4.5.5. GEODETIC MONITORING OF THE SANTORINI (THERA) VOLCANO

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4.5.5.1. Introduction

The Island complex of Santorini is a Quaternary volcanic complex dominated by a partly submerged caldera, with walls up to 300m high above the water, defined by the islands of Thera and Therasia and the islet of Aspronisi. The Thera Volcano is famous mainly from a main eruption which occurred 3,500 years ago, after an about 18,000 years long period of volcanic inactivity. This eruption was responsible for the formation of the present-day caldera, as well as for the burial of the prehistoric ("Minoan") town of Akrotiri, the remains of which have been excavated in the last decades. The Thera volcano was active in the last few thousand years, with explosions and lava flows, the last ones of which occurred in 1925-1928, 1939-1941 and in 1950. In the last decades, however, the Santorini volcano is quiescent.

Volcanic activity in Santorini was in many cases associated with ground deformations, coastal subsidence and uplift; the best examples were the formation of the intra-calderic islets of Nea Kameni and of Palaia Kameni in the historic times. Such ground movements are caused by magma flow at relatively shallow depths and can be regarded as precursors of a future volcanic paroxysm (Sigmundsson et al., 1995, Bonaccorso et al., 1996). For this reason, geodetic monitoring of the volcano was included in an interdisciplinary surveillance project started in 1994, in the framework of the European Union DG XII Environment Project and of the Institute for the Study and the Surveillance of the Santorini volcano, succeeding earlier smaller scale projects. Initially, this project was limited to EDM measurements, but in October 2000 a GPS network was established on the same benchmarks. The results and conclusions from this geodetic subproject are the subject of this article.

4.5.5.2. Surface deformations and magma flow

Experience form numerous active volcanoes and theoretical considerations indicate that any upward or downward movements of magma in vents or chambers produce elastic stresses which are reflected in small-scale topography changes and changes in horizontal distances and elevations of benchmarks around the volcanic centres; such topography changes may range from a few centimetres to several meters (Mogi, 1958, Sigmundsson et al., 1995, Bonaccorso et al., 1996).

Since in the last thousand years the volcanic activity in Santorini was rather confined to the caldera (Druitt et al., 1989, Fyticas et al., 1989), any magma movements would cause geodetically observable changes of distances among points of the caldera.

4.5.5.3. Geodetic network

The topography of the Santorini island complex, a nearly circular caldera with subvertical walls with a radius of 3-6km, is ideal for the establishment of a radial geodetic network dedicated to the identification of baseline length changes; such networks have been used widely to control tectonic deformations (Langbein, Johnson, 1997).

A central station (station number 11) was established at Nea Kammeni and 10 peripheral stations numbered 1 to 10 were established on the caldera walls in Thera and Therasia (Fig. 4.5.5.1.), with baselines were numbered 1 to 10. This network has a nearly uniform azimuthal distribution and can easily and unambiguously control baseline length changes which could reflect possible caldera inflation-deflation processes.

All stations of the network were selected among pillars of the National Triangulation Network (Fig. 4.5.5.2.) established 10 to 30 years ago. Care was taken that pillars selected are founded on stable ground (consolidated pumice deposits, stable rock masses) so they are representative of kinematics and deformation of a wider area. Baseline lengths vary between 3.2 to 6.7km and because of the nearly uniform topography (steep cliffs of the caldera walls 100-300m above sea-level, central station on a peak) all baselines cross a nearly uniform medium, rather free of perturbation of the atmosphere close to the ground or the water (the raypath of all baselines is >100m from the water and only along a short distance at a height <50m from the ground surface).

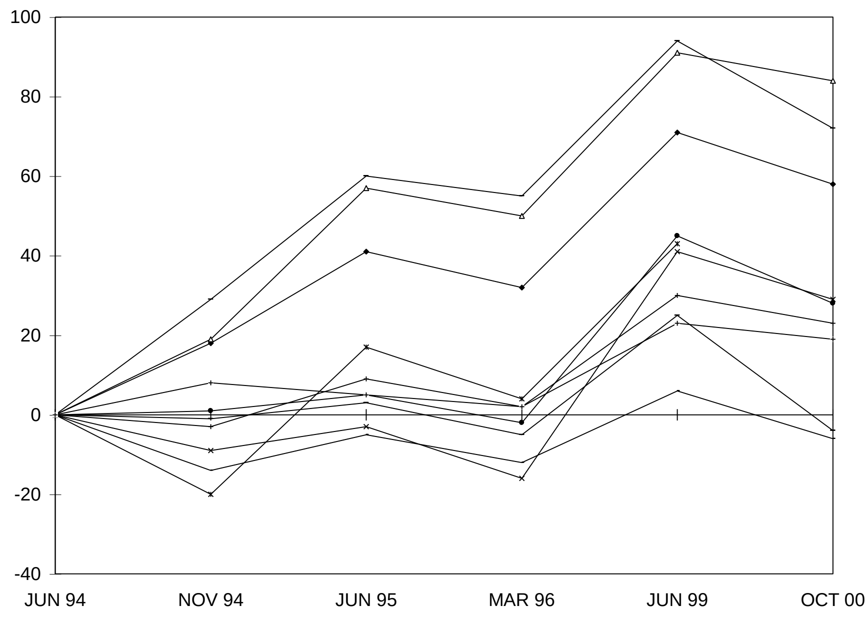

Fig. 4.5.5.1. Geometry of the EDM and GPS network to monitor surface ground deformations of the Santorini (Thera) volcanic complex. Mark that most of stations 1-10 are situated on the edge of steep cliffs of the caldera walls

4.5.5.4. EDM surveys and results

Between June 1994 and October 2000 six epochs of measurements have been made. Measurement procedure was nearly identical in all surveys: observations were made by

the same surveying party, the same instrument, an AGA 6000 laser Geodimeter and the necessary accessories (centering plates, reflectors, etc) permitting to avoid eccentricity errors. Temperature and barometric pressure were estimated at the endpoints of each station. Barometric pressure was measured with barometres providing a resolution of 1mbar. Temperature was estimated at the height of 2m above the ground by thermometers providing a 0.1°C resolution and shielded from direct sun radiation. Care was taken that meteorological conditions were made only under favourable atmospheric conditions (medium to strong winds, slightly clouded to overcast sky) permitting a nearly uniform density of the atmosphere along the raypath. Such specifications are expected to permit an accuracy of about 0.5°C in temperature and an about 1ppm in the sampling of the overall atmospheric density. A number of consistent (differing by up to a few mm) measurements of distances were taken for each baseline for each survey, and their average values were subsequently analytically corrected for meteorological conditions.

Baseline length changes of the six surveys, June 1994-October 2000 are summarized in Fig. 4.5.5.2. Among the 10 baselines, those between Therasia and Nea Kammeni (baselines 1, 2, 3) show maximum cumulative changes between 6 and 9.5cm, while the changes of all other lines are up to ±2-3 cm, and only in one or two cases up to 4.5 cm. This indicates a systematic increase in the length of baselines between Nea Kameni and Therasia, but definitely no changes in the southern part of the caldera (baselines 7, 8, 9, 10).

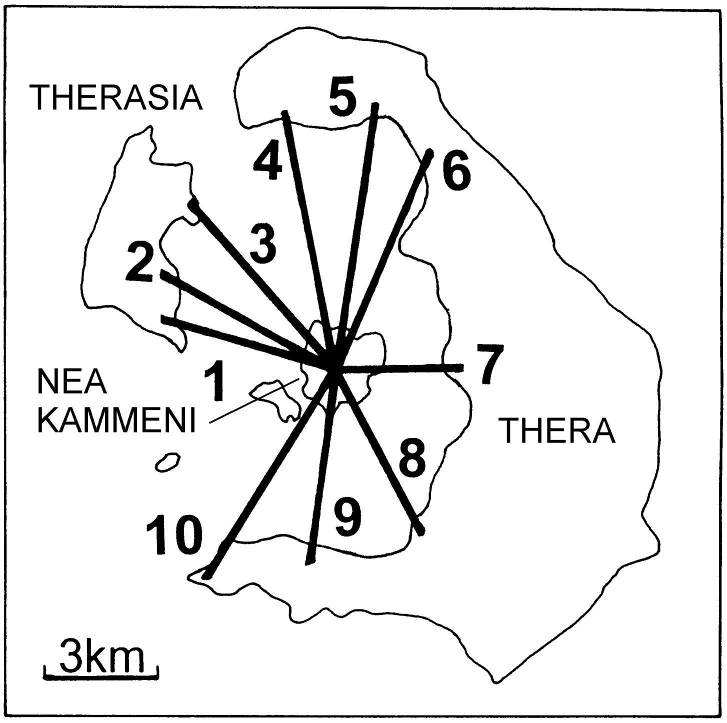

Fig. 4.5.5.2. Graph showing observed baseline length changes versus time. Baseline lengths corrected for atmospheric density and after arbitrary values were subtracted from each one. Mark a systematic, cumulating and statistically significant increase of the lengths of lines 1, 2, 3 (Therasia island to Nea Kammeni, the three upper broken lines), at a rate of 1-1.5 cm/yr, in contrast with baselines in the southern-central part of Thera (remaining seven broken lines) which show no statistically significant change of their length

4.5.5.5. Discussion of the results of the EDM surveys

The typical standard accuracy of the AGA 6000 Geodimeter is 1mm±1mm/km. This formula was adopted here for the second term is compatible with our estimations of precision of meteorological conditions. For baseline lengths of the order of 3.2 to 6.7km, as those in the Santorini network, the corresponding typical error is between 3.4 and 6.8mm. Meteorological conditions as described above can contribute with a maximum error of 1ppm, while the corresponding instrumentation errors (centering, tilting, etc) were up to a few mm. The corresponding cumulative typical error is therefore of the order of 1cm, which corresponds to an accuracy of measurements of the order 2cm against random errors at a 95% confidence level.

Except for random errors, systematic errors may affect geodetic measurements as well. Such errors are: instrument miscalibration, systematic meteorological effects and instrumentation eccentricity errors. We believe that the similarity of the field processes (same instrumentation and survey party in all surveys), the small coverage and configuration of the network, as well as the nearly uniform and favourable meteorological conditions during the surveys permit to exclude such errors. Furthermore, baseline length changes are limited to a geographically precisely defined area (Therasia island) and are not correlated with baseline lengths. Consequently, observed baseline changes seem to reflect real effects and not measurements contaminated by random or systematic errors.

On the other hand, there is no evidence of local ground instability of pillars 8, 9, 10, as well as of pillar 11; any local instability of this last station would also affect the distances to stations on the southern part of the caldera, especially of baselines 7-11 and 8-11.

We can therefore conclude with confidence that between June 1994 and October 2000, there is evidence of gradual dislocation of Therasia relative to Nea Kameni and the central-southern part of Thera with a rate of 1-1.5 cm/yr.

4.5.5.6. GPS network

In October 2000 a GPS network was established on the same stations. Measurements were made with two dual frequency receivers using the rapid-static method and the station in Nea Kameni as a master station. Measurements were made just after the EDM survey. Our strategy is to have a couple of GPS surveys at the same time with EDM surveys before the later are abandoned. The first results of the GPS survey will be presented elsewhere.

4.5.5.7. Interpretation

The observed gradual and systematic dislocation of Therasia relative to the central and southern part of the caldera can only be explained as a result of small-scale inflation of a part of the Santorini caldera. This part of the caldera can be clearly identified with the part between Therasia and Nea Kameni, with baseline lengths showing a nearly systematic increase of 1-1.5 cm/yr during the last 6 years. Recently, however, this inflation may also have affected most of the northern part of the caldera: length changes of the order of 4cm have been observed in baselines 4, 5 and 6 between two consecutive surveys. In line 5, in particular, an increase of 4cm was observed between June 1999 and October 2000, but until new measurements are made, we are suspect it may indicate only local effects or measurements errors, and for this reason this measurement is not shown in Fig. 4.5.5.2.

Whether such small-scale caldera inflation reflects a premonitory phenomenon of a future dangerous volcanic anomaly, or normal effects in the evolution of this active volcano, is a question which cannot be answered at present.

4.5.5.8. Acknowledgements

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4.5.5.9. References

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