Addressing the hazard risks of Kolumbo submarine volcano (Santorini, Greece)

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Abstract. Volcanic eruptions are one of the most captivating natural phenomena on Earth but pose significant risks to nearby communities due to their associated hazards (earthquakes, tsunami, pyroclastic flows, toxic gasses). The implementation of a proactive volcanic risk management is essential to minimize the threat in close populated areas. Kolumbo is a submerged active volcano, 7km northeast of Santorini Island and part of the Hellenic Volcanic Arc. Kolumbo's most recent eruption, in 1650, generated a tsunami causing destruction in the nearby islands as well as several casualties due to poisonous gasses in Santorini. Eyewitness accounts reported maximum run-up heights of 20m on the southern coast of Ios, 240m inundation on Sikinos, and flooding of up to 2km² of land on the eastern coast of Santorini, prompting major destruction in the proximate towns. Recent studies show that a future explosive event of Kolumbo poses a significant hazard to the northern and east coasts of Santorini, however there is no relevant management protocol in place. Therefore, it is proposed that a combination of scientific research (active monitoring, hazard maps), community engagement, preparedness planning with government agencies (Civil Protection), and timely response strategies is crucial to minimize the hazard risks and avoid casualties and the detrimental consequences to the area's economy and infrastructure. At present, we have deployed state-of-the art sensors to monitor Kolumbo active hydrothermal field under the framework of SANTORY project (www.santory.gr). SANTORY aims to create novel communication tools and provide the scientific community, policymakers, and stakeholders with interregional monitoring protocols for assessment of hazard warning codes.

Keywords: volcanic hazards; risk management; submarine volcanoes; monitoring tools.

1 Introduction

Volcanic risk management is a multidisciplinary critical field of study aimed at mitigating the threats posed by volcanic eruptions to human lives, infrastructure, and the environment. This strategy involves a combination of preparedness planning, active monitoring, and response measures. Efforts begin with continuous monitoring of volcanic activity through advanced technology and geophysical tools (Bertin et al., 2018). Early warning systems are then established to provide timely alerts to at-risk communities. Disaster preparedness and evacuation plans, coupled with public education campaigns, help communities respond effectively during eruptions (UNDRR, 2015) while post-eruption recovery and rehabilitation efforts ensure swift restoration of essential services and infrastructure (Lavigne et al., 2013). Overall, volcanic risk management demands a comprehensive and collaborative approach that integrates scientific research, policy development, and community engagement to minimize the potential devastation caused by volcanic eruptions.

Santorini, in the Aegean Sea, has a population of 15,457 (Hellenic Statistical Authority, 2021), but this swells to over 500,000 in the summer due to tourism. Most residents work in tourism-related roles, with only a minority in traditional jobs like fishing and viniculture (Dominey-Howes and Minos-Minopoulos, 2004). The entire population's livelihoods are vulnerable to risks from a potential future volcanic eruption, which could significantly impact the local economy and infrastructure. Kolumbo, located 7km NE of Santorini, is a submerged active volcano, considered the most dangerous in the Mediterranean. Its 1650 eruption caused a tsunami and toxic gas, resulting in casualties and damages (Fouque, 1879). Recent study suggests a future eruption could pose a significant hazard to Santorini's east coast (Karstens et al., 2023a), but there's no management protocol in place. We propose a strategy involving scientific research (active monitoring, hazard maps), community engagement, cooperation with government agencies (Civil Protection), and timely response to minimize hazards, prevent casualties, and protect the area's economy and infrastructure.

2 Geological Setting

The 450km long Hellenic Volcanic Arc (HVA), where subduction of the African plate occurs beneath the Aegean microplate (McKenzie, 1972; LePichon and Angelier, 1979), includes onshore and offshore volcanoes that extend from the Methana peninsula, through the islands of Milos, Santorini up to Kos, Yali and Nisyros in the west (Nomikou et al., 2013). Volcanism in the southern Aegean was initiated in the Pliocene and has continued throughout the Quaternary (Pe- Piper and Piper., 2005). Located on the Hellenic Volcanic Arc, the Christiana-Santorini-Kolumbo volcanic field (CSK) is one of the most hazardous volcanic fields in the world, accounting for more than 100 explosive eruptions in the past 650 k.y. (Druitt et al., 2019a). The CSK (fig. 1b) lies in a 60-km-long, SW-NE oriented rift zone and hosts the Christiana volcano, the Santorini caldera, the submarine Kolumbo volcano (fig. 1a), and the Kolumbo volcanic chain that consists of 24 submarine cones (Nomikou et al., 2019, Preine et al., 2022). Santorini has witnessed a minimum of four significant caldera-forming eruptions. Among them, the most recent one known as the "Minoan" eruption, which took place approximately 3600 years ago, is widely recognized as one of the largest volcanic events during the Holocene (Druitt et al., 1999; Johnston et al., 2014; Nomikou et al.,2016a). It is presumed to have caused significant impacts to human populations in the eastern Mediterranean area with the most notable possible outcome the fall of the Minoan Civilization (Bruins et al., 2008).

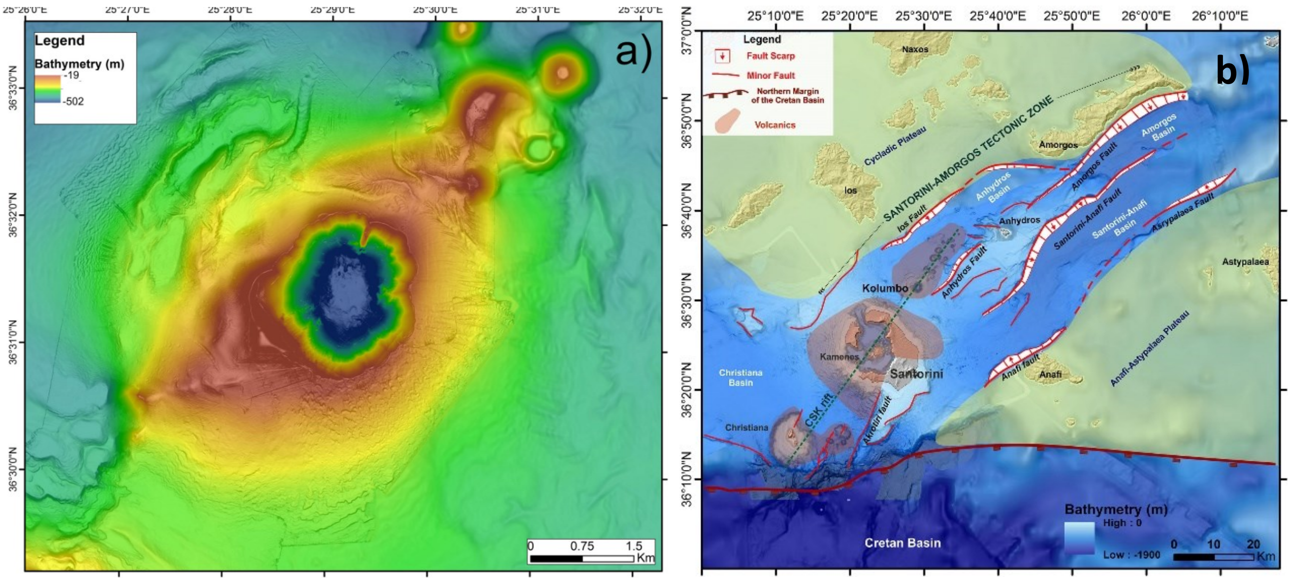

Figure 1. a) AUV high-resolution map of Kolumbo volcano (Nomikou et al., 2022) and b) The Christiana-Santorini-Kolumbo rift (Nomikou et al., 2019).

2.1 Kolumbo Volcano

Kolumbo is a submerged active volcano, located just 7km NE of Santorini. Kolumbo's edifice was created by at least five eruptive cycles, the earliest dating back more than 1 Myrs (Preine et al., 2022). Its most recent eruption, in 1650 CE, formed a cone consisting of up to ~260 m-thick stratified pumice deposits, which breached the sea surface before being destroyed by a violent explosive eruption that formed a 500 m-deep and 2,500 m-wide crater (Nomikou et al., 2012). High resolution 2m bathymetry data and optical data from past oceanographic expeditions revealed the morphological structure of Kolumbo's crater (Nomikou et al., 2022). The cone that formed after the 1650 eruption consists of highly vesicular pumice (fig. 2b), which was deposited as fallout from the eruption column, where many of the large pumice clasts floated at the sea surface before sinking (Karstens et al., 2023b). The cone had a volume of approximately 5 to 7 km³, which was deposited in a very short timeframe of only two weeks, based on eyewitness accounts (Klaver et al., 2016). The seafloor at the northern part of the Kolumbo crater hosts high (up to 220°C) and low (up to 70°C) temperature polymetallic chimneys (fig. 2c) and hydrothermal vents covered by bacteria (Carey et al., 2013; Kilias et al., 2013; Polymenakou et al., 2023).

2.2 The 1650 AD eruption

In 1650 AD, Kolumbo experienced explosive eruptions, with eyewitness accounts documented by Fouque (1879). Activity began with violent earthquakes in March 1650, followed by increased seismic activity. On September 27, ash clouds rose 1.6 km northeast of Santorini, with unpleasant odors appearing inland and a "snow-white" ledge emerging from the sea. Small earthquakes, pumice production, and plumes continued September 29. Lightning, explosive sounds, and powerful earthquakes were felt up to 400 km away in the Dardanelles. Concurrently, there was a notable increase in the frequency of powerful earthquakes, which were felt approximately 100 km away in the island of Crete, and ash fallout reached parts of Turkey. At least one tsunami struck Santorini, resulting in the destruction of buildings, erosion of roadways, and submerging of approximately 2.02 km along the eastern coastline. This tsunami also affected the islands of Ios where it reached 20 m inland and Sikinos (32 m inland), causing damage. After a few days, the eruption gradually subsided. Among the significant dangers faced by local communities were the toxic gas clouds released during the eruptions. These gasses caused various health issues such as eye pain, blindness, and cerebral congestion, leading to temporary loss of consciousness for many residents for several hours. Over 70 individuals perished due to asphyxiation, and numerous animals were killed. A nine-man crew of a ship passing near Kolumbo were asphyxiated. Reports indicated that the gasses also caused discoloration of coins, sacred vessels in churches, paintings, and building walls. In December, earthquake activity marked the end of the eruption. For several years, there were occasional small tremors and elevated water temperatures observed around Kolumbo. However, within a few months after the eruption, the small island eroded beneath the waves.

Volcanic Risk Management

Managing volcanic risk involves a complex, multidisciplinary approach that integrates scientific knowledge, risk assessment, community preparedness, and emergency response planning. Risk management includes hazard assessment, identifying volcanic hazards linked to the volcano. Historical eruption records offer valuable data on eruption frequency, intensity, and patterns, aiding our understanding of the volcano's behavior and regional volcanic history (e.g., Siebert et al., 2010). Active monitoring and early warning systems are vital in volcanic risk management. They rely on techniques like seismic monitoring, gas measurements, and ground deformation analysis (McNutt, 1996). In the case of terrestrial volcanoes, seismic monitoring detects tectonic activity preceding eruptions, while gas measurements track changes in volcanic gasses, indicating increased activity (Oppenheimer, 2011). These methods enable timely warnings, evacuations, and preparedness measures, reducing the impact of eruptions on communities and enhancing disaster resilience.

Kolumbo is but one of many other submarine volcanoes that are currently not efficiently viewed as a threat, despite their activity. The lack of preparedness of decision makers and scientists has already been proven catastrophic, such as the cases of the 2018 Anak Krakatau collapse and its subsequent tsunami that caused over 400 deaths (BNPB, 2019), as well as the most recent eruption of the Hunga Tonga–Hunga Ha'apai submarine volcano in 2022 with at least 6 dead, multiple reported people missing and approximately $90.4 million in damages in Tonga island (The World Bank, 2022). Research and monitoring of shallow submarine arc volcanoes in the Mediterranean Sea are still in its early stages, however, in situ seafloor deep observatories have been established to monitor submarine volcanoes over extended periods of time. These observatories include the Azores node of the European Multidisciplinary Seafloor and Water Column Observatory (e.g., Escartin et al., 2015), the Axial Seamount in the NE Pacific - part of the U.S. National Science Foundation (NSF)-funded Ocean Observatories Initiative (OOI) Cabled Array, Ocean Networks Canada's cabled observatory at Endeavour Ridge Ridge (Kelley et al., 2014), and the Mayotte deep-sea eruption observatory in the North Mozambique Channel, established by France (Feuillet et al., 2021). Some of these observatories have successfully tracked changes in submarine volcanic dynamics. For instance, the 2015 eruption at Axial Seamount was accurately forecasted within a one-year window based on volcanic deformation and was monitored in real time by the OOI Cabled Array (Nooner and Chadwick, 2016). Deformation and seismic monitoring are currently being used to predict future eruptions and place them in the next 4-9 years (Chadwick et al., 2022).

Volcanic risk assessment is essential for informed decision-making and disaster readiness. It combines geological, geophysical, and historical data to evaluate volcano hazards (Marzocchi et al., 2012). Vulnerability analysis considers factors like population density, infrastructure, and land use near the volcano (Lavigne et al., 2008). Recent research examines societal vulnerability indicators, including utilities, power grids, healthcare facilities, and critical infrastructure networks (e.g., Lobban et al., 2021; Boyle et al., 2022). Social vulnerability is considered in disaster preparedness initiatives (Gralla et al., 2014) and humanitarian supply chain management (Huang et al., 2015). Risk assessments use probabilistic models and historical records to estimate hazard likelihood and impact (Spence et al., 2007). Communities then create evacuation plans, hazard zones, robust infrastructure, and safety education, aided by specialized hazard maps. Risk mitigation includes land use planning, zoning regulations to limit development in high-risk areas (Haynes et al., 2008), resilient infrastructure construction (Spence et al., 2007), and community education and preparedness programs (Gregg et al., 2004). Besides the probabilistic methods, novel Artificial Intelligence (AI) techniques, mainly machine learning (ML) and deep learning (DL), are used for disaster/hazard risk management, including assessment, disaster detection and forecasting, in combination with real-time measurements (or historical records) of the associated hazards (e.g., Linardos et al. 2022). In the case of Santorini, a general emergency response plan and immediate/short-term management of the consequences of volcanic activity in the Santorini volcanic complex (TALOS) has been designed by the Civil Protection Agency. The plan considers two possible scenarios of an eruption of Santorini volcano, with a subplinian eruption being the worst-case scenario and a "historic type" intracaldera reactivation of the Kameni volcanic centers as the most likely scenario - similar to the volcanic activity that contributed to the creation of the islets of Palaia and Nea Kameni (TALOS, 2023). Santorini volcano is being monitored by an array of instruments including seismographs, gps, temperature and gas measurements (e.g, Moreira et al., 2019) and TALOS has laid out an efficient response strategy, however, there is no mention of a mechanism in case of an eruption of Kolumbo. Therefore, we believe that a strategy for emergency response regarding Kolumbo's activity is essential to be implemented, that can be designed based on active monitoring of the volcano and its hydrothermal vent field, along with a combination of the already accumulated knowledge regarding Kolumbo.

Our team has multidisciplinary data from past oceanographic expeditions that will help us to understand Kolumbo's behavior. These include a) High-resolution multibeam bathymetry data and optical data., b) a dense network of sub-seafloor seismic reflection profiles, c) a series of the seafloor and sub-seafloor samples of microbial mat and sediments, d) CTD data, e) several polymetallic (Au, Ag, As, Sb, Pb, Hg, Mo, Zn, Cu, Tl) CO_2 diffuser chimney samples and f) tephra in marine sediment cores. Despite the current knowledge that we managed to obtain, monitoring is needed to efficiently assess potential hazards and create early warning systems and management protocols for an imminent eruption from Kolumbo.

Results

High resolution 2 m bathymetry data (Hannington et al., 2018) were combined along with ROV optical data collected from the cruises of E/V Nautilus in 2010 and 2011 to understand the morphology and construct the geological map of Kolumbo crater. The crater is dominated by highly vesicular pumice and lava deposits on its walls (fig. 3a) that derive from the 1650 eruption. The biggest lava deposits lie on the northeast and southwest walls of the crater. The crater floor is covered by an orange microbial mat and its northern sector hosts the active hydrothermal field of the volcano. Steeper slopes are observed on the northern, eastern, and southeastern walls, making the areas vulnerable to landslides due to tectonic activity. The 1650 eruption and subsequent tsunami had detrimental consequences for the east coast of Santorini, especially at the towns of Perissa and Kamari (fig. 3b). Historical accounts mention flooding of up to 2km² of land on the eastern coast of the island, resulting in the destruction of buildings and erosion of roadways.

Considering the historical record, we can identify (i) toxic gasses, (ii) ash fall, (iii) pyroclastic flows and (iv) tsunami generation as the potential hazards of a Kolumbo eruption. Considering the eruptive history of Kolumbo, as well as its architecture, we can come to the realization that a possible eruptive scenario would be a repetition of the 1650 eruption. Such an event would likely span for several weeks, and it is highly possible that discolored sea surface will indicate underwater volcanic activity (Cantner et al., 2014) and a tsunami like 1650 AD will be generated that will reach the coasts of Santorini within 5 minutes, according to simulation models (Karstens et al., 2023b). By taking into consideration that a repetition of 1650 AD events are one of the most likely scenarios of an eruption, the following measures are proposed.

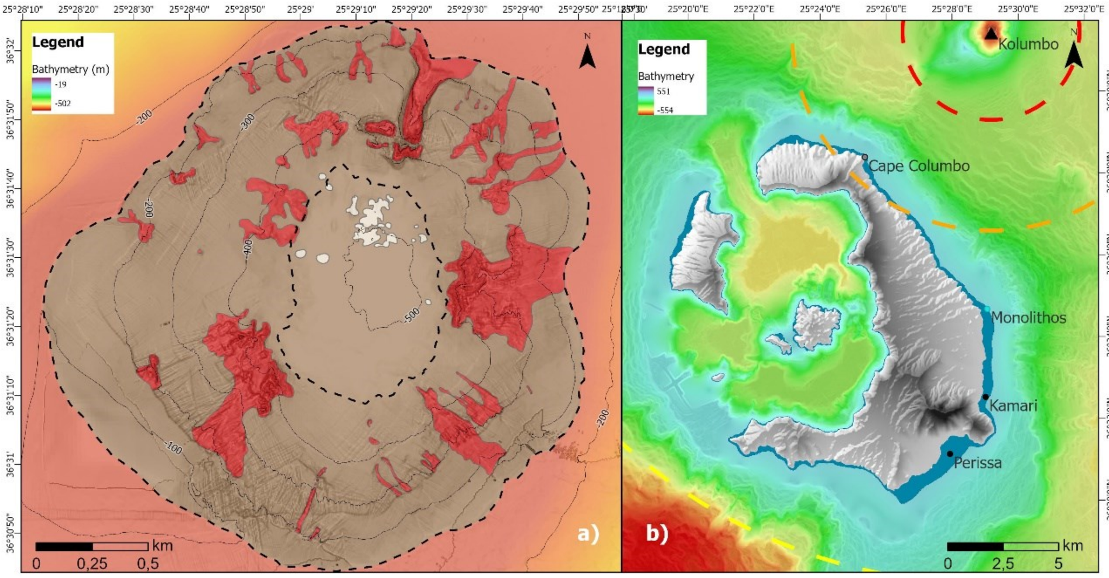

Figure 3. a) Underwater Geological Map of Kolumbo crater. Brown areas are pumice deposits, while lava deposits are shown in red. b) Hazard zonation map showcasing the three distinct hazard zones in Santorini. The red dotted line indicates Zone 1 (4km off Kolumbo), the orange Zone 2 (4-9 km off Kolumbo) and the yellow Zone 3 (over 9 km off Kolumbo). Marked with blue are the areas of Santorini affected by the 1650 tsunami according to historical eyewitness accounts accumulated by Fouque (1879). The towns located at the eastern coast are the most affected with maximum water run-up up to 14m.

Hazard Zonation. Three hazard zones should be drawn, depending on the degree of the dangers that the above hazards pose to life (fig. 3b). Therefore, we propose the following zones.

- Zone 1 (4 km < Kolumbo): In this zone, access must be strictly prohibited due to danger of asphyxiation caused by toxic gas emissions and the proximity to Kolumbo's crater poses imminent threat due to the pyroclastic flows, ash fall and a potential tsunami generation.
- Zone 2 (4-9 km near Kolumbo): In this zone that ends on the northeast coast of Santorini, ash fall, and tsunami generation pose significant threats to life. The area should be evacuated to prevent a repetition of the 1650 casualties both inland and offshore.
- Zone 3 (over 9 km off Kolumbo): In this zone, the area is less likely to be affected by a tsunami, however toxic gas emissions and ashfall still pose a hazard. The use of protective masks, eye protection goggles and burn resistant clothes is mandatory to avoid health associated risks.

Prior to the eruption (pre-eruptive phase) measures. Indicators such as tectonic activity, enhanced hydrothermal activity and water discoloration are expected to last for several days in the vicinity of Kolumbo. During this phase, the Civil Protection

Agency should prepare to inform the public of the volcanic activity and limit access to the vicinity of the volcano. Scientists should aid the government agency and help with early assessments of hazards and action plans. The continuous seismic activity could cause problems to infrastructure, communications, and the area's road network. This should be taken into consideration and authorities should implement the relevant protocol for dealing with risks of seismic activity. The areas that are more likely to be affected are located on the east coast of Santorini and their vulnerability should be assessed thoroughly to consider what should be done in the next phase.

During the eruption (eruptive phase) measures. Following the pre-eruptive events, we can expect dense ash clouds approximately 1.6 km northeast of the island and unpleasant odors arriving inland due to the gas emission while minor earthquakes continue, and the first frequent pumice deposits will be observed. Tectonic activity inside or nearby the crater could induce landslides on the inner walls due to the steep slopes observed in the crater. Landslides could cause water displacement and thus generate a tsunami. At this phase, access to the offshore area should be prohibited and tide gauges should be implemented to monitor the area for a possible tsunami generation. A tsunami watch is issued when a tsunami may later impact the watch area. The watch may be upgraded to a warning or advisory or canceled based on updated information. Emergency management officials and the public should be informed and prepared to act with partial or complete evacuation of the eastern coastal area of Santorini and its ports up to Monolithos and other smaller fishing ports at the easter part of the island (fig. 4) and initiate the plan for disaster prevention. The hazards of ash fallout and toxic gas emissions should also be considered for the problems that they cause on transportation (air transportation is limited or canceled, problems with sea transport due to the ongoing eruption), on health (asthma, emphysema and other chronic lung diseases, eye irritation, respiratory issues, suffocation (CDC)) and on the environment (water contamination, loss of cultivation, air pollution). Protective masks and gear should be issued to avoid asphyxiation and burns. Pyroclastic lava flows could also cause telecommunication issues due to destruction of underwater cables, much like the destruction of a vast network of seafloor telecommunication cables by volcanic debris from the Hunga eruption in 2022 that traveled under the sea more than 100 km (Clare et al., 2023). The above should be put into consideration by the relevant authorities to plan for alternative uses of transport, establishment of mobile healthcare facilities and alternative modes of communication.

Conclusions

Managing the risk that stems from volcanic activity is a complicated and multidisciplinary procedure that involves scientific knowledge, risk assessment, community preparedness, and emergency response planning. Current research shows that Kolumbo volcano poses a significant hazard to the northern and eastern coast of Santorini and a future eruption could cause devastating consequences for the island, to the population, the infrastructure, and the environment. Our current knowledge regarding Kolumbo's mechanisms and eruptive history is still at its infancy. Despite the potential hazard that Kolumbo poses to the nearby communities, it is not taken into account in any strategy for emergency response and risk mitigation. We consider that such a strategy should be designed, where a hazard and risk assessment is conducted, and mitigation measures are stated that all provide a sufficient risk management method. AI techniques, in particular ML and DL, can be used in combination with the active monitoring hazard data and volcanic hazard maps, to develop an on-line early warning system and decision-support system for emergency responders. Moreover, ML and DL combined with high quality volcanic data, can be used to assess the components of risk, namely vulnerability and exposure, towards a holistic and more accurate risk management system for emergency responders and local communities. An important measure for risk management is the active monitoring of a volcano, to gather more information about the volcano's evolution and mechanisms, as well as recognizing early signs of an eruption to inform the public. In the case of submarine volcanoes there are certain limitations. These involve the difficulty of implementing and maintaining monitoring systems underwater for a long period of time as well as developing the necessary instrument for this endeavor, although several prominent efforts have been made globally in recent years.

At present, we are monitoring Kolumbo with a deployed underwater observatory. SANTORY (SANTORini's seafloor volcanic observatorY) is a research project with partners from international institutions (INGV-Palermo, GEOMAR) and universities (NKUA, HCMR-IMBBC, NTUA, ENS-PSL, UNIWA) funded by H.F.R.I. (Hellenic Foundation for Research and Innovation). The project aims to comprehend the links between deep-seated geological processes that have associated risks and their expression in hydrothermal activity. Our international research team monitors Kolumbo by developing and integrating state-of-the-art technology for in situ monitoring along with discrete sampling and measurements. So far, we conducted two oceanographic expeditions funded by the municipality of Thera - Santorini to a) deploy and maintain the seafloor observatory, which is a new generation automated geochemical recording system that collects data of acoustics, dissolved CO2, H2S, O2, T °C, pressure, EC, pH, and turbidity, b) conduct various measurements on Kolumbo's crater with multiple innovative sensors (T-sensors, Inclinometers, Pressure gauges), c) continuously record the active hydro-thermal vent field with Stand-alone optical cameras, multispectra and the "THEIA" stereo camera and d) make for the first time, real-time measurements for radioactivity using gSniffer and γ-radiation imager "SUGI".

This ongoing observation of Kolumbo's activity provides scientists with invaluable information that in turn could aid government agencies and local communities in their efforts to strategize and ready themselves for potential crises. The unique, never seen before, time series data that is collected by the instruments of SANTORY will complement the already existing database that we have compiled in numerous oceanographic expeditions and provide us the necessary knowledge for Kolumbo's activity and dynamics. This acquisition of knowledge is essential for an implementation of hazard assessments, evaluating volcanic risks and safeguarding vulnerable communities near Kolumbo. By examining volcanic systems over extended periods, we can identify recurring patterns and unusual occurrences, thereby improving our capacity to forecast eruptions and minimize their consequences.

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