Application of Gravimetry to Investigation of Volcanism—Examples from West Bohemian Massif and Greece

Jan Mrlina
Institute of Geophysics CAS, Applied Geophysics Team, Prague, Czechia
Email: jan@ig.cas.cz

***Abstract*—Gravimetry as a geophysical technique can be applied in various fields of geosciences. Typically it is used in exploration for mineral resources, geoengineering, basic geological research, archaeology, etc. In this paper the focus is concentrated on discovering unknown maar structures and monitoring of volcanic activity in Greek volcanic islands of Nisyros and Santorini (Thira). Maar structures may not be simply visible in morphology and gravity surveys proved that they are characterized by striking negative gravity anomalies of about 2 to 5 mGal. Six till then unknown maars were discovered in the western Bohemian Massif in Central Europe.**

Mass changes in the intrusive system of volcanoes may be reflected in gravity monitoring data. The author performed such repeated observations of gravity field in the two Greek islands. It turned out that in both cases the data show certain unrest of the volcanic system, while especially in Thira an extensional process related to the new Kolumbo submarine volcano seems to continue.

***Keywords*—gravity survey, density model, maar volcanic structure, Greek volcanic islands, gravity monitoring, volcanic activity**

I. INTRODUCTION

Volcanic structures and volcanic activity is one of the most impressive expressions of the dynamic processes in the Earth crust. Active volcanoes represent high hazard for local population. The search for unknown volcanic structures can reveal till then underestimated extent of volcanism in a region. This may affect the planning of the development in such a region including necessary level of population awareness.

What can be done with gravimetry?

Many authors presented the application of gravity surveys to investigating the internal composition of known volcanoes. The target was mainly to define the size and position of the magma chambers in the underground, or the extent of lava flows. Often gravimetry was supported by magnetic and resistivity measurements to constrain the results.

In this paper the motivation was to present the gravity surveys searching for hidden unknown structures, as discovering unknown volcanoes is not so frequent. Since the first discovery of an unknown maar presented in 2007 and 2009 in [1, 2], respectively, another 5 unknown maars have been disclosed by gravity surveys in the western Bohemian Massif, see Fig. 1 and [3, 4].

Another motivation was to present some example of the temporal gravity changes related to active volcanoes. Such investigations are often performed e.g. in Italy on very active volcanoes like Etna. The example here is from Greece, where volcanic activity is much lower, but still it is proved by increased seismicity and gas emissions. The author performs repeated campaigns of gravity observations in Nisyros and Thira (Santorini) volcanic islands in Greece. These two volcanoes represent the highest environmental volcanic hazard in Greece.

II. GRAVITY OBSERVATIONS

Gravity survey used to discover the maar structures in western Bohemian Massif in Central Europe, but also for gravity monitoring network measurements in Greece, were performed with two gravimeters—LaCoste&Romberg-D and Scintrex CG-6. The survey data were processed in regular way and the accuracy of the Bouguer anomaly values were about 0.015 mGal (1 mGal = 10^{-5} m/s^2). This was indeed sufficient to recognize the target structures, as the maar negative gravity anomalies had the amplitudes of −2.5 to −4.5 mGal.

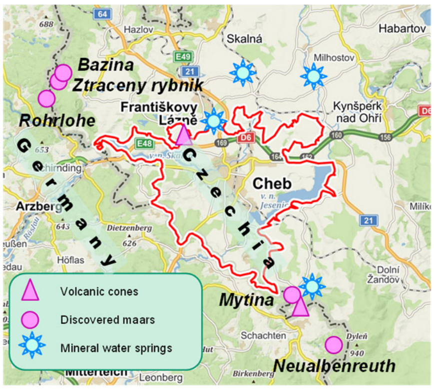

Fig. 1. Location of two well-known Quaternary volcanic cones in the West Bohemian Massif region and five discovered maar structures (one discovered maar is located further to south). The geodynamic activity in the region is also expressed by local earthquake swarms and numerous mineral water springs and gas emissions.

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Fig. 2. Position of the Greek volcanic arc in the Aegean Sea at the back of the subduction zone between Africa and Europe. Santorini (Thira) and Nisyros represent the most active volcanic structures in this volcanic arc.

In case of the monitoring networks in Greece the same instruments were used, but the accuracy of measurements was much higher (about 0.005 mGal) as the expected gravity signal from the mass and fluids changes may not exceed 0.050 mGal. There are about 25 monitoring stations at both networks—in Santorini (Thira and Nea Kameni) and Nisyros volcanic islands located along the Greek volcanic arc, see Fig. 2.

An example of a monitoring station is shown in Fig. 3. The observations are normally performed at the end of summer in order to avoid any rain and keep the same stable weather conditions. Each tie between any two stations was usually observed four times, the network was composed of number of polygons and the whole network was adjusted at the end of an observation campaign.

Fig. 3. Gravity/GNSS monitoring station in Nea Kameni in Santorini caldera, Greece, built on a lava outcrop. Gravimeter LaCoste&Romberg-D during observation. One of the young volcanic craters behind the station, and Thira caldera cliffs at the back.

III. RESULTS OF MAAR INVESTIGATION

As mentioned above, the maar structures are characterized by negative gravity anomalies caused by lower density of the breccia filling the volcanic diatreme, and young sediments of the maar lake filling the crater. In most cases the lakes have already disappeared and the terrain is usually wet and swampy, covered by wild vegetation, which makes the survey very challenging.

Typical anomalies are represented by the Mytina maar gravity low, see Fig. 4.

The Mytina maar was the first discovered one. When the Bouguer anomaly map was completed (and magnetic map as well), a simple maar model with the two principal formations was calculated, see Fig. 5. The main open question was “what may be the thickness of the maar lake sediments?” After calculating the model by direct method (no inversion applied) the model was adjusted with the bottom of sediment at the depth of 90 m [1]. Later we got a chance for scientific drilling, and we found this boundary at 84 m—it was very good fit with the model. Below the sediments the breccia formed mostly of country rock clasts (phyllite) was filling the diatreme, but also some small volcanic bombs were found [2]. This was the final prove of the existence of a maar.

What was exciting in the MY-1 well was the section containing a lot of organic mass in the clay sediments. The core samples from this section at the depth of about 70–75 m were investigated in a palynological laboratory. It showed that these sediments are from young Quaternary period. Together with age determination by Ar-Ar method of some xenolith samples we could estimate the age of the maar eruption around 288 thousand years. It means that this maar is probably the youngest volcano in the volcanic region of the Eger Rift, as described in [1, 2, 5].

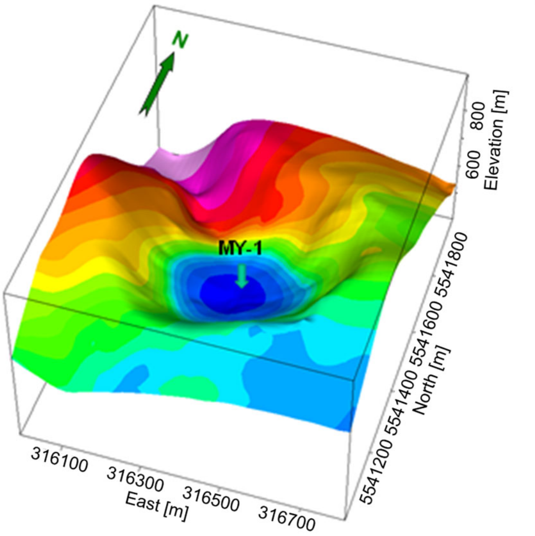

Fig. 4. Example of a negative gravity anomaly indicating a maar structure (here the Mytina maar, see location in Fig. 1), laid over a topography model showing a circular depression (former crater). The amplitude of this residual anomaly is −2.30 mGal. MY-1 is a scientific drilling performed near the center of the maar. Coordinates WGS84/UTM33N.

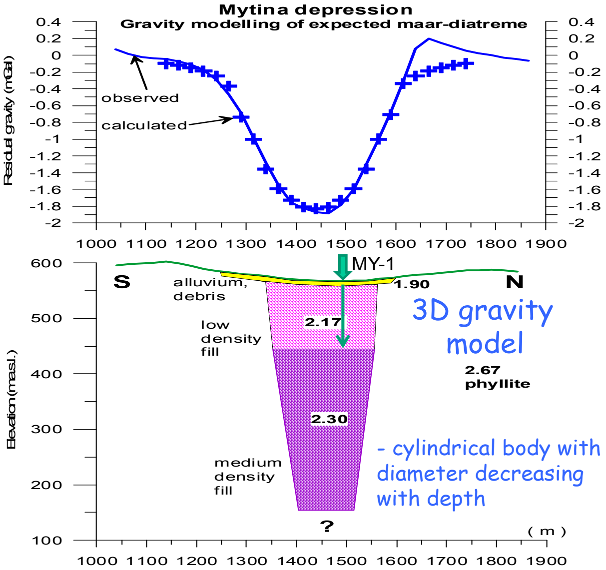

Fig. 5. Simple model of Mytina maar from Fig. 3 consists of two principal formations: breccia filling the lower part of the structure, and very low density Quaternary lake sediments. The model was calculated before the exploration drilling with the thickness of sediments about 90 m; the drilling ended up in breccia at 85 m, which confirmed the modelling result.

In case of the Bazina maar (in Fig. 1) gravity modeling was performed in 3D style. In this maar a borehole S4 was planned to provide volcanological information on one side, and position for the installation of a borehole seismometer in the surrounding granite massif.

Based on the gravity model with inclined maar contact with granite massif the cross-point of the borehole from the maar into granite was estimated at 160 m depth. In reality the borehole penetrated to granite at 170 m [6].

IV. MONITORING GREEK VOLCANOES

Gravity monitoring data in Nisyros were processed and evaluated. In Fig. 6 the island topography with clear image of the central caldera are presented. The activity of the volcanic system is documented by gas emissions at Stefanos crater (see Fig. 7), but at a few other sites in the caldera, too. The stations are distributed all around the island, inside and outside the caldera (Fig. 8). GNSS data show that the subsidence still continues since the active period in the late 1990s [7] with maximum negative value in the central valley of the caldera close to the Stefanos crater. The gravity data were corrected for this subsidence, while it should be increasing with time due to decreasing elevation; however, this applies in the western part of the island, but not at the place of the maximum subsidence. This indicates ongoing reduction of mass in the volcanic system.

In Santorini the observed negative gravity change in the northern part of the Thira island can be related to the extensional evolution of the Christiana—Thira—Kolumbo zone oriented SW-NE. There are actually numerous small sumarine volcanoes along this zone to NE, starting with the biggest one—Kolumbo—about 7 km from the Thira shore. The morphology of these edifices was investigated by bathymetric and seismic surveys [8]. The negative changes of gravity (Fig. 8) are one of the expressions of an extensional geodynamic regime due to decrease of the volume density. However, the deflation of the volcanic system in the Thira island [9] may be also indicated by the dismiss of the fluids which are rather released from the Kolumbo volcano.

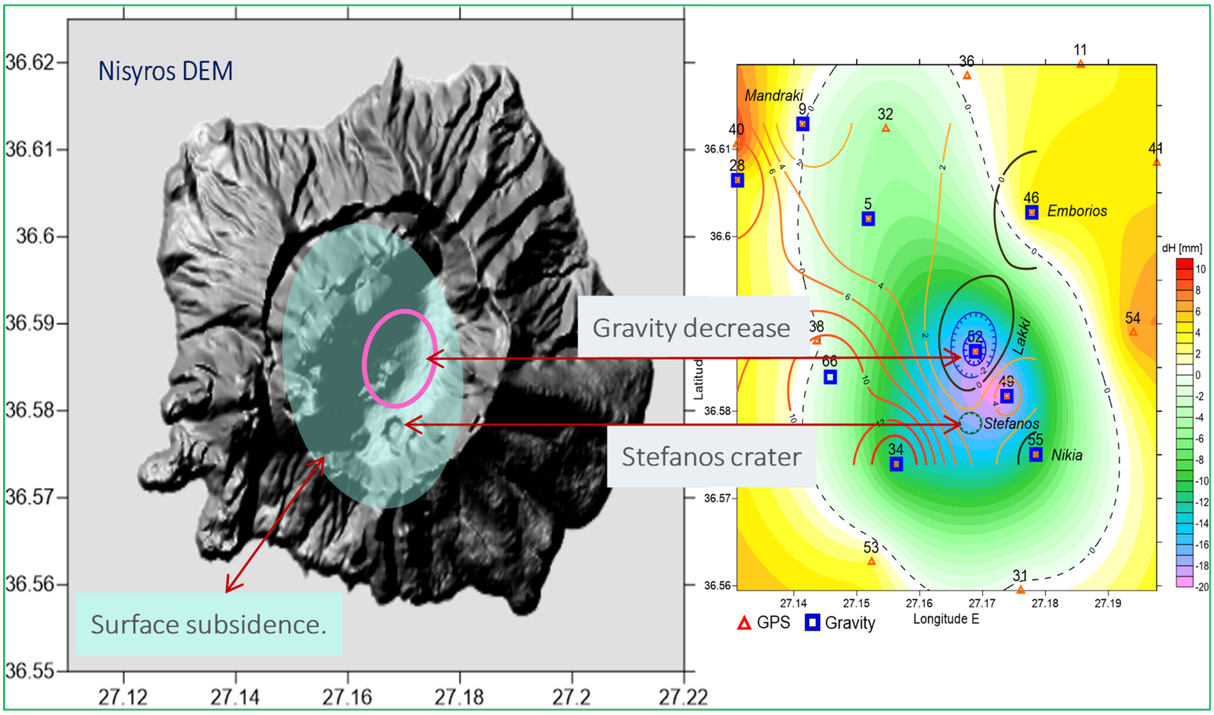

Fig. 6. Left: Topographic model of Nisyros island with the central caldera and the youngest small Stefanos crater. Right: Colored map shows continuation of surface subsidence, while the contours express temporal change of gravity in 2012–2014.

Fig. 7. Gravity measurements at the bottom of the Stefanos crater in Nisyros island. Gas activity in the crater is well visible.

Unfortunately, we do not have means for extending our monitoring to offshore.

As the Kolumbo fault zone is very significant geodynamic element, the author performed gravity measurements with simple GNSS support aimed at producing a Bouguer anomaly map at the NE part of Thira near the Kolumbo peninsula (Fig. 9). The gravity points are located on the coastal plain in the eastern part, then crossing morphological expression of a fault to higher elevated blocks and ending in the west again in the coastal plain. At the first look the plain areas are characterized by positive gravity, while the elevated blocks by negative anomalies. The reason can be that at higher position there is quite thick cover formed by pyroclastic rocks with high porosity and lower density, while the plains can actually have the hard limestone basement in the near subsurface. The map has to be further extended in future so that the red division lines (faults) can be prolonged and confirmed (this map was observed just before paper deadline in July 2024).

Similar monitoring was performed e.g. at the Merapi volcano area by [10], but the data processing was different due to high number of stations without fixed monuments in the field.

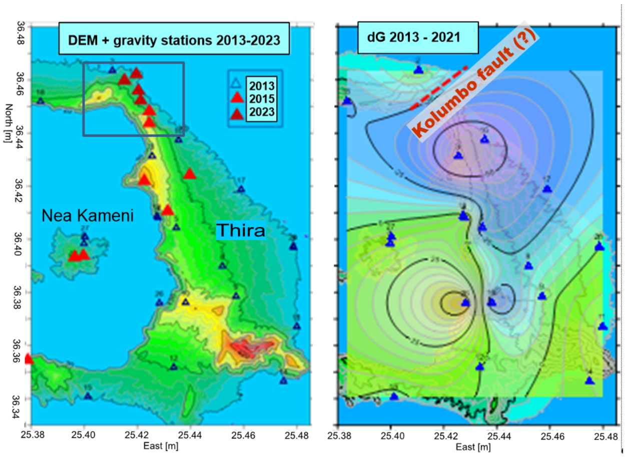

Fig. 8. Elevation model of Thira with gravity monitoring network stations (left) and temporal changes of gravity field (in uGal) between 2013 and 2021 (right). The network was updated by additional stations as shown on the left. Location of the gravity map in Fig. 9 is marked by the black rectangle.

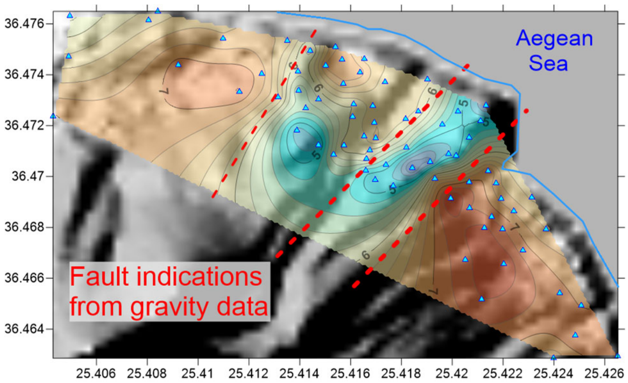

Fig. 9. Preliminary gravity map (measured in July 2024, contours interval 0.20 mGal) laid on top of DEM with indications of Kolumbo fault zone fractures derived from gravity survey data.

So only the simple Bouguer anomaly values were compared between particular campaigns. It demonstrates that the logistics of such monitoring projects may differ from case to case.

V. CONCLUSIONS

The two examples of the gravimetry applications to volcanism investigations proved that:

- Gravity survey may reveal the existence of unknown volcanic structures like maars by quite striking negative anomalies
- Gravity/density modelling can estimate the geometry of volcanic bodies as mentioned in this paper
- Precise gravity can be applied for active volcanoes monitoring, as temporal changes of gravity indicate changes of mass and fluids content in the volcanic system
- Supplementary gravity mapping can provide information on tectonic frame within volcanic areas.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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REFERENCES

[1] J. Mrlina, H. Kämpf, W. H. Geissler, and P. V. D. Boogart, “Assumed Quaternary maar structure at the Czech/German boundary between Mýtina and Neualbenreuth (western Eger Rift, Central Europe): geophysical, petrochemical and geochronological indications,” *Z. geol. Wiss.*, vol. 35, no. 4–5, pp. 213–230, 2007.

[2] J. Mrlina *et al.*, “Discovery of the first Quaternary maar in the Bohemian Massif, Central Europe, based on combined

geophysical and geological surveys," *J. Volc. Geoth. Res*., vol. 182, pp. 97–112, 2009. doi: 10.1016/j.jvolgeores.2009.01.027

[3] J. Mrlina, H. Kaempf, V. Polák, and M. Seidl, "Indications of two unknown maar-diatreme volcanoes of Quaternary age near Libá in western Bohemia by gravity survey," *Bulletin Brown Coal*, vol. 2, pp. 19–23, 2019.

[4] J. Rohrmüller *et al.*, "Reconnaissance study of an inferred Quarter-nary maar structure in the western part of the Bohemian Massif near Neualbenreuth, NE-Bavaria (Germany)," *Int. J. Earth Sci. (Geol Rundsch)*, vol. 107, pp. 1381–1405, 2018. doi: 10.1007/s00531-017-1543-0

[5] C. Flechsig *et al.*, "Integrated geophysical and geological methods to investigate the inner and outer structures of the Quaternary Mýtina maar (W-Bohemia, Czech Republic)," *Int. J. Earth Sci. (Geol. Rundsch.)*, pp. 2087–2105, 2015. doi: 10.1007/s00531-014-1136-0

[6] P. Hrubcová, T. Fischer, and V. Rapprich *et al.*, "Two small volcanoes, one inside the other: Geophysical and drilling investigation of Bažina maar in western Eger Rift," *Earth and Space Science*, vol. 10, pp. 1–8, 2023. doi: 10.1029/2023 EA003009

[7] E. Lagios, V. Sakkas, I. Parcharidis, and V. Dietrich, "Ground deformation of Nisyros Volcano (Greece) for the period 1995–2002: Results from DInSAR and DGPS observations," *Bull Volcanol.*, 2005.

[8] J. Preine, C. Hübscher, J. Karstens, and P. Nomikou, "Volcano-tectonic evolution of the Christiana-Santorini-Kolumbo rift zone," *Tectonics*, vol. 41, 2022.

[9] E. Lagios *et al.*, "SqueeSAR™ and GPS ground deformation monitoring of Santorini Volcano (1992–2012): Tectonic implications," *Tectonophysics*, 2013.

[10] R. D. Indriana, M. I. Nurwidiyanto, and J. Mrlina, "Merapi complete Bouguer anomaly changes based on gravity data of Merapi in 2020-2019," in *Proc. AIP Conference Proceedings*, vol. 2738, 2023. doi: 10.1063/5.0140956

Jan Mrlina was borne in former Czechoslovakia, now living in the Czech Republic (Czechia). He graduated from the Charles University in Prague in the Applied Geophysics department with RNDr. title. In 2009 he received the Ph.D. title with the thesis topic of 4D Gravity. Principal field of work is gravimetry applied to various geoscience and exploration projects and targets.

He started his career in Geofyzika company in exploration gravimetry, later as head of gravity department. He participated in exploration missions, mainly in the Middle East and Africa. Later he moved to the Institute of Geophysics of the Czech Academy of Sciences in Prague. He was a leader of many research projects focused on exploration, geoengineering, volcanology, archaeology, etc. He published about 80 scientific papers, while the most cited is the Mrlina *et al.* (2009) mentioned in References in this article, because the discovery of an unknown maar structure started "maar fever" of extensive interest in such volcanic structures in the region.

Dr. Mrlina is a member of numerous international associations and organizations, like SEG, EAGE SPE, IAVCEI, IAEG, etc.; he was also selected as Distinguished Lecturer of EAGE. In 2018 he received the Honorary membership of the Myanmar Association of Petroleum Geologists, and in 2021 he was awarded a medal of the Arab Association of Geophysics and Astronomy for his contribution to the development of gravimetry in Egypt.