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GEODETIC MONITORING OF THE SANTORINI (THERA) VOLCANO

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ABSTRACT

Santorini (Thera) is a volcanic island complex dominated by a partly submerged caldera and famous from an eruption which buried the 3,500 years old Minoan town of Akrotiri. The volcano is active, and the last periods of its paroxysmal activity date to the 1920s, 1940s and 1950s, but in the last decades is dormant. A geodetic monitoring system aiming at an early identification of a future dilation of the caldera as a result of magma inflation was established in 1994, in the framework of an interdisciplinary project for the surveillance of this volcano.

The geodetic monitoring system consisted of a radial EDM network with a central point at the Nea Kammeni islet and 10 stations in the Thera and Therasia islands. Baseline lengths were ranging between 3.2 and 6.5km, most of the paths were >100m above the water and survey stations are selected among those of the national geodetic network.

Between June 1994 and October 2000 six epochs of baseline measurements at a centimetre-level accuracy were made using an AGA 6000 Geodimeter and sampling of meteorological conditions at baseline endpoints at the height of 2m above ground. In October 2000 a radial GPS network has been installed on the same pillars and was measured using the kinematic method. A small-scale (a few-cm level), gradual inflation of the northern part of the caldera (between Nea Kammeni and Therasia), possibly associated with magma ascent along a dike, has been inferred from EDM measurements.

INTRODUCTION

The Island complex of Thera or Santorini is a Quaternary volcanic complex dominated by a partly submerged caldera (i.e. a circular, high-gradient topographic depression produced by volcanic eruptions) with walls up to 300m high above the water. This caldera is defined by the islands of Thera and Therasia (Figure 1) and the islet of Aspronisi. The Thera Volcano is famous mainly from a main eruption which occurred 3,500 years ago, following 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, marked by explosions and lava flows; the last ones 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 Kammeni and of Palaia Kammeni 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 **[1,2]**. 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 [**3**], 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.

SURFACE DEFORMATIONS AND MAGMA FLOW

Experience from 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 **[1-2, 4]**.
Since in the last thousand years the volcanic activity in Santorini was rather confined to the caldera **[5,6]**, any magma movements would cause geodetically observable changes of distances among points of the caldera.

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 **[7]**.

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 (Figure 1), with baselines 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 (Figure 1) 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 above the water and only along short distances at a height <50m from the ground surface).

EDM SURVEYS AND RESULTS

Between June 1994 and October 2000 six epochs of measurements were 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 barometers providing a resolution of 1mbar. Temperature was estimated at a height of 2m above the ground by thermometers providing a 0.1°C resolution and shielded from direct sun radiation. Care was taken that measurements 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.

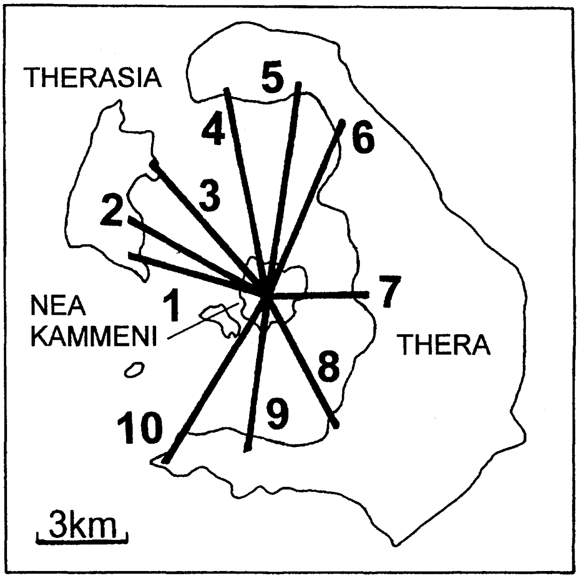

Figure 1. Geometry of the EDM and GPS network to monitor surface ground deformations of the Santorini (Thera) volcanic complex. Notice that most of stations 1-10 are situated on the edge of steep cliffs of the caldera walls.

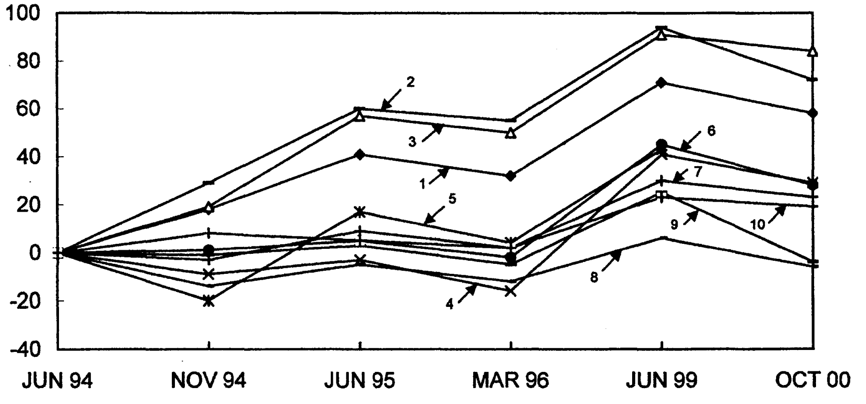

Figure 2. Graph showing observed baseline length changes (mm) versus time. Baseline lengths are corrected for atmospheric density and arbitrary values have been subtracted from each one. Notice a systematic, cumulating and statistically significant increase of the lengths of baselines 1, 2, 3 (Therasia island to Nea Kammeni), at a rate of 10-15mm/yr, in contrast with baselines in the southern- central part of Thera (remaining lines) which show no statistically significant change of their length.

Such specifications are expected to permit a 0.5°C accuracy in temperature and a 1ppm accuracy 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 Figure 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 ± 2-3cm, and only in one or two cases up to 4.5cm. This indicates a systematic increase in the length of baselines between Nea Kammeni and Therasia, but definitely no statistically significant changes in the southern part of the caldera (baselines 7, 8, 9, 10).

Discussion of the Results of the EDM Surveys

The typical standard accuracy of the AGA 6000 Geodimeter is 1mm±1mm/km, which is compatible with our estimations of precision of meteorological conditions. For baseline lengths of the order of 3.2 to 6.7 km, 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 a precision in 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 mis-calibration, systematic meteorological effects and instrumentation eccentricity errors. It is believed that the similarity of the field processes (same instrumentation and survey party in all surveys), the relatively small baseline lengths and the similarity of the topography profile along them, as well as the nearly uniform and favourable meteorological conditions during the surveys permit to greatly reduce such errors. Furthermore, significant baseline length changes are limited to a geographically precisely defined area (Therasia island, stations 1-3) and are not correlated with baseline lengths. On the other hand Figure 2 shows a rather uniform change pattern for nearly all baseline lengths. A possible explanation would be the presence of a systematic effect contaminating measurements (for instance of a systematic error in the estimation of the temperature, and hence of the density of the atmosphere). However, the non-uniform distribution of baseline lengths is likely to exclude such a possibility. Consequently, observed baseline changes seem to reflect real effects and not measurements contaminated by random or systematic errors.

Furthermore, 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 and 8.

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

GPS Network

In the year 2000 it was decided that GPS would gradually replace EDM measurements. GPS measurements were not expected to improve significantly the accuracy in baseline lengths, but to permit less expensive less expensive measurement and to provide estimates of the displacements of all stations in an independent coordinate system. In October 2000 a GPS network was established on all EDM stations and measurements were made just after the EDM survey with two dual frequency receivers using the kinematic method and the station in Nea Kammeni as a master station. The strategy is to have a couple of GPS surveys at the same time with EDM surveys before the latter are abandoned. The first results of the GPS survey will be presented elsewhere.

INTERPRETATION

The observed gradual and systematic dislocation of Therasia relative to Thera and Nea Kammeni can only be explained as a result of small-scale inflation of the NW part of the Santorini caldera. This part of the caldera can be clearly identified with the part between Therasia and Nea Kammeni, where baseline lengths show a nearly systematic increase of 1-1.5 cm/yr between 1994 and 2000. 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 Figure 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.

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