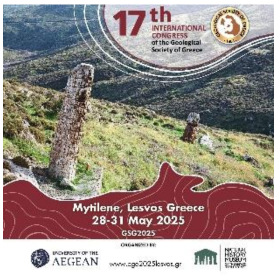

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Gravity monitoring at Santorini volcanic island, Greece

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Introduction and objectives

Santorini island in the Aegean Sea is a famous volcanic structure, not only because of its beauty, but mainly for its catastrophic eruption about 3500 years ago. This eruption eliminated the Minoan civilization in Crete, and caused the volcano collapse forming the current day caldera. The volcano is one of the principal volcanoes of the Greek volcanic arc related to the collision of the African and Eurasian plates. The arc comprises also Kos-Nisyros volcanic system, the Milos island, and the Methana peninsula, see Fig. 1.

This volcano is still active, with the last lava flow in the central island of Nea Kameni in 1950. The island hosts numerous population and therefore is a subject of multiparameter control, starting with seismological permanent observations, GNSS (Global Navigation Satellite System) with permanent and campaign-style stations, gas monitoring, etc.

This situation was a motivation of introducing repeated gravity monitoring campaigns in 2013, after the volcano increased activity in 2011-2012. There was no lava eruption, however, the signals from GNSS were showing the inflation of the caldera with the central point in Nea Kamenni. Previously, there was an attempt of such research, but actually only two campaigns could be compared – the one in the 1970s, and the other in 2012-2014 (Paraskevas et al., 2021). Such gravity monitoring was applied e.g. in the Merapi volcano area (Indriana et al., 2023).

IGCAS (Institute of Geophysics, Czech Academy of Sciences) could support and perform this 4D gravity investigation thanks to the EPOS/CzechGeo project, see Acknowledgement. The objective was to indicate possible changes in the gravity field that may be related to mass changes and/or fluids movements inside the caldera.

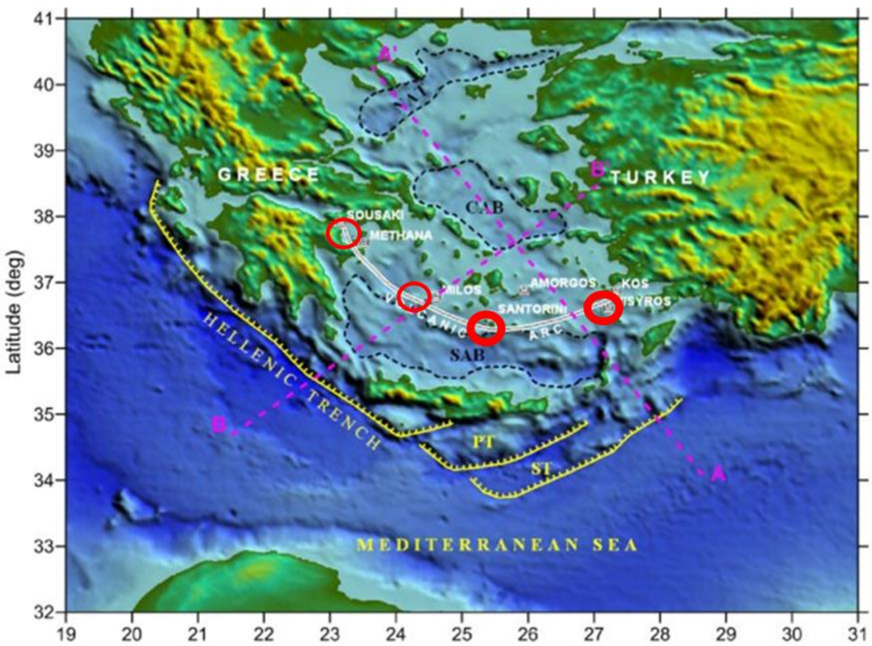

Figure 1. Position of Greek volcanic arc with four principal volcanic edifices – from left to right – Methana, Milos, Santorini, Nisyros.

The island is formed by lava extrusions of dacite, ryodacite, andesit and basalt, but the surface is covered mainly by pyroclastic formations of various composition, see Fig. 2. There are also outcrops of basement formed by carbonates (E, SE), but also metamorphics (slope to the new port) on the western side of Thira (Thera in Fig. 2). Tectonic zones are marked by white lines, as the principal ones of Columbo and Kammeni ones.

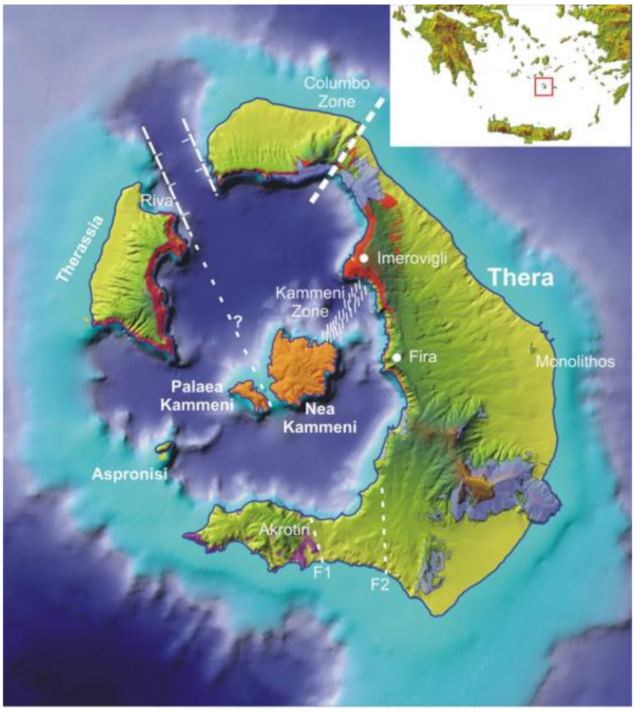

Figure 2. Position of principal tectonic features (Kammeni zone, Columbo zone) in Santorini, and principal lava flows (brown – dacite, ryodacite, andesite; light violet – basalts; medium violet – carbonate basement; green – various pyroclastic formations); after Lagios et al. (2013) and Druitte et al. (1999). Bathymetry after Nomikou et al. (2012).

The primary geophysical method for monitoring volcanoes and active faults is seismology, showing the active regions within the Earth crust. In Santorini two areas of different type of seismicity are located in the center of the caldera, and to the NE of Thira part of Santorini, see Fig. 3. Around Nea Kameni the epicenters are concentrated to a small area of about 5 x 3 km, actually along the Kammeni fault zone (see Figs. 2, 3), while in the NE they are spread on a large area with a diameter of more than 10 km.

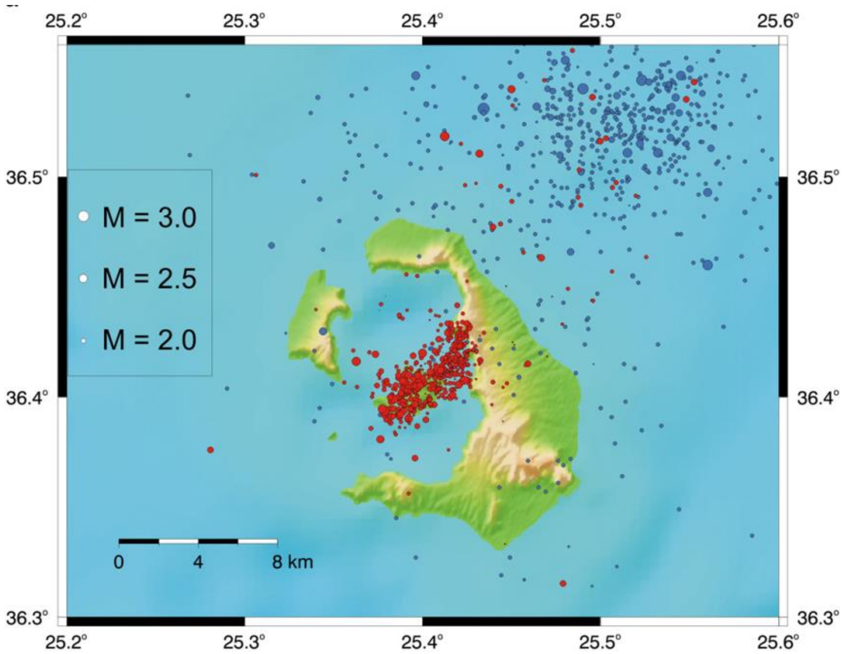

Figure 3. Seismicity around Santorini volcano in 1990-2010 (Lagios et al., 2013). It is evident that many events were recorded inside the caldera where Nea Kameni island is located. Earthquakes epicenters are accumulated within quite small elliptical area with longer axis less than 5 km. On the other side, in the area NE of Santorini seismicity shows much larger spread of epicenters around submarine volcano Kolumbos.

Gravity monitoring

The gravity monitoring is based on repeated measurements of gravity at a fixed network of stations. The observations at each station consist of a set of gravimeter readings, when a homogenous set has to be achieved (outlying readings are cancelled), as presented e.g. by Mrlina (2009, 2024).

Most, or all stations of the daily observation loop are measured three to five times in order to evaluate daily drift of the gravimeter. In this project one LaCoste&Romberg D-188 was used (2013-2021), later the Scintrex CG-6 gravimeter (2019-2024) was used, while in 2019 and 2021 both gravimeters were used simultaneously to provide enough overlap, see Fig. 4.

The network was based on the stations of NKUA (National Kapodistrian University of Athens) with the reference base stations No. 20, see the photos in Fig. 4. This base seems to be a reference point also for other gravity surveys in the Santorini island.

The old stations were continuously supplemented by new stations, as the author wished to cover some areas more densely, or to focus on some areas of higher interest, see Fig. 5. These new stations were selected in stable locations near churches, or similar, to ensure stable gravity observations. However, due to the general noise from the sea and from the volcano itself, exceptionally also of vehicles/people movement, some disturbed readings had to be eliminated. Some stations are increasingly difficult to operate due to difficult access in towns with enormous traffic (Fira, Oia).

The gravity campaigns usually lasted 9-13 days and also included one or two days to connect to Nea Kameni island stations by boat.

Each tie between any two stations was measured normally four times, which required a lot of driving by car (about 4 – 5 thousand km), or, in some cases, walking.

All these measurements, even simultaneous with two gravimeters, were performed as a single-man-job by the same operator (author), with the same gravimeters, and in the same period of a year.

Figure 4. Position of the principal reference base station in Monolithos to NE of the airport. It is a solid pillar with concrete filling at the parking near Monolithos church, built on the limestone basement block (see the hill behind the base). Gravity readings were always stable at this base. Gravimeter Scintrex CG-6 is presented at the bottom photo, LaCoste&Romberg D-188 gravimeter is inside to black box to stay protected from sunshine.

Some ties were repeated in other days in order to evaluate the repeatability. Standard deviation of the measurements was usually better than 4 uGal.

Each campaign was processed and the differences (ties) between stations were calculated. Then these differences were compared between any couple of campaigns. In this way the temporal changes of gravity field were evaluated.

Then, the changes for each point were obtained and could be interpolated into a map. Such differential map is presented in Fig. 6 for the years 2013 versus 2021.

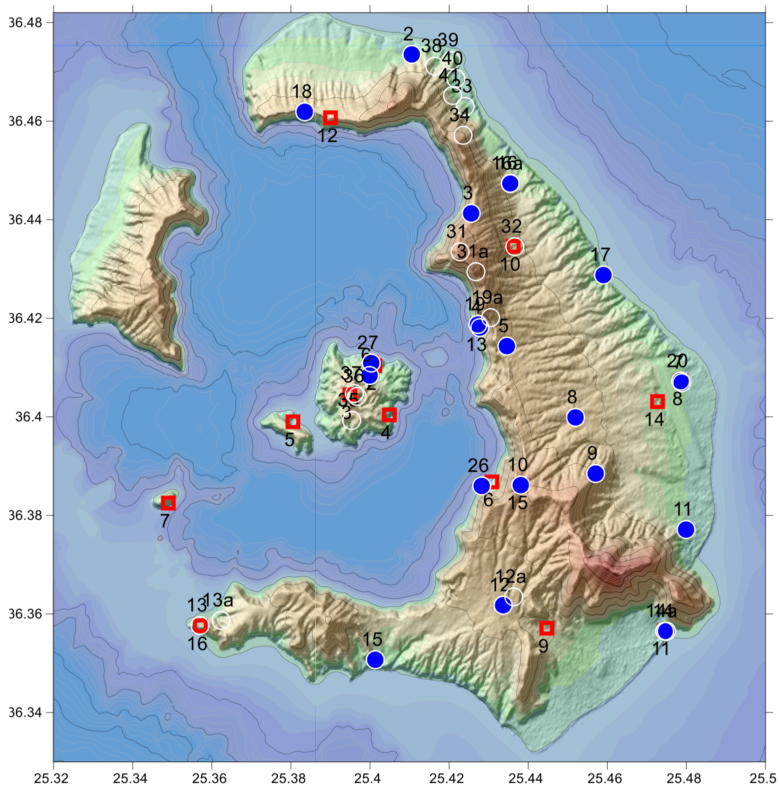

Figure 5. Position of the gravity monitoring network. Red rectangles are the old stations of the 1970s, full blue circles are the stations established by NKUA (Lagios et al., 1988), and white circles are stations used and established by author (IGCAS). Reference base station is No. 20 located in Monolithos to NE of the airport.

Results and discussion

The analysis of the data was focused on the temporal gravity difference between 2013 and 2021 (as in 2021 the campaign was performed with the LaCoste&Romberg D-188 gravimeter for the last time).

As mentioned above, the gravity differences at each station were used to interpolate all the differential values and the differential map was obtained, see Fig. 6.

There are two principal features in the map. The negative gravity changes in the northeastern side of Thira at the stations 3 and 16, and the positive change at the station 26 in the new port.

Most important is the negative change. It can be caused by continuous extension along the Kolumbo fault zone, which may decrease the volume density of the rocks within this zone. At the same time it may be responsible for the development of the Kolumbo submarine volcano with huge amount of fluids emissions through the opening fractures.

In order to exclude the impact of elevation change (that affect gravity values), the vertical component of the permanent GNSS station SANT was checked (courtesy of V.Sakkas). It is clear that within the period under study there was just a slight uplift 2013-2015 of less than 10 mm. Such value cause a gravity change of 2 uGal, which is almost negligible in respect to the amplitude of the negative zone (-50 uGal). Therefore the vertical displacement cannot be responsible of that significant decrease of gravity.

Another potential cause of the gravity decrease could be the emissions of fluids, but this is less probable as the released fluids would be substituted by water or other fluids coming from the deeper subsurface.

On the other hand, the old data 1976-2012 were showing the principal gravity increase in Nea Kameni (evaluated from data of Paraskevas et al., 2021), which was probably related to the magma and fluids rising to surface before the 2011-2012 crisis. During this crisis no lava erupted to surface, but the GNSS data showed inflation of the caldera and active fluid emissions were also encountered. In the NE there was also relative gravity decrease recorded.

This may justify the hypothesis that in the NE side of Santorini there may be an ongoing extension process.

For this reason the Author established another four new gravity monitoring stations 38-41 in the northeastern side of the island, see the white circles 38-41 in Fig. 5 and dark red triangles in Fig. 6. These stations were observed in 2023 and 2024, which is too short period for making any conclusions. The stations will be repeated in each potential future gravity monitoring campaign in the Santorini caldera.

The sharp gravity change between two nearby stations 10 and 26 (Fig. 6) can be affected by very sharp vertical difference, as 10 is located on the top of the cliff, while 26 is down in the new port. Here more investigation is needed to evaluate the impact of enormous change of air pressure during the measuring of this tie.

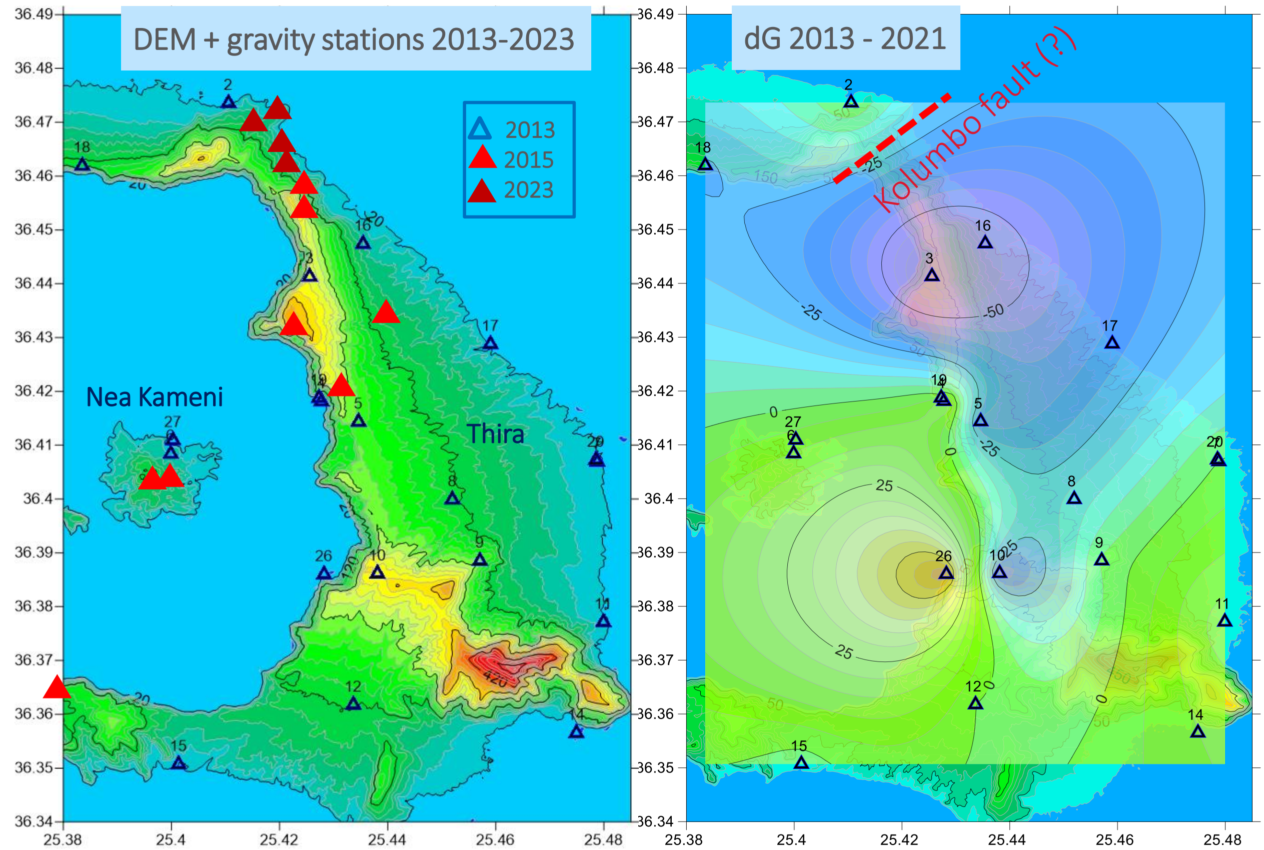

Figure 6. Left: Gravity monitoring stations used by IGCAS in 2013 (blue triangles established by Lagios et al., 1988), and established by IGCAS in later years 2015 and 2023 (red and brown triangles) for 4D gravity measurement campaigns. Right: Gravity difference between 2013 to 2021 in uGal (10^{-8} ms^{-2}) - principal feature is the gravity decrease in NE part of Thira (over -50 uGal) at stations 3 and 16.

Conclusion

This paper documents that the gravity monitoring of the Santorini volcanic island shows temporal gravity changes. As the vertical surface displacements play negligible role in affecting the gravity changes in the study period 2013 – 2021, the changes must be explained by geological/geodynamic processes.

Most significant is the temporal gravity decrease in the northeastern side of Santorini (Thira) where a long-term extension process in the underground may be causing the decrease of the volume density of the rock massif. Such extension within the Kolumbo fault zone also enables the opening for the currently active volcanic process around the Kolumbo underwater volcano with active fluids emissions.

In order to investigate this feature of the gravity field change, dense network of the monitoring stations was established in 2023 around the assumed Kolumbo fault zone.

Additional Comments

- In 2024 the author performed a small gravity survey in the NE part of Thira in order to investigate the Kolumbo fault zone which is related to the Kolumbo underwater volcano. This volcano has been recently very active with a lot of gas emissions. Seventy gravity stations were measured and data processed into the Complete Bouguer anomaly (CBA) with a traditional formula with normal gravity field correction, elevation correction and Bouguer plate reduction for density of 2.50 g/cm3. Terrain corrections were computed to the distance of 167 km from each point. Terrain model included both onshore and offshore topography. The gravity map has to be enlarged during next campaigns so that the tectonic pattern of this part of Thira can be updated.
- Similar gravity monitoring is performed by Author in Kos- Nisyros caldera, to be presented next time.

Acknowledgements

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