---

layout: post

title: 3D image of the Kolumbo anomaly

date: 2022-06-16 12:00:00 +0200

description:

img: kolumbo-final-model.jpg

tags: [Earth science, volcanology, seismic tomography, high-resolution imaging, full-waveform inversion] # add tag

## Summary

We used a high-resolution technology based on inverting full seismic waveforms to image a small, high-melt-fraction magma chamber that was not detected with standard seismic tomography. The melt reservoir extends from ∼2 to at least 4 km below sea level (b.s.l.) at Kolumbo - a submarine volcano near Santorini, Greece. The chamber coincides with the termination point of the recent earthquake swarms and may be a missing link between a deeper melt reservoir and the high-temperature hydrothermal system venting at the crater floor.

## Interview

Below is the translation of the interview I gave for wulkanyswiata.blogspot.com, the most comprehensible blog about volcanoes in the Polish internet:

(https://wulkanyswiata.blogspot.com/2023/02/badania-podmorskiego-wulkanu-kolumbo-w.html).

**Q:** **Where is the submarine volcano Kolumbo located, and what are its characteristics?**

Kolumbo is located about 7 kilometres northeast of Santorini, a very popular tourist destination in the Greek archipelago of Cyclades. Santorini is not just one island but five subareal fragments of a massive caldera spanning more than 10 km in diameter, which I probably don't need to introduce to the readers of the blog. Kolumbo's crater is several times smaller, with its highest and lowest point at about 20 and 500 m below the sea, respectively.

Geologically, Kolumbo, along with Santorini and several other volcanoes, form the so-called Hellenic volcanic arc created by the collision of Africa and Eurasia, a process that has been going on for millions of years.

It is worth mentioning that volcanic arcs are probably the most important of several genetic types of volcanoes, not only because of their explosiveness but primarily due to their fundamental role in the process of creating new continental crust.

Curiously, these volcanoes would never have formed without enormous amounts of water that saturates the subducting tectonic plates plunging deep into the mantle along the curved subduction zones. It is the water released at great depths from hydrous minerals making up those plates that causes the mantle to melt and give birth to magmatic plumbing systems (volcanic arcs are merely a surface expression of these vertically extensive systems). Mind you, even at this depth, the high temperature alone is not sufficient to cause melting, neither of the mantle nor of the rapidly (for a geological process) subducting cold slab.

Returning to Kolumbo and Santorini, despite their proximity, these two volcanoes exhibit strikingly different behaviour. Historically, Santorini has erupted much more frequently, but it is Kolumbo that is the centre of current hydrothermal and seismic activity. We know it since 2006, when a large field of polymetallic hydrothermal chimneys emitting gases above 200 degrees Celsius was discovered at the bottom of Kolumbo's crater, sparking a flurry of studies of this previously poorly recognised volcano.

One of our findings is that the swarms of micro-earthquakes that characterise Kolumbo subsurface very likely are “footprints” of magma and hydrothermal fluids migrating through the rigid crust towards the surface.

**Q: What is the history of Kolumbo eruptions, and what are the hazards associated with the potential awakening of this submarine volcano?**

We know little about the history of Kolumbo's eruptions, but it appears that there have been only a few, with an average frequency of one eruption every 200,000 years. *(EDIT: most recent, still unpublished, studies suggest higher frequency).* The last eruption in 1615 AD caused significant devastation due to the resulting tsunami. Today, we would classify the magnitude of that eruption as VEI 4-5. For comparison, last year's Hunga Tonga-Hunga Ha'apai eruption, the most powerful explosion on the instrument record, had a magnitude of VEI 5-6, and the famous Krakatau eruption in 1883 was VEI 6.

The current hazards are greater than they were 400 years ago. Firstly, neighbouring Santorini is besieged by tourists for most of the year with obvious consequences in an event of eruption. An ash plume and pumice rafts could also disrupt air and sea transportation. What is less often discussed is the carbon dioxide bubble accumulated at the bottom of the crater, the release of which could lead to a phenomenon similar to the one known from Lake Nyos in Cameroon. **A successful geoengineering project that de-gassed the lake was carried out in 2021.**

**Q: Why is it essential to monitor submarine volcanoes, and what challenges are posed by their monitoring?**

Submarine volcanoes are exceptionally dangerous, primarily due to the threat of a tsunami. While on land various physical and chemical measurements can be employed, monitoring underwater volcanoes is much more challenging. Methods based on electromagnetic radiation, such as satellite radar interferometry used elsewhere for highly precise monitoring of vertical ground movements, are also practically impossible due to strong absorption of EM of this frequency range by water. All instruments need to be installed underwater during costly marine expeditions. Fortunately, Kolumbo now has a subsea volcanic monitoring observatory called SANTORY, and its development can be followed at https://santory.gr/.

**Q: What is full-waveform inversion (FWI) seismic imaging, and how is it used in the study of the Kolumbo submarine volcano?**

The FWI method can be thought of as a combination of two diagnostic medical techniques - ultrasound and computed tomography (CT). As a result, we can not only precisely determine the contours of the studied object (as in ultrasound), but we can also determine its physical properties by seeing through it from different angles (as in tomography).

Unfortunately, we cannot place a volcano in a CT scanner and illuminate it with rays from every possible angle. Therefore, geophysicists had to develop much more sophisticated mathematical tools than those used in medicine, in order to provide reliable and useful results despite less-than-perfect data. Instead of X-rays and ultrasounds, we use seismic waves generated by natural earthquakes or minor tremors generated by research equipment.

**Q: How was the presence of a magma chamber in the Greek volcano detected?**

The FWI imaging method allowed us to obtain a three-dimensional model of elastic properties, specifically the seismic wave velocities, inside the volcano. These velocities are directly related to the extent to which the rock is molten. The more molten the rock, the slower seismic waves travel through it. A similar observation led to the discovery of Earth's liquid outer core.

The connection between the rock's physical state and the wave's speed can be understood using the stadium wave analogy. A stadium (or Mexican) wave created by audience can often be seen during big sport events, e.g. London Olympics (<https://t.ly/3NciT>). If spectators were tightly packed in a row, holding hands, a jump of the first person would immediately “lift” the next, and the wave would propagate much faster than if they were sitting far apart. Similarly, in solid rocks, molecules are densely packed in a crystalline lattice and transmit vibrations much faster than in a liquid, even a one as viscous as magma.

Under Kolumbo, we found an area with dramatically reduced seismic wave velocities. Interestingly, this anomaly almost completely eluded the standard imaging method (applied to the data from the same experiment) which has been the primary geophysical tool for studying volcanoes worldwide.

The velocity under Kolumbo turned out to be so low that it could not be explained solely by high temperature. In other words, some rock must exist there in a molten form. Furthermore, the degree of melting is likely high enough to refer to it as magma, rather than a so-called crystal mush in which very small (a few % of the rock volume) amounts of melt are distributed in microscopic spaces between crystalline grains. Interestingly, the current paradigm, contrary to the familiar textbook images depicting a large magma chamber beneath every active volcano, regards mush as the prevailing form of "existence" of melt inside the Earth, and magma chambers are considered transient, and therefore challenging to detect with geophysical methods. Magma chambers will turn into mush zones by cooling down and partially crystallising if an earthquake or hot basaltic magma from greater depths does not arrive in time to trigger an eruption

**Q: How do geophysicists estimate the size/growth of a volcano's magma chamber (using the example of Kolumbo)?**

Using the theory of homogenisation (also called effective-medium theory), we can calculate the proportion of melt to solid rock from the seismic velocity of partially molten rock. Based on a three-dimensional image of the seismic wave velocity, we can estimate how much melt in total is present inside the volcano. We can also determine what proportion of melt resides as magma and how much of it is crystal mush. However, this calculation is burdened with significant uncertainty due to the fundamental ambiguity of possible geometries of rock pores in which the melt can accumulate.

Estimating the growth rate in our case is based on the assumption that all the melt was delivered/produced since the previous eruption. In other words, the previous eruption completely emptied the magma chamber. Of course, this is an oversimplification, and the result is subject to the greatest uncertainty among those mentioned.

**Q: In what time frame could a theoretically awakening of the Kolumbo volcano occur?**

Such estimates are usually made based on the average frequency of past eruptions. In Kolumbo's case, we know for certain that there have been at least six eruptions in the last million years, giving an average eruption frequency slightly greater than 1 every 200,000 years. Considering that the last eruption was 400 years ago, we might think we are safe. However, the inaccessibility of the deeply lying products of the past eruptions makes our understanding of the Kolumbo history quite patchy. The vigorous hydrothermal and seismic activity going on under Kolumbo calls for continuous monitoring and led to creation of a seafloor observatory.

Currently, an expedition of the International Ocean Discovery Program (IODP) is drilling for sediment cores in the immediate vicinity of Kolumbo. The analysis of these drilling cores will provide us with a much better understanding of the history of previous eruptions and improve our very imperfect predictions.