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Surveillance of Thera Volcano, Greece: Monitoring of the Local Gravity Field

ABSTRACT

This paper outlines the results of a microgravimetric network established in Thera as part of a multi-disciplinary program for the assessment of volcanic hazard in the area. The network of fifteen gravity stations has been remeasured annually since 1984. The essentials of the network adjustment program applied to the data are also presented. The results from the network have been particularly successful; an overall RMS error of 7.0, 3.2, 2.6 and 3.7 μGal (1 μGal = 10^{-2}gu) was calculated from the network adjustment in 1984, 1985, 1986 and 1987 respectively. It was found that a few stations (Oia, Imerovigli and probably Pyrgos) show a tendency to uplift. On the contrary, stations at Messaria and Phira Port (Yialos) show a persistent tendency to subside; this, however, is attributed to non-tectonic effects. Generally most of the stations on the network do not exhibit statistically significant gravity changes. This, therefore, implies that no detectable subsurface mass redistribution has taken place in the area between 1984 and 1987.

Introduction

The volcano of Thera is one of the most active in the eastern Mediterranean. There have been more than thirteen eruptions in the past. The most significant occurred about 1450 BC and resulted in the formation of the present caldera. Subsequent eruptions were responsible for the formation of the other smaller islands, such as Palaea and Nea Kameni (Fig. 1). The last major episode of lava outpour occurred in 1950.

It is therefore evident that there is a potential volcanic hazard in the area, a fact of some concern especially during summer, when the population of the island is considerably increased. As a consequence, the need to assess the volcanic hazard of the area is imperative. For this purpose a

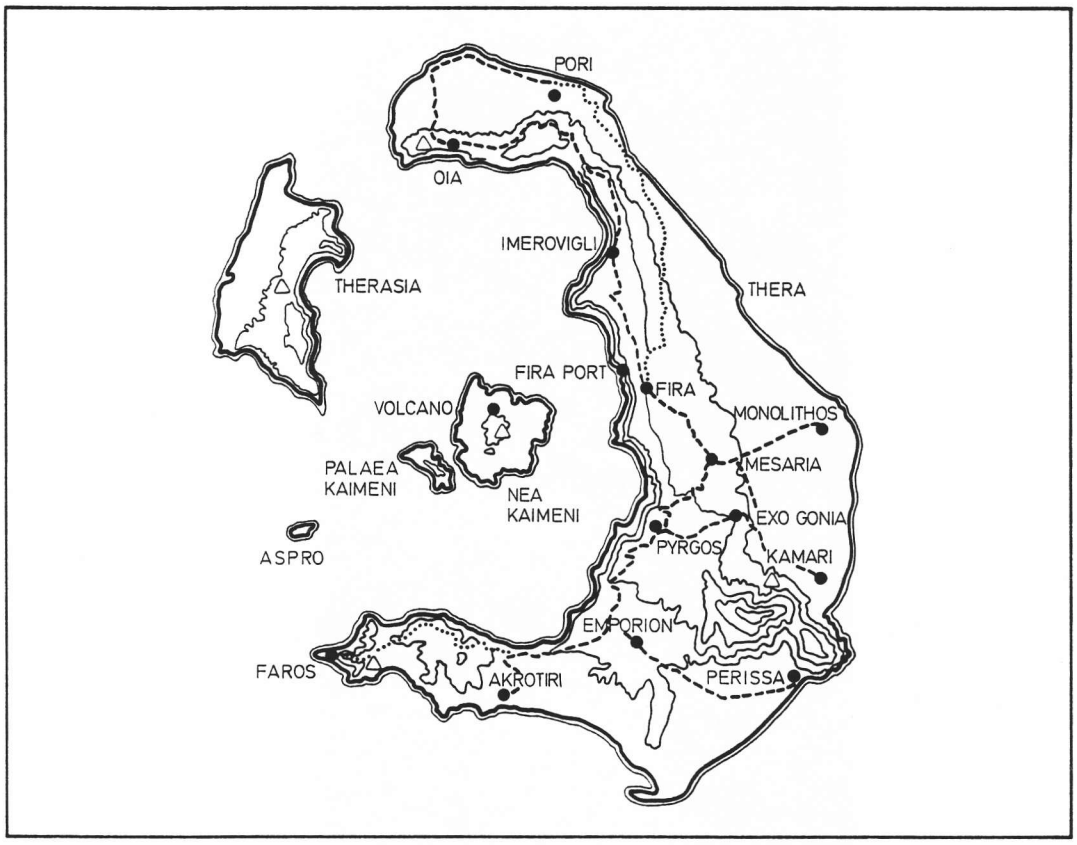

Fig. 1. Map of Santorini showing the gravity stations of the network, access roads, and 100 m contours.

multi-disciplinary research project was inaugurated in 1984 by the Institute of Geology and Mineral Exploration (IGME) and the Department of Geophysics and Geothermy of Athens University. The project involves geophysical, seismological and geochemical studies.

High precision gravity surveying (microgravimetry) can assist in the assessment not only of ground deformation prior to earthquakes (extensive dilatancy of rocks), but also of the volcanic hazard of an area; similar studies are currently taking place in several volcanic areas around the globe.

The application of the microgravimetric method is based on the fact that if upward magma movements are initiated, it is expected that, among other effects, certain changes will be noticeable in the local gravity field due to subsurface mass redistribution. Therefore, by setting up and remeasuring a high precision gravity network covering Thera and the nearby islands, it is expected that such gravity changes will be locally registered.

Magma movements detected by microgravimetry have already been reported at Mount Etna (Sanderson 1982), while gravity changes have been observed in Vesuvius (Berrino *et al.* 1985a, 1985b).

The microgravimetric network

A network of fifteen permanent gravity stations was established on Thera in 1984 (Fig. 1). Three LaCoste and Romberg (LCR) gravity meters of model G (G-275, G-496) and D (D-92) were used. LCR model G instruments have been shown to be capable of measuring single gravity differences with a standard error of 0.018 gu, when rigorous measuring procedures are followed (Hipkin 1978). Other high-precision surveys quote errors in the range 0.10-0.20 gu (Kinviniemi 1974; Torge and Drewes 1977). However, considerably smaller errors have been achieved in similar high-precision networks in Greece, mainly for earthquake-prediction research studies (Lagios and Hipkin 1986; Lagios *et al.* 1988; Lyness and Lagios 1984).

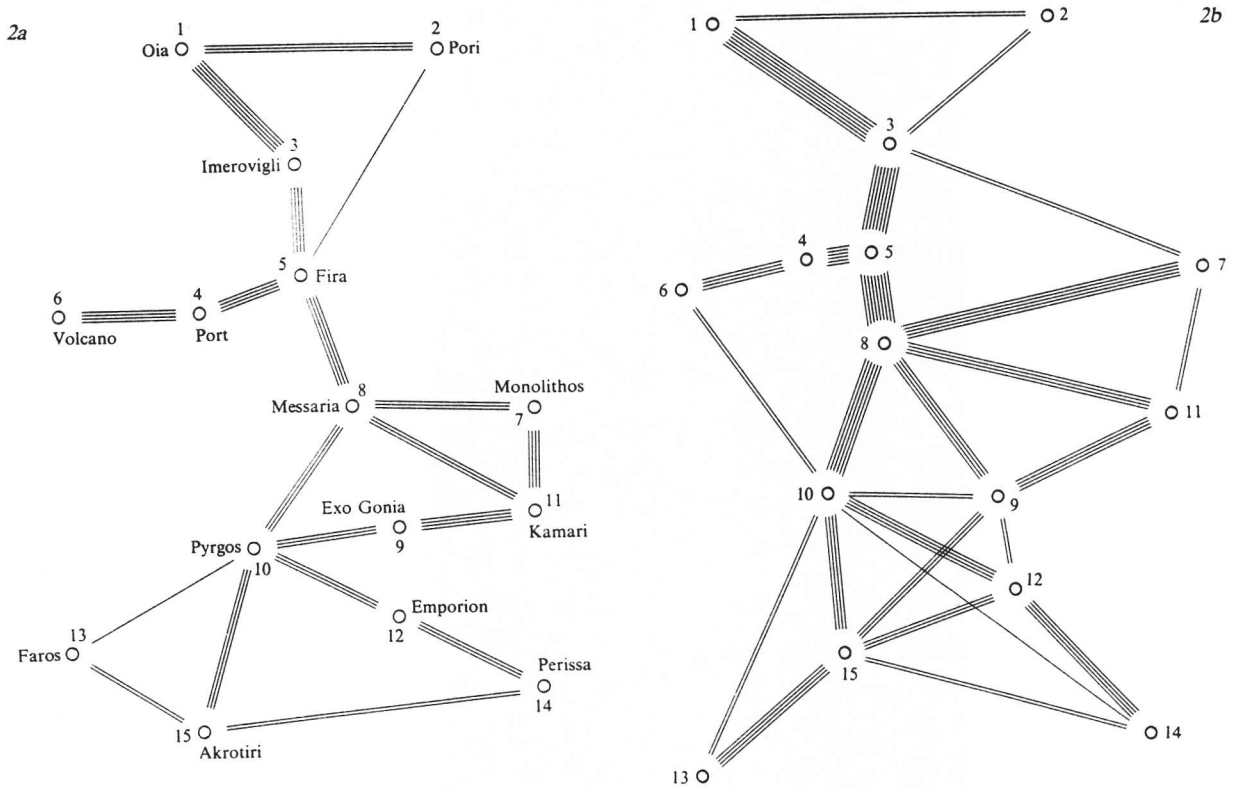

Fig. 2a. Observation diagram of the Santorini network in 1984. Each line represents the simultaneous transport of three gravity meters.

Fig. 2b. Observation diagram of the Santorini network in 1985. Each line represents the link made by G-496 gravity meter.

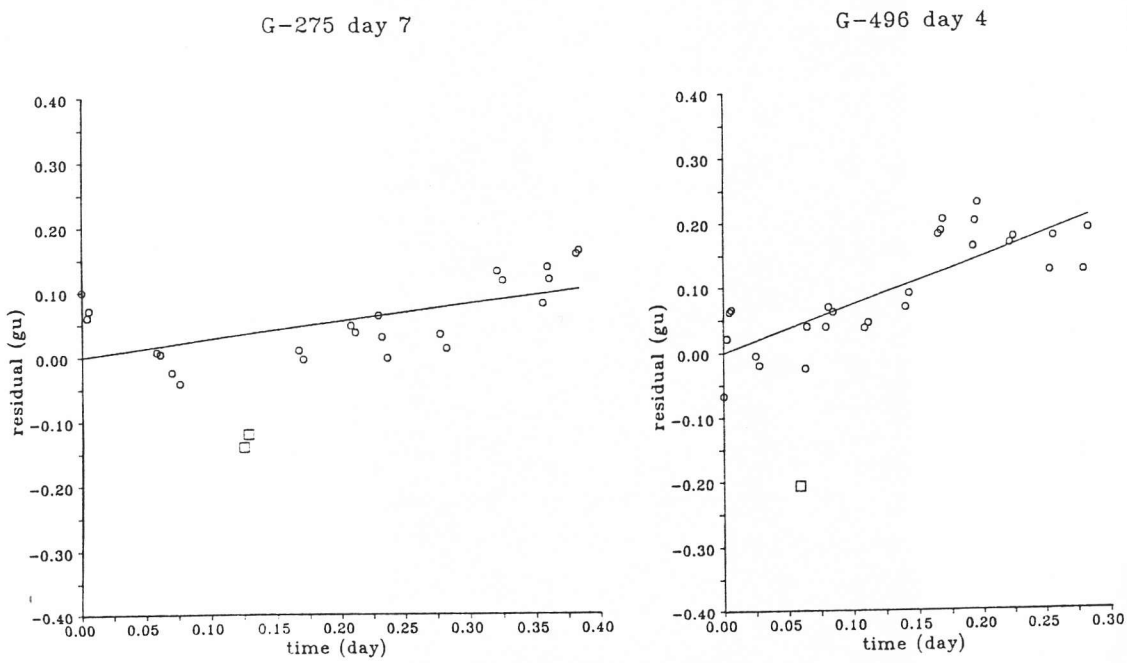

Fig. 3. Typical examples of scatter about the fitted linear drift functions. Square symbols represent suppressed outliers.

A special procedure was applied during any gravity observation at every station, so that height variations of the instruments upon return to a station were in the range 0.2 mm and in any case never exceeded 5 mm. Pressure measurements were taken simultaneously with the gravity measurements, to an accuracy of $\pm$ 0.01 mbar, in order to facilitate atmospheric pressure variation corrections.

All measurements were made in a ladder sequence of the form ABCDEEDCBA (where A,B,C,... are stations of the network) which allows the control of a wide spectrum of instrumental imprecisions (drift). Stations were measured in more than one sequence and efforts were made to ensure that each station was tied (linked) independently with as many others as possible. However, the measurements between any two gravity stations (ties or links) of the network are significantly dependent on the road-network of the island and its narrow shape to the north, which makes it difficult to effect extensive ties between stations in the north and those in the central and south parts of the island. Despite the road conditions, considerable efforts were made to ensure that the ties between gravity stations constituted a branch network. Only one station was established on the volcano — new volcanic crater (Nea Kameni). This particular station was linked directly with the one at Phira Port (Yialos) through multiple ties, the instruments being transported by hired boat. Fig. 2a is a diagram of the links between gravity stations made in 1984. Each line represents the links made with the simultaneous operation of three gravity meters. A similar diagram is also shown in Fig. 2b, where the ties made in 1985 are shown. Additional links were made between stations; this was considered necessary since only one gravity meter, G-496, was available for the remeasurement of the network in all subsequent years. The additional links provided a 'tighter' network, with as many observations as possible per station. Efforts were made to ensure that marginal stations (i.e. Pharos, Volcano, Pori, Perissa) were tied in with more than one station of the network.

Data analysis

All gravity observations were reduced to gravity units (gu) — 1 gu = 10^{-1} mGal = 10^{-6} m/sec^2 — multiplying the reading of each instrument by a standard calibration factor, which remains the same for all the remeasurements. Subsequently the data were corrected for elastic earth tides using the harmonic expansion of Cartwright and Taylor (1971) as amended in Cartwright and Edden (1973). In the eastern Mediterranean the ocean-loading signal is not well determined, but may be assumed to be small, because of the limited tidal range in the Mediterranean and its distance from large oceans (Lagios and Wyss 1983).

Pressure corrections of 0.004 gu/mbar were also applied (Brien *et al.* 1977). Note here that the pressure systems over the Aegean, even during summer, when the seasonal winds blow, are quite stable. Often, the pressure difference on returning to a station during a measuring (ladder) sequence was less than 1 mbar.

After all the data were corrected for pressure and earth tides, they were adjusted automatically using an iterative routine. This network-adjustment computer program (an advanced modified version of Lagios and Hipkin 1980) performs a least-squares adjustment to all the data and also fits an independent first or optionally second-degree polynomial to the variation of instrumental drift on each observation sequence; only first-degree polynomials were considered here, for results were not improved by fitting higher-order drift curves. The application of a more complex drift model for every daily sequence is certainly not justified for these data, and results in significant bias and instability.

Even though a brief description of the adjustment analysis has been given elsewhere (Lagios *et al.* 1988), it is considered necessary to mention the fundamentals of this algorithm. An independent observation taken at one gravity station by one of the gravity meters and reduced to a relative (not absolute) gravity value g_i (i=1,I) forms an observational equation with weight w_i of the form:

$$w_i g_i = \Sigma_m (a_{im} w_i) G_m + \Sigma_k (\beta_{ik} w_i) a_k + \Sigma_k (\beta_{ik} w_i t_i) b_k - \Sigma_n (\gamma_{in} w_{in} g_i) \delta C_n + w_i \varepsilon_i$$

where G_m is the adjusted value of gravity at site m; a_k and b_k are the constant and linear terms describing drift during the kth traverse and $1+ \delta C_m$ is the multiplicative correction to the provisional scale factor used for gravity meter n, with respect to instrument 1. The array elements α_{im} β_{ik} and γ_{in} take the value one if the ith observation is at site m, on traverse K and made with instrument n; otherwise they are zero. ε_i is the residual (error) associated with the ith observation. A set of normal

TABLE 1. *Adjusted gravity values of Santorini network (*)*

STATION	1984	1985	1986	1987
1 OIA	301.533±0.048 (28)	301.528±0.019 (10)	301.551±0.019(16)	301.556±0.027(16)
2 PORI	611.589±0.050 (12)	611.456±0.026 (7)	611.636±0.020(10)	611.726±0.030(10)
3 IMEROVIGLI	0.000±0.047 (38)	0.000±0.019 (12)	0.000±0.019(11)	0.000±0.025(31)
4 PHIRA PORT	652.184±0.047 (37)	652.387±0.019 (16)	652.444±0.023(13)	652.530±0.027(16)
5 PHIRA	195.871±0.040 (46)	195.910±0.017 (31)	195.965±0.017(35)	195.947±0.024(37)
6 VOLCANO	482.569±0.048 (28)	482.759±0.027 (17)	482.747±0.024(6)	482.677±0.028(15)
7 MONOLITHOS	690.017±0.032 (24)	690.124±0.017 (15)	690.048±0.016(10)	690.130±0.030(13)
8 MESSARIA	415.873±0.031 (49)	415.995±0.013 (41)	416.064±0.013(23)	416.192±0.021(47)
9 EXO GONIA	321.364±0.041 (22)	321.386±0.018 (10)	321.519±0.020(7)	321.506±0.023(17)
10 PYRGOS	61.143±0.040 (51)	61.032±0.012 (17)	61.137±0.017(24)	60.960±0.023(30)
11 KAMARI	715.207±0.037 (29)	715.234±0.017 (12)	715.261±0.015(14)	715.325±0.021(16)
12 EMPORION	399.620±0.046 (21)	399.653±0.014 (14)	399.781±0.019(15)	399.806±0.024(17)
13 FAROS	286.922±0.049 (13)	286.876±0.021 (7)	287.048±0.025(6)	286.920±0.027(11)
14 PERISSA	751.828±0.045 (19)	751.903±0.015 (13)	751.996±0.019(15)	751.957±0.025(12)
15 AKROTIRI	431.010±0.044 (27)	431.172±0.016 (16)	431.257±0.020(16)	431.177±0.024(21)

(*) Gravity values are in gu with estimated standard error and number of observations in parenthesis.

equations is found by differentiating the sum of the squared weighted residuals with respect to each of the unknowns G_m, m = 1, M; α_k, b_k, κ=1, K; δC_n, n=2,N. The resulting M+2K+N-1 normal equations are not independent and, as consequence, one must be replaced by a further constraint. The most obvious constraint is to assign to the gravity datum at site m_o the value zero, i.e. $G_{mo} = 0$.

The adjustment algorithm also iteratively assigns *a posteriori* weights. In comparison with the early analysis by Lagios and Hipkin (1980), this has the advantage of suppressing the biasing effects of grossly erroneous observations (henceforth to be called 'blunders'), and normalizing the quality of different gravity meters and the subjectivity of the observers. Consequently, no observations are now rejected *a priori*. The weights w_i are the product of two factors, $w_i = W_n W_i$. The first term W_n normalizes observations made with different instruments and W_i suppresses blunders, i.e. large residuals (see Fig. 3). Initially, a unit weight is assigned to each observation. Then, iteratively, the value of the weight changes and equation (1) is resolved until it converges to stable estimates of G_m and w_i. The value of w_i is controlled by comparing the residual ε_i with the overall RMS error of the adjustment. Once ε_i exceeds a pre-set limit, w_i assumes a value less than 1, the magnitude of which depends on the magnitude of ε_i. The procedure is terminated when w_i does not change significantly. In this way, blunders are efficiently suppressed and their contaminating contribution eliminated. Further accounts of the adjustment routine would be beyond the scope of this paper. However, we present some typical examples of drift variation in Fig. 3. The observations have been taken from the 7th and 4th day of the 1984 campaign with the gravity meters G-275 and G-496, respectively. The blunders (represented by rectangles in Fig. 3) are successfully suppressed.

Results and discussion

Table 1 outlines the adjusted results of the Thera microgravimetric network since 1984. Relatively larger values of standard errors, up to 0.05 gu, derive from the 1984 network adjustment compared to those of the following years. This should be attributed to the larger errors contributed by the gravity meter D-92, due to its irregular drift (see Table 2). This was, at the time, a brand new instrument used in real field conditions for the first time. It is expected that its drift behaviour will improve with utilization and age. The adjusted gravity values of all stations are referred to the station at Imerovigli, where a zero level was assigned. Table 2 summarizes the RMS errors of the network adjustments. The consistent performance of G-496 is remarkable, as demonstrated by the low level of standard errors achieved. The standard error value at Messaria is only 1.3 μGal (0.013 gu), while the largest is 3 μGal (0.030 gu). This corresponds with a maximum of ± 1 cm of 'free-air' elevation change, or ± 1.5 cm, applying the Bouguer gradient (2 μGal/cm).

To obtain a clearer picture of gravity changes in time and space, Fig. 4 was prepared. Gravity

TABLE 2. *Thera network adjustment*

Year	Gravity Meter Used	RMS Weighted Error of Adjustment (μGal)	Correction to Scale Factor with respect to G-496
	G-496	6.2*	—
1984	G-275	6.4*	1.0000917±0.000419
	D-92	10.3*	0.9997660±0.000619
1985	G-496	3.2	—
1986	G-496	2.6	—
1987	G-496	3.7	—

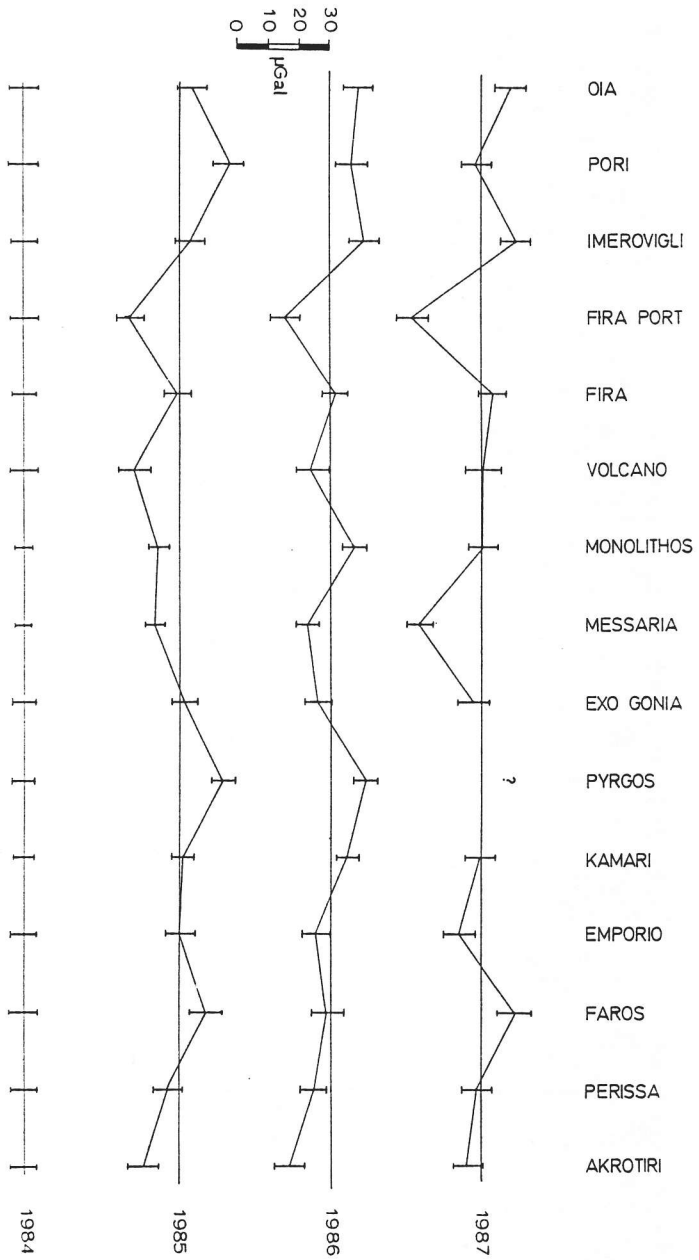

Fig. 4. Gravity differences observed at the stations of the Santorini network between 1984 and successive years.

differences between 1984 and 1985, as well as between 1984 and 1986 and 1984 and 1987 were calculated and reduced to a zero mean population. The 1984 gravity values were therefore made the datum; their differences from the corresponding adjusted gravity values of 1985, 1986 and 1987 indicate an apparent positive or negative change from year to year at each station, corresponding to uplift or subsidence, respectively.

During the remeasurement of the network in 1987, it was found that the level of the measuring point at Pyrgos junction station had changed. A 3-5 cm thick concrete layer had been laid on top of the previous surface of the church yard, where our station had been established. It is estimated that this change, as well as the material in between, can cause a difference of at least 0.09 gu. Therefore, the estimated relative value of 60.960 gu observed at Pyrgos (Table 1) could be accordingly corrected and a probable gravity-difference value could be estimated for 1987.

Messaria is a very well-controlled station, where multiple observations have been made in all years (49, 41, 23, 47 respectively, see Table 1). This station has exhibited a persistent tendency to subside since 1984. Even though we are confident about the observed change (the maximum being -18.6 ± 3.7 μGal), we are not certain about its causes. A probable explanation could possibly be local subsidence around the Messaria cemetery area, where soft and unconsolidated sediments prevail. Unfortunately, bedrock cannot be encountered everywhere on the island, and Messaria is one of those places.

Another significant change is the one observed at Phira Port (Yialos). We are inclined to attribute this to non-tectonic effects. The most probable cause could be the subsidence of the unfirm ground immediately outside the entrance of the chapel where our station lies.

Few changes in the values of gravity are noticeable in most stations established near the caldera cliffs (Oia, Imerovigli and possibly Pyrgos junction). These changes are not statistically significant, however, because they are in general smaller than the calculated standard deviation range for all years. Thus, we cannot assert whether they are real or not; this seems to imply that no detectable subsurface mass redistribution that might be associated with magma movements has taken place between 1984 and 1987.

It is hoped that the remeasurement of the network will be more frequent in the future. If the seismicity of the area is found to be increased, it is suggested that more regular monitoring of the local gravity and magnetic fields should begin at once.

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DISCUSSION

STAVROS KALOGEROPOULOS: How do you correlate the results of the previous stock with this one in terms of the thermal upheaval in certain areas as compared to the absence of any detectable causes of the previous product, as indicated by the gravity data?

EVANGELOS LAGIOS: The results of the seismicity paper indicate that a cluster of epicentres is located just north or north-east of the island. From our magnetic measurements we have established a gradient of positive magnetic change to the north, which was detectable between 1987 and 1988, and which remained in 1989 but didn't increase.

If this is a case of something happening in the area it is probably heat transfer or something correlated with heat. We don't have additional geophysical evidence to be certain. There is a correlation of some hypocentre governing the north-east of the island as detected by the seismic network with some change in the magnetic field over that direction. But it needs more observations to establish the facts.

KURT BOSTRÖM: You had no station on the Kameni islands. Is there a specific reason for that? Because I think that one could see very local changes very conveniently with a station, for instance on Palaea Kameni.

EVANGELOS LAGIOS: Certainly we would like to establish stations not only on the main island but also on Nea Kameni and Therasia. But this would increase the cost dramatically.

NIC FLEMMING: Do you think that the changes which you observe in the microgravity are influenced both by magma movements or changes in density subsurface, and by changes in topography? Would it be worth cross-checking this with some kind of small tide gauge installation. It would be very interesting to see if there were small fluctuations in the crustal elevation which could be correlated with your other two variables.

EVANGELOS LAGIOS: The results of the microgravimetric method have to be related to other evidence, of course, such as tide gauges, and other levelling information. Again, it's the lack of funding. We would like to establish a tide gauge network on the island so that we can estimate tilts as well as changes. Recently, we have put forward a programme for this particular purpose and I hope it will go through successfully, so that we can establish more systematic observation.

MICHAEL EVANS: You assert that heat is a demagnetizing factor. In fact, it is well known that the susceptibility of many minerals increases with temperature. This is a well-established phenomenon, called the Hopkinson effect. So, in fact, increased temperature could increase the magnetization, not necessarily decrease it.

SOTERIOS VARNAVAS: It has been reported that where we have leaching of the rocks by the sea water and hydrothermal exhalations and precipitation of the metalliferous sediment, we have lows in magnetic intensities. If you measured the magnetic intensities in the areas of the recent mineralization, perhaps you would get lows in magnetic intensities.