the first having at 3:11:40 UTC with magnitude M = 7.5 and the second one at 3:24:03 UTC with magnitude M = 6.9 (Shirokova , 1972; Papazachos et al., 1985; Ambraseys and Jackson, 1990; Papadopoulos and Pavlides, 1992; Papazachos et al., 2001). The epicentral region of the main earthquake has been located 5 km south of the center of the Amorgos's island, while the main aftershock has been located 20 km south-west of the epicenter of the main earthquake (Figure 4). As a result, 53 people have died, 100 people have been injured, 529 buildings have been destroyed and many others have been severely damaged (Galanopoulos, 1957; Papazachos et al., 1985; Papadopoulos and Pavlides, 1992;) while the tsunami that was generated induced significant damages to nearby harbors.

2. The seismic activity before the unrest of the volcano

In figure (5) we present the seismic activity of the main volcanic center of Santorini - Columbos for the period from October 2008 to May 2010 (left) and from January 2006 to October 2008 (right). As is clearly defined from figure (5), almost the complete seismic activity, before the crisis of 2011-2012, was mainly distributed at the area of the volcano around the Columbo Reef and along the seismotectonic line of Santorini – Amorgos. This observation is not due to any space-time catalogue incompleteness effect, since the permanent seismological networks of the broader Aegean area, in collaboration with the local permanent seismological network of the Institute of ISMOSAV, which is established in the Santorini's

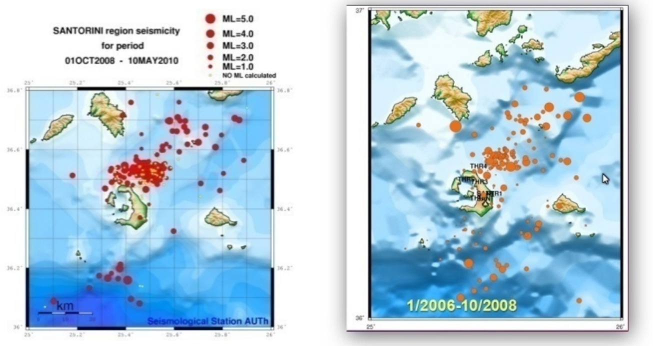

Figure 5. *The seismic activity of the volcanic center of Santorini for the periods: A) October 2008 to May 2010 (left side) and B) January 2006 to October 2008 (right side).*

island, were capable to record even small magnitude events occurring near the volcanic center.

Figure (6) shows the spatial distribution of the seismic sequence of June 26 to June 29 2009. The main earthquake of this sequence with magnitude M = 5.1 was particularly felt in the island of Santorini without any serious effects (damages or injury to people) on the Thera island. The earthquakes have been recorded by the Santorini's seismological network, as well as the Greek National Seismograph network, while the employed catalogue was compiled by the Seismological Station of the Geophysical Department of the Aristotle University in Thessaloniki.

This seismic sequence was distributed over the three days period (26 to 29 June 2009) at the area of Columbos reef, which is a part of a major underwater volcanic edifice. It is clear that the spatial distribution of the foci in figure (6) delimit the southern linear limit of the Anydros's tectonic graben, which is a local normal active fault.

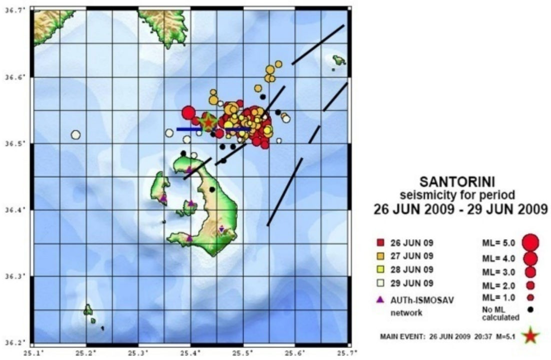

Figure 6*. Seismic activity of the broad volcanic center of Santorini - Columbos for the period 26 to 29 June 2009. The main earthquake had a magnitude of M = 5.1 (Int. report of IMPIS, 2010).*

3. The basic monitoring of the Santorini's volcano

As it is well known, the volcanic multilateral monitoring is mainly based on the continuous data collection and analysis of several local networks (seismological, geodetic, geochemical, geophysical, tide gauge, etc.). This monitoring is based on the principle that the magma, during its rise to the earth's surface, causes not only microseismic activity but also other phenomena (significant crustal movements, temperature changes, migration of hydrothermal fluids, etc.). These phenomena can be recorded by dedicated and specialized local networks, the same way that earthquakes can be recorded by seismographic networks.

In the area of the volcanic complex of Santorini islands ISMOSAV operates since 1995 various monitoring networks (seismic, geodetic, thermal, geochemical, geophysical), forming a reliable early-warning system, capable to possibly forecasting future reactivations of the volcano. The main scope of ISMOSAV's operation is also to evaluate and identify false alarms, as well as to handle the provision of reliable information to the public with respect to the volcanic activity, in close cooperation with the local island authorities.

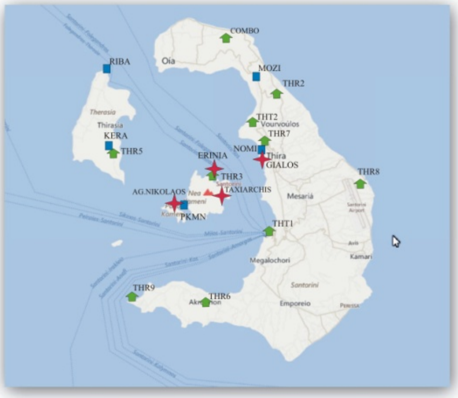

Figure 7. *Main monitoring networks of the Santorini volcano, currently operated with the support of ISMOSAV (Seismograph: greens lodges, Tide Gauge-Temperature Measurement: red stars, Geodetic-GPS Stations: blue squares).*

The main stations of the entire monitoring network are presented in figure (7). A very important tool for the assessment of volcanic activity is the monitoring of microseismic activity. The ISMOSAV in cooperation with the Seismological Station of the Geophysical Department of the Aristotle University of Thessaloniki currently operates a network of 11 permanent seismological stations (six analog and five digital stations). The recordings of the seismological network, which are the basic tool for the correct monitoring of the Santorini's volcano, are transmitted to the central Seismological Station of the Aristotle University in Thessaloniki. All data are recorded and analyzed (together with the data of the digital stations of the Institute of Geodynamic – National Observatory of Athens which are also installed in Thera island) in a continuous 24-hour basis.

All these data, since 1995, when a small analog seismological network was installed in 1994 in Thera island, until 2010, have shown (Figure 5) a continuous seismic activity located mainly in the area of the Columbos's volcano, as well as at the tectonic faults north of Santorini island (e.g. the earthquake sequence of M = 5.1, June 2009, Figure 6) and in the active tectonic line of the Columbos - Amorgos (Dimitriadis et al., 2005). These results have been confirmed by portable local dense seismic networks which were installed on the island and the surrounding area for the time periods from September 2002 to July 2004, June 2006 to March 2007 and September 2002 to September 2005 (Bohnhoff et al., 2004; Bohnhoff et al., 2006; Hensch et al., 2008, Dimitriadis et al., 2009, 2010).

4. The history of the volcano's unrest by seismic activity in 2011-2012

During the period of January 2011 to May 2012 an unusual and gradually increasing seismic activity occurred in a linear feature located at the central area of the Santorini's caldera. As shown by both the spatial distribution, and the cross-sections (Figure 8), there was an almost linear concentration of epicenters on the volcano - tectonic line of Kameni-Firostefani (Fira). This well-defined fault is almost vertical (dipping angle ~ 800), as seen from the perpendicular cross-section (Figure 8, right part). From the map, and the along-fault cross section (Figure 8), it appears that the seismic activity originated in January 2011 in the NE coast of New Kameni and extended mainly towards the NE direction (and less to the SW direction) in February. In March and April 2011 the seismic activity was continuing both in the NE (Firostefani - Imerovigli) and SW lineament segments (Old and New Kameni region). The seismic sequence seems to be completed in May 2012, with an almost complete absence of microseismic events after July 2012.

The seismic foci have mainly concentrated at depths around 2.5-5.5 km (Figure 8, right part), but exhibit a slight slope along the profile of the seismic sequence, with shallower foci (depths of 1-3.5km) close to the region of Old and New Kameni islands. At the same cross-section, an increase of the depths foci is observed towards the Firostefani's direction. We have to note that the mean uncertainties of the foci's determination, were 0.7km and 1.4km for the horizontal and vertical coordinates, respectively, (smaller for the most recent data, after installing an additional monitoring station in Athinios port). As a result, the "thickness" of 2km which is shown for the normal cross-section view of seismicity (Figure 8, right part) may be erroneous and the actual foci distribution is most probably a thinner and almost vertical

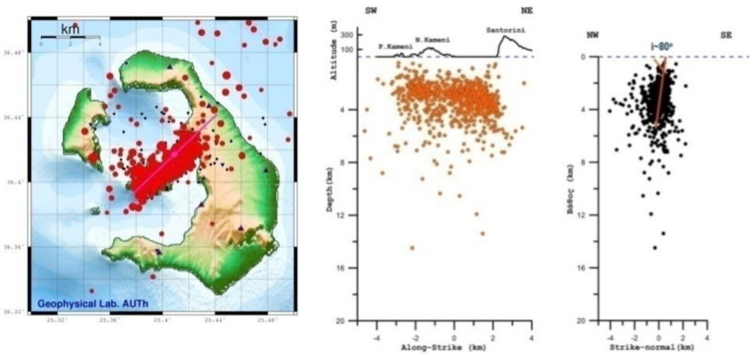

Figure 8. *Seismic activity (left part) in the region of Santorini, during Jan 2011 - Sept 2012. The seismic foci are shown in strike-parallel and strike-normal cross-sections of the main seismotectonic lineament (purple line) of the seismic sequence (right part).*

plane. The seismicity for the periods October 2012 to September 2013 and September 2013 to October 2014 has been significantly reduced, and thus has practically returned to the pre-crisis levels.

It is interesting to note the similar features of the seismic activity in 2013 with that of the year 2014. Figure (9) shows the relatively high seismicity in the region of the Columbos Reef and the reduced, practically non-existent, seismic activity in the area of the Santorini's caldera.

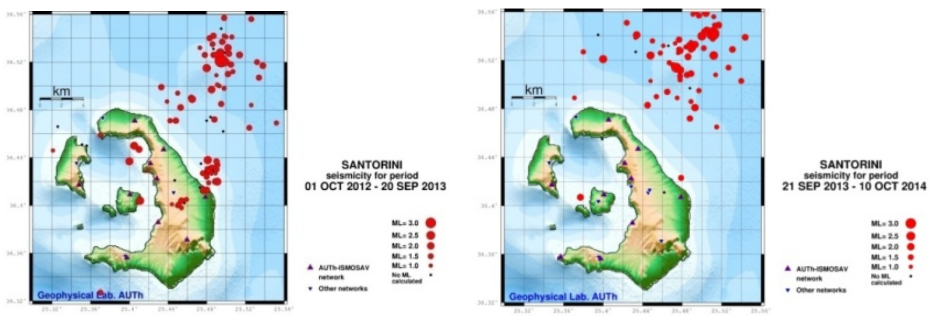

Figure 9. *The seismic activity in Santorini region, during the periods October 2012 to September 2013 (left part) and September 2013 to October 2014 (right part).*

Of particular interest is the temporal variation of the cumulative number of earthquakes which is shown in Figure (10). During the crisis the magnitude of earthquakes that was monitored by the local network starts up from very low magnitudes (M_L~0.2-0.3), however the average completeness for the whole time period (i.e. not missing earthquakes) was around $M_L \geq 1.1$.

The data show a gradual increase in the average magnitude from ~ 1.2 to 1.65, with a relatively sharp increase in the ~50th day (~February 20, 2011) and many variations up to 31/10/11. On the other hand the average magnitude of the shocks over the whole period has remained within a stable band with limits ranging from 0.7 to 1.7. At same time, the rate of earthquake occurrence was ~ 0.2 earthquakes per day until ~ February 10/2011, but this rate had increased to 1.2 earthquakes per day until ~ February 20, at ~ 1.9 earthquakes per day until May 14/2011, and even more at ~ 2.4 earthquakes day after May 14/2011. In the next period, up to September, the rate had declined up to ~ 0.2 earthquakes per day, to rise sharply again in October/2011 up to ~4.0 earthquakes per day.

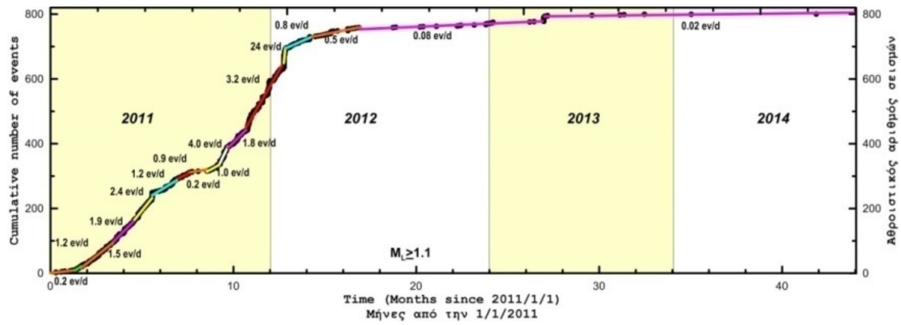

Figure 10. *Temporal variation of the cumulative number of earthquakes in the area of the Santorini's caldera with magnitude $M_L \geq 1.1$, for which data is complete (the earthquakes at the Columbo's underwater volcano are excluded).*

During this time there were many small-scale "jerks" of the seismic activity, the most important of which was in May 24, 2011 where we observed the occurrence of 18 earthquakes (maximum magnitude M_L=2.5), while during a similar increase on February 23/2011 (8 earthquakes) the strongest earthquake (M_L = 2.9) occurred, which was felt on the island of Santorini. Respectively, on June 16th/2011, 17 earthquakes had occurred with the larger magnitude of M_L = 3.2 and the next day, June 17th/2011, 23 earthquakes had occurred with the larger magnitude of M_L = 2.6. Also during October/2011 several peaks of the seismic activity had been observed in the 8th, 14th, 15th and 18th days with the occurrence of 15, 14, 16, 13 earthquakes, respectively. The seismicity culminated in December 2011 and January 2012, with the occurrence of ~ 24 earthquakes per day with magnitudes M_L > 1.1. After January 2012 a stepwise decline in the seismic activity is observed and the activity appears now to have stabilized at a very low constant rate of occurrence (~ 0.02 earthquakes per day). During the last year (2014) the monitoring of the volcano showed that the seismic activity had stabilized at levels similar to those before the beginning of the seismic crisis in 2011.

5. The history of the volcano's unrest by other networks

The time and spatial distribution of Figures (8) shows that the length of the fault which was activated during this crisis was about ~ 5.0km. This means that the maximum magnitude of a future shock, generated from this fault, corresponds to an earthquake about M ~ 5.2 (if the event would rupture the complete activated zone). The occurrence and geometry of seismic activity which is shown in Figure (8), with the most shallow seismicity occurring closer to the region of New Kameni island, is compatible with the changes in temperature of the sea-water at the thermal-stations in Santorini's caldera shown in Figure (11).

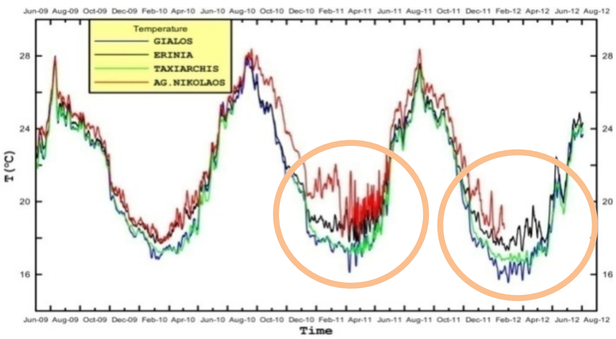

Figure 11. *Temporal variation of sea-water temperature in four tide-gauge stations of the ISMOSAV's network, exhibiting a strong temperature increase at the Agios Nikolaos's station, starting about August, 2010.*

Figure (11) shows a significant variation of the average sea water temperature for the tide-gauge station of St. Nikolas in Old Kameni island, starting at October 2010. This differentiation started gradually, but from January to early June 2011, the deviation became stronger, showing a completely different behavior from the previous period. On the contrary, the other thermal observation at the station of Taxiarchis, which is located at the eastern part of New Kameni island (outside of the New Kameni fault zone) towards the island of Thera and the thermal station in Yalos (port of Fira), do not show such intense variations.

It is interesting to note that the thermal station of St. Nikolas (Old Kameni) continues to deviate by roughly one (1) degree C0 in relation to the Erinia's thermal station from the beginning of June 2011 until today. It should also be noted that the tide gauge's network had recorded, in the same period, significant changes of the sea level, with a decrease of the sea level (corresponding to a rise of the island of Santorini) with respect to Syros island, of the order of 20 cm (Figure 12).

Although this increase of the sea level was confirmed locally by field observations, additional processing is required to investigate this local rise of the Santorini island in relation to other environmental causes that may affect the changes of the sea water level.

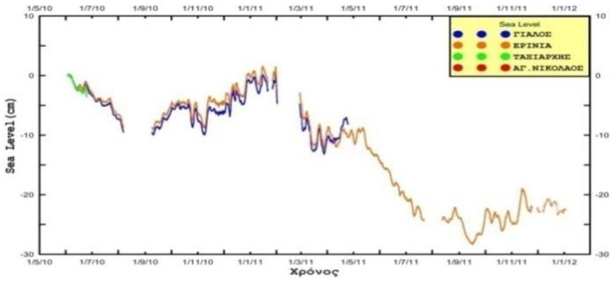

Figure 12. *Temporal variation in the level of sea-water (measured with tide gauges network) at Santorini in relation to the tide gauges station of Syros's island (Geographical Survey). It shows the average fall of the sea water level (land uplift) of about 20 cm from the middle of 2010 to early 2012.*

It is also important to emphasize that the soil temperature of New Kameni island did not show any significant change during this crisis, while the emissions of the CO_2 were slightly increased after January 13, 2011 (Figure 13), with maximum values (60 to 90 ppm/sec) which are 30% greater than the normal average values. This differentiation was not evaluated as an alarming indication.

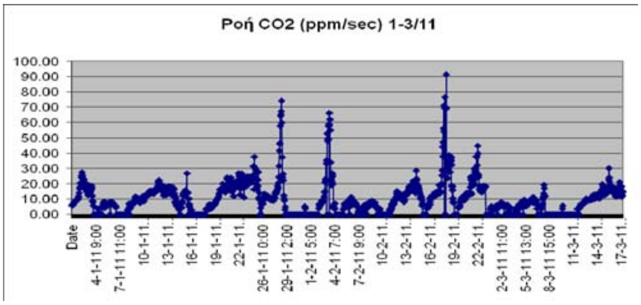

Figure 13. *Temporal continuous recording of CO_2 in New Kameni*

The ISMOSAV in collaboration with the University of Florence (Italy) had carried out a geochemical survey of fumarolic and subsurface gases from fluid discharges which were located in the islands of New Kameni and Old Kameni, before, during and after the period of the volcano's unrest in 2011-2012. The observed changes deduced from this survey (Tassi et al., 2013) were related to the anomalous high seismicity, along the tectonic line of Kameni - Fira (Figure 8) and ground deformation activity, which had been measured by the permanent and temporary GPS networks (Newman et al. 2012, Saltogianni et al., 2014), that affected the seismo-volcanic of Santorini center since January 2011.

According to the results of the geochemical survey a significant increase of H_2, CH_4 and $\log(H_2/H_20)$ concentrations related to the increase of seismic activity during the period May 2011 – February 2012 was recorded (Figure 14). After this

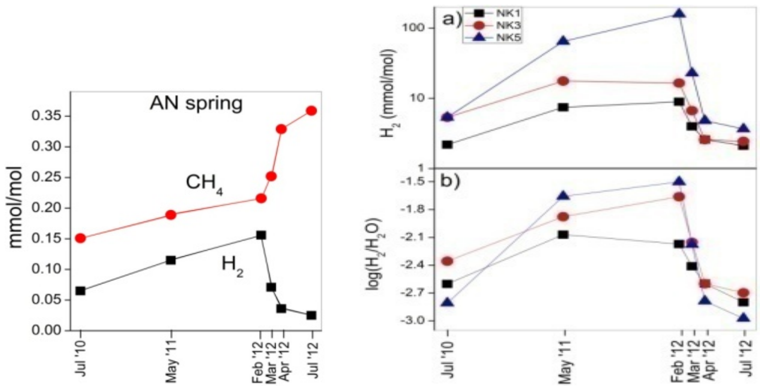

Figure 14. *Temporal continuous recording of H_2 and CH_4 at station of AN spring at the Old Kameni island (left part) and H_2 and log(H_2/$H_2$0) at stations NK1, NK3 and NK5 located on New Kameni island (Tassi et al., 2013).*

increase, an abrupt decrease in the H_2 content correlated to the decrease of seismic activity. The general increase of light hydrocarbons (e.g. CH_4) had continued until July 2012.

All these phenomena can be explained by a convective heat pulse (a new rise of magma) from a depth which is associated with the seismic activation at the tectonic lineament of Kameni-Fira. It is possible that a new injection of magma below the New Kameni island had triggered the whole seismo-volcanic activity, as apparently is suggested by the evolution of the seismic and ground deformation activity at the caldera's area.

The University of Patras in cooperation with ISMOSAV, the University of Georgia Tech (USA) and UNAVCO (a non-profit university-governed consortium in USA) and the support of the GSRT of Greece, had installed in 2006 an automatic telemetric network of three (3) permanent GPS monitoring stations, after they had established a larger network of GPS stations (19 points) for periodic measurements (Figure 15, left part).

Data of that network had been recollected in June 2008 and in June 2010. During this period, until 2010, no surface deformation was observed in the area of the volcano. After the start of the crisis, in June 2011 a new measurement of the GPS network was made together with the an upgrade of the GPS system. Moreover, in July 2011 a new data collection and extensive maintenance of the network has been performed. In August and September 2011 two additional GPS permanent stations were installed in Thera and Therasia island (Figure 15, left part) and the entire network was re-measured. The entire network was re-measured at the beginning of 2012 and in September of the same year, while a new GPS station was installed by the University of Patras in the SE part of Thira Island (Figure 15, left part).

Figure (15, right part) shows the total ground deformation during the period of the

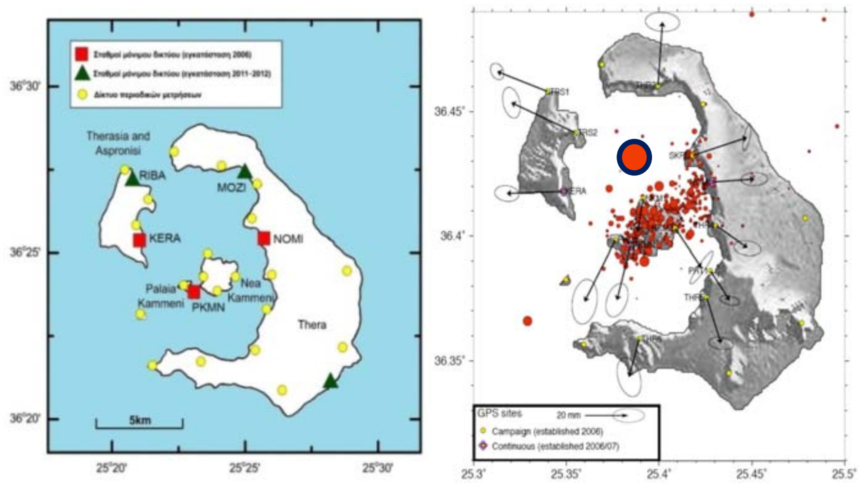

***Figure 15**. (Left): Position of the GPS stations (red squares and green triangles) of the permanent geodetic network and the corresponding places of the periodic measurements of GPS network (yellow circles).*
(Right): Horizontal velocity vectors derived from GPS measurements (black arrows) calculated for the best fit of a spherical magma's source (MOGI) related to the seismo-volcanic activity of 2011 -2012 (Newman et al., 2012).

crisis in 2011-2012 in the region of Santorini volcanic complex related to the seismic activity and the position of the magma's chamber (MOGI source) at a depth of approximately 4 kilometers (Newman et al., 2012). The GPS-team had intensively continued the collection and processing of the data of the GPS stations, as the experience of other volcanoes in the world showed a rather long period of activity which requires a systematic surveillance and monitoring of all available networks of scientific instruments. In this phase of the crisis's end, even though the deformation has significantly decreased, it has however continued with lower rates and different characteristics, which show some longer and more complex magma movements at the area under the Santorini caldera. The main problem, which needed to be resolved by scientific community, was the full and precise interpretation of the magma's expansion in 2011-2012 at the Santorini's caldera. This magma's expansion was not fully interpreted by the first published results (Newman et al., 2012, Parks et al., 2012, Lagios et al., 2013).

On this issue a research work performed by the team of the Laboratory of Geodesy of the University of Patras took place in 2013-2014, in order to estimate and recalculate the intrusion's mechanism of magma during 2011-2012 with the assumption of a more complex deformation model (Saltogianni et al., 2014). The data reveal a more complex scenario for the seismo-volcanic crisis in 2011-2012, in very good agreement with the related seismic activity and the other geophysical - geochemical data.

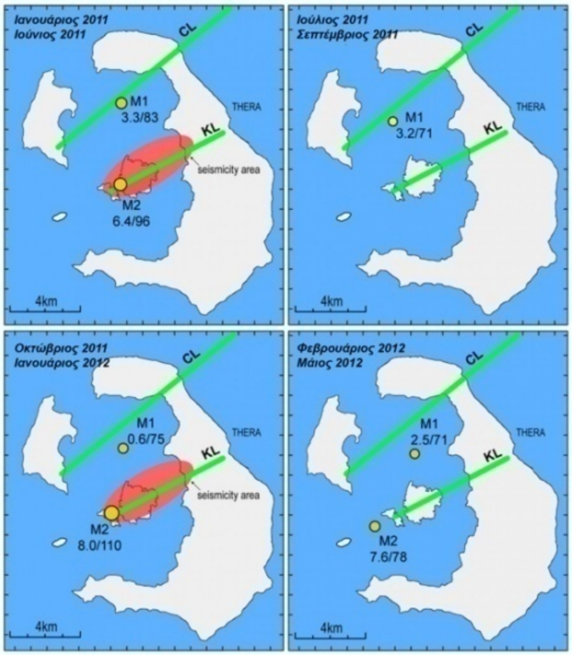

Figure 16. *An evolution model of the magmatic intrusions (M1 and M2) in the tectonic lines of the Kameni (KL) and Columbo (CL) and their relation to the seismicity (red deficiencies), as it was developed in the four main phases of the seismo-volcanic activity between January 2011 to May 2012. The numbers next to each source corresponds to the depth and radius of magmatic intrusion (Saltogianni et al., 2014).*

According to this scenario, the ground deformation and seismicity were caused by the rising of magma materials in two volcanic centers, and not one as initially proposed. In particular, the first and largest volcanic center was activated on the tectonic line (KL) of the cluster of Kameni island (in New Kameni area), while the smallest one was activated at the region of the Columbos tectonic line (CL), at the northern part of the caldera (Figure 16).

6. Conclusions and discussion

The volcanic activity in the wider Santorini island region has started about before two million years (approximately Lower Pliocene) and continues until today, with the most recent eruption to be recorded in the island of New Kameni on 1950 (Fytikas et al., 1990; Friedrich , 1994). Nevertheless, most of the volcanic materials have been produced in the last 200,000 years, by tje creation of almost twelve centers of extrusive and mainly explosive activity (Friedrich, 2000). The volcanic center of Santorini (Figure 3) is considered as the most active volcanic one of the southern Aegean Sea, after its activation at least nine times in the last 600 years (1457, 1508, 1573, 1650, 1707-1711, 1866-1870, 1925-1928, 1939- 1941 and 1950) (Papazachos, 1989). At present, the main active centers of volcanic activity at the Santorini complex are the islands of New Kameni in the center of the caldera and the external underwater volcano of Columbos (about 7 km northeast of the homonymous cape of Santorini). According to the available data the only volcano which can create problems to the residents of this region is that of the complex of the Santorini islands (Papadopoulos, 1985).

The unrest of the Santorini volcano at the center of the caldera in the period 2011 - 2012 was recorded by all the available networks of ISMOSAV. This activity was a seismo-volcanic one related to the tectonic line of the Kameni-Fira. All the recorded data (seismicity, tide gauges, temperature of gases, concentrations of gases such as CO_2, H_2, CH_4, and GPS data), show a possible magma intrusion in two specific sources (Figure 16) which are related to the tectonic lines of the Kameni (KL) and Columbo (CL). This intrusion has been developed during four main phases of the seismo-volcanic activity that evolved from January 2011 to May 2012 at the center of Santorini caldera. By the end of 2012, the whole activity has been practically finished and stabilized to pre-crisis levels.

It is of great importance to note that the active fault which was activated at the tectonic line of Kameni-Fira (Figure 8) has a length of about 5.0 km. That suggests that the possible maximum magnitude of an earthquake in future (or at the time of a similar crisis), which would be generated from this fault, corresponds to an earthquake with magnitude M~5.2 (if the event simultaneously ruptures the whole seismo-tectonic lineament), in which case the possible effects in the city of Fira and other nearby villages would perhaps be more serious.

The seismo-volcanic crisis's management requires a very careful evaluation by the involved scientists and government agencies. This is even more pronounced when cities and areas of very high tourist interest like Santorini are affected. The effects of speculation and scaremongering scenarios will have important consequences in such cases of possible natural disasters. The entire activity of ISMOSAV and its colleagues from other universities had positively contributed to the recent crisis (2011-2012). All activities of ISMOSAV and the other cooperating organizations and institutes are intended to upgrade all their individual methodologies and monitoring, in order to achieve a better and effective protection of the Santorini island area from its volcanic risk.

This seismo-volcanic activity provided an opportunity for the Institute and the island's local authorities to test the effectiveness of all the monitoring networks. In addition it proved to be a great opportunity to start the procedure for the preparation and edition of emergency plans.

References

Ambraseys N.N. and Jackson J., 1990. *Seismicity and associated strain of central Greece between 1890 and 1988*, Geophys. J. Int., 101: 663-708.

Bohnhoff M., Rische M., Meier T., Endrun B., Harjes H.P. and Stavrakakis G., 2004. *A temporary seismic network on the Cyclades (Aegean Sea, Greece)*, Seosmolo. Res. Lett., 75, 3: 352-357.

Bohnhoff M., Rische M., Meier T., Becker D., Stavrakakis G. and Harjes H.P., 2006. *Microseismic activity in the Hellenic Volcanic Arc, Greece, with emphasis on the seismotectonic setting of the Santorini–Amorgos zone*, Tectonophysics, 423, 1–4:17-33.

Dimitriadis I.M., Karagianni E.E., Panagiotopoulos D.G., Papazachos C.B., Hatzidimitriou P.M., Bohnhoff M., Rische M. and Meier, T., 2009. *Seismicity and active tectonics at Coloumbo Reef (Aegean Sea, Greece): Monitoring an active volcano at Santorini Volcanic Center using a temporary seismic network*. Tectonophysics, 465, 1-4: 136-149.

Dimitriadis I., Papazachos C., Panagiotopoulos D.G., Hatzidimitriou P. M., Bohnhoff M., Rische M. and Meier T., 2010. P and S velocity structures of the Santorini–Coloumbo volcanic system (Aegean Sea, Greece) obtained by non-linear inversion of travel times and its tectonic implications, Journal of Volcanology and Geoth. Res., 195, 1: 13-30.

Dimitriadis I.M., Panagiotopoulos D.G., Papazachos C.B., Hatzidimitriou P.M., Karagianni E.E. and Kane, I., 2005. *Recent Seismic Activity (1994-2002) of the Santorini Volcano Using Data from Local Seismological Network*, Int. Conf. of The South Aegean Active Volcanic Arc: Present Knowledge and Future Perspectives (SAAVA 2003), 17-20 Sept., Milos, Greece, In: Fytikas M. and Vougioukalakis G. (eds), Elsevier Book Series: Development in Volcanology,7:185-203.

Friedrich W. L., 1994. *Feuer im Meer*, Spectrum Akademischer Verlag, Heidelberg, Berlin.

Friedrich W. L., 2000. *Fire in the Sea: Volcanism and the Natural History of Santorini*. Cambridge University Pr., Cambridge.

Fytikas M., Kolios N. and Vougioukalakis G., 1990. *Post-Minoan Volcanic Activity of the Santorini Volcano: Volcanic hazard and risk, forecasting possibilities*, In: Hardy D.A. (Editor), Thera and the Aegean World III, 2, The Thera Foundation, London, pp. 183-198.

Galanopoulos A.G., 1957. *The seismic sea wave of July 9, 1956*. Proc. Athens Acad., 32, pp. 90-101.

Hensch M., Dahm T., Hort M., Dehghani A. and Hübscher C., 2008. *The EGELADOS working group, First results of the ocean-bottom-seismometer and-tiltmeter experiment at Columbo submarine volcano (Aegean Sea, Greece),* EGU General Assembly, Geophysical Research Abstracts, 10: EGU2008-A-02760.

Lagios E., Sakkas V., Novali F., Belloti F., Ferretti A., Vlachou k. and Dietrich V., 2013. *SqueeSAR^{TM} and GPS ground deformation monitoring of Santorini Volcano (1992-2012): Tectonic implications*, Tectonophysics, TECTO-125831, (in press), pp. 22.

Newman A.V., Stiros S., Feng L., Psimoulis P., Moschas F., Jiang Y., Papazachos C., Panagiotopoulos D., Karagianni E. and Vamvakaris D., 2012. *Recent Geodetic Unrest at Santorini Caldera Greece*, Geophys. Res. Lett., doi: 10.1029/2012GL051286.

Parks M.M., Biggs J., England P., Mather T.A., Nomikou P., Palamartchouk K., Papanikolaou X., Paradissis D., Parsons B, Pylw D.M., Raptakis C. and Zacharis V., 2012. *Evolution of Santorini Volcano dominated by episodic and rapid fluxes of melt from depth*, Nature Geoscience, DOI:10.1038/NGEO1562.

Παπαδόπουλος Γ., 1985. *Ο ηφαιστειακός κίνδυνος στην Ελλάδα*, Δελτίο Ελληνικής Γεωλογικής Εταιρείας, 17:316-323.

Papadopoulos G. A. and Pavlides S. B., 1992. *The large 1956 earthquake in the South Aegean: Macroseismic field configuration, faulting, and neotectonics of Amorgos Island*, Earth and Planetary Science Letters, 113,3:383-396.

Papazachos B.C. and Panagiotopoulos D.G., 1993. *Normal faults associated with volcanic activity and deep rupture zones in the southern Aegean volcanic arc*, Tectonophysics, 220: 301-308.

Papazachos B.C., 1989. Long and short term prediction of the volcanic eruption in Santorini, 3rd Int. Congress "Thera and the Aegean World", September 4-8 1989, pp. 125-129.

Papazachos B.C., Koutitas Ch., Hatzidimitriou P.M., Karacostas B.G. and Papaioannou Ch.A., 1985. *Source and short distance propagation of the July 9, 1956, Southern Aegean tsunami*, Marine Geology, 65:343-351.

Papazachos B.C., Papadimitriou E.E., Kiratzi A.A., Papazachos C.B. and Louvari E.K., 1998. *Fault plane solutions in the Aegean sea and the surrounding area and their tectonic implications*, Bolletino di Geofisica Teorica ed Applicata, 39:199-218.

Papazachos B.C., Mountrakis D.M., Papazachos C.B., Tranos M.D., Karakaisis G.F. and Savvaidis A. S., 2001. *The faults which have caused the known major earthquakes in Greece and surrounding region between the 5th century BC and today*, 2nd National Conference Anti-Seismic Engineering and Technical Seismology, November 28-30 2001, Thessaloniki, Greece, pp. 17-26.

Papazachos B.C., Dimitriadis S.T., Panagiotopoulos D.G., Papazachos C.B. and Papadimitriou E.E., 2005. *Deep structure and active tectonics of the southern Aegean volcanic arc*. Int. Conf. of The South Aegean Active Volcanic Arc: Present Knowledge and Future Perspectives (SAAVA 2003), 17-20 Sept., Milos, Greece, (ed), Elsevier Book Series: Development in Volcanology, 7:47-64.

Saltogianni V., Stiros S.C., Newman A.V., Flanagan K. and Moschas F., 2014. *Time-space modeling of the dynamics of Santorini volcano (Greece) during the 2011-2012 unrest*, JGR-Solid Earth, 119, 11:8517-8537.

Shirokova E.I., 1972. *Stress pattern and probable motion in the earthquake foci of the Asia-Maditerranean seismic belt*, In: L.M. Balakina et al. (Eds), Elastic Strain Field of the Earth and Mechanisms of Earthquake Sources, Nauka, Moscow.

Tassi F., Vaselli O., Papazachos C.B., Giannini L., Chiodini G., Vougioukalakis G.E., Karagianni E., Vamvakaris D. and Panagiotopoulos D., 2013. *Geochemical and isotopic changes in the fumarolic and submerged gas discharges during the 2011-2012 unrest at Santorini caldera (Greece)*, Bull. of Volcanolgy, BUVO-D-12-00141R3, (in press).

Zellmer G., Turner S. and Hawkesworth C., 2000. *Timescales of destructive plate margin magmatism: new insights from Santorini, Aegean volcanic arc*, Earth Planet. Scie. Lett., 174:265-281.