Scientific report for ECORD MagellanPlus Workshop Series Program

Volcanic, tectonic and hydrothermal processes in an island-arc caldera environment. Development of an IODP Drilling Proposal at Santorini-Kolumbo Marine Volcanic System

A Workshop in Athens, Greece, *21-23 November 2017, Athens, Greece*

Funded by the MagellanPlus workshop series and the Department of Geology and Geoenvironment (National and Kapodistrian University of Athens)

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Summary

A MagellanPlus workshop was held on 21-23 November in Athens, Greece, to begin preparation for a proposal to drill at Santorini-Kolumbo volcanic field on the Hellenic island arc. The workshop was attended by thirty researchers, including eight early career scientists, and was successful in bringing together a team of marine and onland geologists and geophysicists in preparing the first stages of proposal development and identifying potential drilling sites. A pre-proposal will be submitted to IODP in April of 2018.

1. The scientific objectives

The Christiana-Santorini-Kolumbo (CSK) volcanotectonic line in the South Aegean Sea (Greece) is one of the most important volcanic fields in Europe, having produced more than 100 explosive eruptions in the last 400,000 years. It lies in a 100-km-long, 45-km-wide zone of en-echelon NE-SW-trending rifts (Santorini-Amorgos Tectonic Zone, or SATZ) that cuts across the Hellenic Volcanic arc. The CSK line hosts volcanic centres including (from SW to NE) the extinct Christiana Volcano and associated seamounts, Santorini caldera with its intracaldera Kameni Volcano, Kolumbo seamount, and 25 other submarine cones of the Kolumbo chain.

Natural hazards from the rift zone threaten the eastern Mediterranean region. They include earthquakes, onland or submarine volcanic eruptions, gas releases from volcanoes, tsunami inundation of neighbouring coastlines due to eruptions or submarine landslides, and aviation impact from volcanic ash. The Late-Bronze-Age ('Minoan') eruption of Santorini may have influenced the decline of the great Minoan civilization on Crete, making it an iconic event in both volcanology and archaeology. The eruption of the submarine Kolumbo Volcano in 1650 killed 70 people and thousands of animals on Santorini due to gas release and tsunami inundation. Kolumbo is currently the most active and dangerous submarine volcano in the Mediterranean Sea. The levels of seismicity in the region are the highest in Europe. Indeed, the largest 20th century earthquake in Greece (Ms = 7.5) occurred along a 40-60 km long rupture between the islands of Santorini and Amorgos on 9 July, 1956. The earthquake was accompanied by tsunamis of significant runup generated by activation of Amorgos Fault zone. In 2011-12, intrusion of 14 million cubic metres of magma at about 4 km depth caused 14 months of seismic unrest and uplift at Santorini, raising awareness of the threat of eruption at an island archipelago visited by almost 2 million tourists per year.

Better understanding of the mechanisms of natural hazards, and the development of more effective risk mitigation strategies, requires us to tackle fundamental questions on magmatic, volcanic, tectonic, hydrothermal and biological processes in an island arc environment. What are the links and feedbacks between regional tectonics and volcanism in an arc rift setting? How does the opening and propagation of the rift zone relate to the history and mechanics of backarc spreading of the Aegean basin on a large scale, as well as to the history of slab tearing and rollback? What are the dynamics and products of submarine explosive activity? What are the mechanisms of caldera collapse at island arc volcanoes? What is the evolution of magmas with

time at an arc, with what contributions from the slab, mantle wedge and continental crust? What are the features of shallow hydrothermal systems associated with submarine volcanoes? What microbial ecosystems can thrive in these environments? What were the environmental impacts of the iconic 'Minoan' eruption on the late Bronze-Age world, and how does such knowledge translate to the present day?

The need for drilling at Santorini-Kolumbo is founded on many years of intensive onland and offshore research on the rift and it volcanoes. Santorini caldera has been the subject of numerous volcanological and petrochemical studies. The volcanic products have been mapped and dated, resulting in field and chronological constraints on the eruptive activity at a level of detail that is rare for an arc volcano. Many Santorini whole rocks and glasses have been analysed chemically, with a subset of those analysed isotopically for radiogenic and stable isotopes. The 1650 products of Kolumbo Volcano have also been characterised chemically and isotopically. Deep sea ash layers have been sampled by gravity coring at numerous sites of the Eastern Mediterannean; many of the ash layers have been correlated chemically with onland products, resulting in a tephrostratigraphic record for the last 200,000 years. Eight of the identified ashes are derived from Santorini.

Over the last decade, however, research on the CSK has moved firmly into the marine realm. Several marine campaigns of seismic study since 2006 have generated a dense network of sub-seafloor seismic reflection profiles in and across the SATZ rifts, along the CSK line, in the Christiana Basin, and within Santorini caldera, providing detailed images of sedimentary fills and fault patterns that provide a firm foundation for deep-sea drilling. High-resolution bathymetric surveys of the area have been carried out in several joint Greek-US-German oceanographic cruises, allowing detailed imagery of submarine volcanic edifices, tectonic fault zones and caldera floors. In 2010-11 and 2013-14, Remotely Operated Vehicle (ROV) investigations and manned submersible dives performed on Santorini caldera floor enabled sampling of submarine volcanic products, hydrothermal deposits and bacterial mounds, as well as documentation of surface and subsurface biosphere compositions and metagenomics. ROV dives at Kolumbo volcanic field discovered active hydrothermal vents, massive sulphide formation, and diverse bacterial and archaeal communities. In 2015, a joint US-Greek-UK team (NSF project) carried out a high-resolution, active seismic tomography experiment of the CSK system, providing a 3D marine-land active-source seismic dataset on an arc volcanic system that is unique in the world, offering an outstanding context for future drilling. Furthermore, three marine expeditions in 2017 by scientists from GEOMAR, Germany, and NKUA, Greece, carried out sampling of sediments and tephra at over 60 sites around and east of the CSK and within Kolumbo's crater, stratigraphically controlled ROV and dredge sampling of volcanic products from submarine edifices and from the submarine flanks of Santorini and Christiana volcanoes, and AUV mapping of Kolumbo Volcano and the northern part of Santorini caldera.

The questions raised by these data require deep drilling in order to push forward our understanding of the SATZ rifts, and of the volcanoes of the CSK line, and to address the questions listed above.

1. To sample depositional packages visible on our dense arrays of seismic profiles for textural, petrophysical, petrologic and chemical characterisation. Pyroclastic flow deposits, debris flow deposits and turbidite successions around the CSK line contain a rich record of past eruptions, as many of the products of volcanism entered the sea. This will allow reconstruction of the history of volcanism since its inception in this part of the Hellenic arc, as well as the petrological and chemical evolution of the CSK magmas through time and the importance of different magma sources in magma genesis. It will also enable improved understanding of volcanic processes involved in submarine eruptions and the entry of subaerially erupted pyroclastic flows into the sea.
2. To use chemical correlation of Santorini-derived mass flow deposits and deep-sea ash layers in the cores with the well dated onshore stratigraphy, thus providing a tight chronostratigraphic framework for submarine successions. A huge advantage of drilling in the neighbourhood of Santorini is (1) the very detailed work that has already been carried out on the volcanic history and products of Santorini, one of the best characterised arc volcanoes in the world, and (2) the dense seismic profile network necessary to trace key horizons over large areas. Recognition of mass flow deposits and fallout tephra from Santorini eruptions will provide excellent chronostratigraphic marker beds for correlation within drill core sequences and with the volcanic products of submarine volcanoes. This will enable construction of a complete volcanic stratigraphy of the SATZ rift and evaluation of eruption recurrence rates. Direct radiometric dating of submarine products, or dating using oxygen isotope stratigraphy, will enable reconstruction of an absolute chronology. Correlation of Santorini-derived deposits with seismically imaged unconformities and fault terminations will allow dating of episodes of rifting and allow comparison between adjacent rifts as well as with periods of volcanic activity.
3. To sample ancient shallow marine hydrothermal systems within Santorini caldera, as well as the fluids present within those systems and associated microbial colonies.

2. Workshop organisation

The workshop assembled a working group of thirty scientists in order to initiate an IODP proposal: scientists familiar with the onland and marine geology of the area, experts in key fields relevant to the questions posed, and eight early career scientists currently at postdoctoral or PhD level. Importantly, a number of the participants already had experience of previous IODP expeditions, and others had experience in ocean-floor drilling and core analysis through national programmes. We were also lucky to include participants with knowledge of the evaluation procedure for IODP proposals, who were able to advise us on a number of issues. All participants contributed in an open manner that was both rewarding and productive.

Prior to the meeting all participants were provided with background documents for the meeting, including the MagellanPlus proposal, a selection of publications on Santorini-Kolumbo, and some documents on other successful IODP proposals downloaded from the IODP website. The participants were also provided with a very early ‘working document’ drafted in advance of the

meeting by the organisers. The purpose of this was to provide a text depository that could act as a starting point for the meeting, serve as a basis for edits and suggestions, and be exploited subsequently as a source of text, facts and ideas for preparation of the pre-proposal, then later the full proposal.

The first day of the meeting was devoted to a series of thirteen carefully chosen presentations, the purpose of which was to summarise knowledge and understanding to date, major science questions to be addressed by drilling, databases available for a proposal, and additional data required for a convincing proposal to be feasible. The presentations were organised into three sessions: (1) summaries of the volcanology and tectonics of the region; (2) swath and seismic databases and current interpretations; (3) a general session concerning hydrothermal processes, microbial colonies and existing records of tsunamis and ash fallout in marine and onland successions. This day was extremely useful in summarising what is known, or not known, about the volcanic field for participants less familiar with Santorini-Kolumbo, as well as in beginning to focus attention on the key issues to be tackled over the second two days.

The morning of the second day began with a presentation of ideas and possible initiatives by the early career scientists, based on their own experience and research. There was also an impromptu presentation on drilling techniques. This was followed by summaries (by members of the organising committee) of scientific questions, objectives, IODP strategy, and possible site candidates, with discussions and ideas for other ones.

In the afternoon of day two, the meeting strategy changed. The participants were split into three thematic groups of participants (volcanology-petrology, tectonics-seismics, and hydrothermal-biological), who then spent the afternoon brainstorming relevant parts of the working document, exchanging ideas, and identifying problems and further necessary initiatives.

On day three, the results of the brainstorming sessions were discussed. We then exchanged ideas for the strategy for final proposal preparation, possible future participants from outside Europe, particularly the USA and Japan, and proposals for education and outreach initiatives.

The meeting ended with an excellent half-day field excursion to the Soussaki volcanic field, west of Athens.

3. Workshop deliverables

The meeting proved to be extremely efficient and productive, with the following main deliverables.

- The development of a cross-disciplinary dynamic between all participants, many of whom did not know each other before.
- The sharing of knowledge and expertise between onland volcanologists, marine geologists and geophysicists, and scientists with prior experience of IODP missions.
- Full involvement of a number of experienced and highly motivated early career scientists.

- A list of possible participants from the US and Japan to be approached for integration into the (at present mainly European) team at pre-proposal stage.
- The selection of six sites most appropriate for addressing the science questions and with suitably detailed seismic and bathymetric coverage.
- Initial lists of core-analysis techniques to be explored.
- An agreement to focus the project on the relationship between volcanism and tectonics, as this was seen as the most innovative strategy addressing a particularly big question in Earth Sciences.
- Following long discussion, an agreement to omit a previously favoured drilling site in the crater of Kolumbo crater. This site, originally envisaged as an exploration of a hot, active hydrothermal system, was seen to pose a number of technical issues that would significantly complicate, or even threaten, the proposal. Moreover insufficient geophysical site characterisation data are available for this site which, it was concluded, should form the basis for a separate drilling proposal at a later date.
- A realisation that existing seismic coverage of the anticipated sites was generally of very high quality. Funding applications will be made, however, in early 2018 to make additional seismic surveys at one site where existing seismic coverage or quality are deemed insufficient.
- A decision to submit a pre-proposal to IODP in the spring of 2018, with (if possible) a full proposal in October 2018, the aim being to possibly try and benefit from the presence of the Joides Resolution in the north Atlantic region in 2022.
- Plentiful notes and a draft working document full of modifications and ideas. The working document was very significantly improved by the input of all participants, and will be used as a basis for the pre-proposal.

4. Forthcoming initiatives

The following reports on the MagellanPlus meeting will be submitted in the coming weeks (1) the ECORD newsletter, (2) the journal EOS (American Geophysical Union), and (3) an abstract for a presentation at the forthcoming IODP/ICDP workshop in Bochum (March, 2018).

We will contact a certain number of US and Japanese scientists who have been recommended as appropriate possible collaborators on the pre-proposal. We will also contact the IODP science operator in order to increase our knowledge of technical aspects of drilling and core analysis and to seek advice on certain drilling issues.

Funding applications will be submitted for additional seismic surveys at one proposed site where existing seismic coverage or quality are deemed insufficient. A pre-proposal for the initiative will be submitted for the April 2018 deadline.

Participants at the meeting in Athens

Half-day field excursion to the Soussaki volcanic field, west of Athens

5. Participants

Athanassas	Constantin	National Tecnical University of Athens	Greece	
Behrmann	Jan	GEOMAR	Germany	
Brandl	Philipp	GEOMAR	Germany	Early career scientist
Druitt	Tim	Université Clermont Auvergne	France	
Drymoni	Sandy	Royal Holloway College, London	UK	Early career scientist
Flaherty	Taya	Université Clermont Auvergne	France	Early career scientist
Freundt	Armin	GEOMAR	Germany	
Geldmacher	Jorg	GEOMAR	Germany	
Gertisser	Ralf	University of Keele	Germany	
Hooft	Emilie	University of Oregon	USA	
Huebscher	Christian	University of Hamburg	Germany	
Ioannou	Thoedaora	University of Athens	Greece	Masters student
Ivarsson	Magnus	Swedish Museum of Natural History	Sweden	
Kieth	Manuel	University of Leicester	UK	Early career scientist
Kilias	Stephanos	University of Athens	Greece	
Klaver	Martijn	University of Bristol	UK	Early career scientist
Kotopoulou	Ilektra	CSIC-UGR	Spain	Early career scientist
Kutterolf	Steffen	GEOMAR	Germany	
Lampridou	Danai	University of Athens	Greece	Early career scientist
Myers	Madison	Université Clermont Auvergne	France	Early career scientist
Nomikou	Evi	University of Athens	Greece	
Pantelia	Sorottou	University of Athens	Greece	Masters student
Papanikolaou	Dimitrios	University of Athens	Greece	
Papazachos	Costas	Aristotle University	Greece	
Paris	Raphael	Université Clermont Auvergne	France	
Polymenakou	Paraskevi	Hellenic Centre of Marine Research	Greece	
Pyle	David	University of Oxford	UK	
Satow	Chris	University of Kingston	UK	
Triantaphyllou	Maria	University of Athens	Greece	
Zafeirakopoulou	Efrosini	University of Athens	Greece	Masters student

6. Workshop agenda

Tuesday 21 Nov. Keynote presentations (allotted times include 5 min of questions)

09.30-09.50 Coffee, welcome and meeting logistics (P. Nomikou)
09.50-10.15 Scientific objectives and deliverables (T. Druitt)
10.15-10.35 The International Ocean Discovery Program (J. Behrman)
10.35-11.00 The regional tectonic setting (D. Papanikolaou)
11.00-11.20 Santorini caldera: evolution; chronological and chemical databases (T. Druitt)
11.20-11.35 Kameni volcano and the unrest of 2011-2012 (D. Pyle)

11.35-12.00 *Coffee break*

12.00-12.25 Christiana-Santorini-Kolumbo line and Kolumbo Volcano (P. Nomikou)
12.25-12.45 Seismic imagery and stratigraphy of Santorini-Kolumbo volcanic field (C. Huebscher)
12.45-13.00 The 2015 deep active seismic tomography experiment (E. Hooft)

13.00-14.30 *Lunch break*

14.30-14.45 The marine tephra stratigraphy database (C. Satow)
14.45-15.00 Tsunami history and sediment record (R. Paris)
15.00-15.20 Hydrothermal and fluid flow processes (S. Kilias)
15.20-15.40 Seafloor and sub-seafloor microbial ecosystems (P. Polymenakou)
15.40-16.00 The recent GEOMAR cruises and their scientific objectives (A. Freundt)

16.00-16.30 *Coffee break*

16.30-18.00 General discussion

19.00 Communal dinner

Wednesday 22 Nov. Brainstorming sessions, addressing the following objectives.

09.30-09.50 Presentation of key ideas and possible initiatives from day 1 (representative of the early career scientists)
09.50-10.40 Presentation of scientific questions, objectives and IODP strategy

10.40-11.00 *Coffee break*

11.00-13.00 Presentation of the site candidates, with discussions and ideas for other ones

13.00-14.30 *Lunch break*

14.30-16.00 Split into multiple brainstorming groups, each focussing on one or more related sites. Each group edits/writes text for (1) their particular site, (2) the scientific text in general, and (3) any core-analysis technique or group of techniques relevant to their expertises.

16.00-16.30 *Coffee break*

16.30-18.00 Continuation of brainstorming and writing.

19.00 Communal dinner

Thursday 23 Nov. Refinement of the proposal

09.30-11.00 Discussion of site candidates, drilling strategies, technical drilling issues, calendar

11.00-11.20 *Coffee break*

11.20 –13.00 Final discussion points

- Strategy for final proposal preparation.
- Identification of teams for helping in writing of technical methods sections
- Proposals for invitation of participants from outside Europe, particularly the USA and Japan.
- Proposals for education and outreach initiatives

13.00-14.00 *Lunch break*

14.00-17.00 *Excursion to Soussaki volcanic field*

19.00 Communal dinner