MagellanPlus Workshop Series Program
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Scientific report for
ECORD MagellanPlus Workshop Series Program

Structure and Evolution of Magmatic and Hydrothermal Volcanic Systems in offshore collapse/resurgent calderas: Development of an IODP Drilling Proposal at Campi Flegrei linking to active ICDP Drilling Initiatives

Napoli, Italy (25-28 February 2017)

Report to ESSAC

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Napoli, Italy
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CONTENT

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1. SUMMARY

Active calderas are major volcanic features of the Earth's crust associated with large shallow magma reservoirs, high geothermal gradients, and geodynamic unrest often documented through historical time. Explosive caldera-forming eruptions are among the most catastrophic geologic events that may affect the surface of our planet within the interaction zone among lithosphere, hydrosphere, biosphere and atmosphere. These eruptions often result in huge volumes of pyroclastic deposits accompanied by large collapse structures and late stage deformation and uplift of the intra-caldera floor region (Smith and Bailey, 1968; Henry and Price, 1984; Lipman, 1984, 1997; Komuro, 1987; Newhall and Dzurisin, 1988; Cole et al., 2005; Acocella, 2008; Kennedy et al., 2012; Sacchi et al., 2014; De Natale et al., 2016; Steinmann et al., 2016).

Campi Flegrei (i.e. "burning fields") is one of the most dangerous volcanoes on Earth. It is an active caldera located on the coastal zone of SW Italy, close to the city of Naples, that has been characterized by explosive activity and unrest throughout the late Quaternary. This region represents an active segment of the Eastern Tyrrhenian margin and may be regarded as an ideal natural laboratory to understand mechanisms of caldera dynamics and the interplay between explosive volcanism, tectonics and sedimentary processes at continental back-arc margins.

The Campi Flegrei area hosted the largest eruption that ever occurred in Europe in the last 200.000 years, namely the Campanian Ignimbrite (39,000 years BP), VEI 6-7 with about 300 km^3 of erupted volume (Rosi and Sbrana, 1987; De Vivo et al., 2001; Fitzsimmons et al., 2013). More recently, about 15,000 years BP, another large eruption occurred, the Neapolitan Yellow Tuff, which emitted 40 km^3 of pyroclastic products, forming the present caldera (Scarpati et al., 1993; Deino et al., 2004; De Natale et al., 2016).

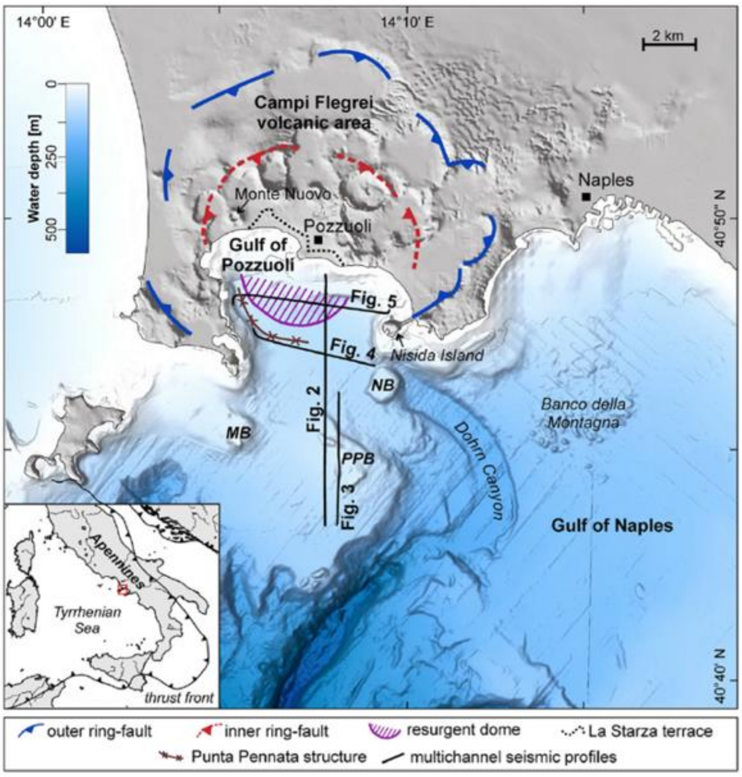

Fig.1. Morpho-bathymetry of the Campi Flegrei volcanic area and the Gulf of Naples (from Steinmann et al., 2016)

During the Magellan Plus workshop held in Naples on 25-28 February, 2017, 35 participants from 4 European countries, USA, and Japan, gathered to discuss the key scientific issues for a coordinated IODP-ICDP proposal dedicated to the drilling of the Campi Flegrei Caldera. The workshop built upon previous research and networking activities conducted by the proponents that included: 1) Coordinated ICDP Workshop and ESF Magellan Workshop held on 13-15 November 2006 in Naples; 2) Submission and approval of a ICDP full proposal (Campi Flegrei Deep Drilling Project) in 2006-2008; 3) Submission of IODP pre-proposal# 671 in 2006-2007 with indication of re-submission on the basis of an implemented site survey package; 4) Realization of 2 pilot holes (namely 500 m and 200 m deep) as a preliminary phase to the ICDP deep drilling; 5) Acquisition of new offshore site survey data (multiscale reflection seismics, multibeam bathymetry and gravity core data) between 2008 and 2016.

Researchers participating in the Magellan Plus workshop represented a wide range of disciplines related to the field of volcanology, geology, geophysics, geomorphology, petrology, geochemistry, geochronology, numerical and analogue modelling. The initiative was intended to bring together experts, young researchers and other representatives from the academia and industry involved in both marine and continental research drilling. The aim of the workshop was to strengthen a large community dedicated to develop new ideas for the understanding of a): caldera-forming volcanism and unrest off continental margins; b) the dynamics of shallow water hydrothermal systems, and c) the seafloor morphological and structural changes induced by frequent uplift/subsidence phases and active degassing processes.

Participants were asked to contribute to scientific debate on volcanism and associated hazards over coastal areas and identify problems that can be addressed by coordinated marine and continental drilling, with reference to the Campi Flegrei Caldera, as a case history. The workshop programme addressed data integration, and the building of a scientific rationale for drilling strategies and scientific partnering through a multidisciplinary approach, by linking geology, geophysics and geotechnology. The event has been among the first efforts to assess scientific themes directly related to volcanic hazard in highly populated coastal areas within the context of fully integrated ICDP-IODP drilling research.

The outcomes of the workshop provided a conceptual frame to support the preparation of a full-proposal for the Drilling of the Campi Flegrei Calera to be jointly submitted to IODP and ICDP Programmes according to the IODP Guidelines for joint review of “Amphibious Drilling Proposals” (ADPs). The Campi Flegrei ADP shall address complementary research topics, into a general view based on the analysis of collapse – resurgent calderas that develop over continental margins. Coastal offshore settings in fact provide a unique opportunity to reconstruct the chronostratigraphy and kinematic evolution of individual structures and components and understand the interaction between magmatic and hydrothermal processes that characterizes the hinge zone between marine and continental areas.

2. INTRODUCTION

Large collapse calderas are associated with exceptionally explosive volcanic eruptions, which are capable of triggering a global catastrophe second only to that from a giant meteorite impact. Therefore, active calderas have attracted significant scientific attention However, some important aspects on caldera dynamics and structure remain uncertain and controversial and they may be very different from those characterizing the more commonly studied stratovolcanoes or shield volcanoes. As large collapse calderas occur on all continents in various geological settings and often in densely populated areas, understanding their dynamics and evolution in order to assess volcanic hazards and risks is a matter of global relevance.

Large scale calderas are found, for example, in New Zealand (Taupo), Hawaii, North America (Crater Lake, Long Valley, Valles, Yellowstone), Asia (Lake Toba, Rabaul, Toya, Shikotsu, Kuttara), and also in Europe (Santorini, Campi Flegrei). Among those, only a few are located in proximity to coastlines and continental shelves, where hydrothermalism and groundwater supply may connect to the expression of volcanism and distribution of its products in a changing depositional regime, with average high sedimentary supply. Underwater/coastal calderas on continental shelves further provide access to unique stratigraphic archives of interbedded volcaniclastic and marine deposits with high potential of preservation.

Traditionally calderas have been analyzed through field studies, analogue models and numerical simulations (e.g. Druitt and Sparks, 1984; Komuro et al., 1984; Martí et al., 1994; Bower and Woods, 1997; Gudmundsson et al., 1997; Gudmundsson, 1998; Burov and Guillou-Frottier et al., 1999; Acocella et al., 2000, 2001, 2004; Guillou-Frottier et al., 2000; Martí et al., 2000; Roche et al., 2000; Roche and Druitt, 2001; Folch and Martí, 2004; Gray and Monaghan, 2004; Lavallée et al., 2004; Geyer et al., 2006; Martí et al., 2008). Collapse calderas have also received considerable attention due to their link to geothermal energy resources (e.g. Lipman, 2000). More recently, offshore reflection seismic imaging has emerged as a tool to understand the stratigraphic architecture and shallow structure of collapse, resurgent calderas developing at continental margins (e.g. De Natale et al., 2006; Sacchi et al, 2009, 2014; Passaro et al., 2016; Steinmann et al., 2016).

The Campi Flegrei caldera has been the world’s most active unrest caldera (non-erupting) for the last 67 years, a time interval of unrest episodes involving significant ground deformation (uplift) and seismicity. Besides these short-term ground deformation phases (e.g. 1982-1984, uplift rate of 100 cm/yr) (De Natale et al., 2006; Kilburn et al., 2017), long-term ground deformation with rates of several tens of meters within a few thousand years was also documented. Consequently, the central part of the caldera was uplifted and the La Starza marine terrace emerged ~5,000 years ago (Di Vito et al., 1999). The cause for uplift (magmatic vs. hydrothermal) is still under debate (De Natale et al., 1991; De Natale et al., 2006; De Vivo and Lima, 2006; Lima et al., 2009; Troiano et al., 2011; Moretti et al., 2017) and likely consist of periods of shallow magmatic intrusions accompanied or intercalated by overpressure and heating of shallow aquifers. While the uppermost hundred meters of the submerged part of the Campi Flegrei caldera have been intensively studied in the last decades, the deeper section remains largely unknown.

Understanding the mechanisms for unrest and eruptions is of paramount importance, as they are required to establish measures to predict type, intensity and frequency of future eruptions of the Campi Flegrei caldera and similar systems worldwide. Here, more than 600,000 people would be exposed to pyroclastic flows, rising to about 2 million considering the most dangerous ash falls (Rossano et al., 2004; Mastrolorenzo et al., 2008).

3. GEOLOGICAL FRAMEWORK OF CAMPI FLEGREI

The Campi Flegrei is an active volcanic district that lies west of the town of Naples near the Pozzuoli bay coastline (Fig. 1). This area represents a very mobile segment of the eastern Tyrrhenian margin during the late Quaternary (Oldow et al., 1993; Ferranti et al., 1996) and may be regarded as a privileged natural laboratory to study the interplay between tectonics and explosive volcanism associated with rifted back-arc margins (Milia and Torrente, 1999; Acocella et al. 1999).

Many authors agree in considering the Campi Flegrei and the Pozzuoli Bay as a remnant of a quasi-circular caldera, about 13 km in diameter. The present-day shape of the caldera is commonly regarded as the result of two large collapses related to the Campanian Ignimbrite (ca. 39 ka; De Vivo et al., 2001) and the Neapolitan Yellow Tuff eruptions (ca. 15 ka; Deino et al., 2004). Evidences of large ignimbritic events older than the Campanian Ignimbrite (i.e. 205 ka and 157 ka) have been reported in the Campania Plain (De Vivo et al., 2001) and are also recorded in the distal marine archive (Insinga et al., 2014).

Although the Campanian Ignimbrite (CI) has been previously considered as the main caldera-forming events (Rosi and Sbrana, 1987; Orsi et al., 1996), De Vivo et al. (2001), Rolandi et al.

(2003), and Bellucci et al. (2006) presented evidence in favor of different, mostly northernmost horizontal fracture vents as the origin of the CI. Recently, De Natale et al. (2016) found in the CFDDP pilot hole the first evidence of buried CI products in Campi Flegrei. Their findings, given the shallow and thin character of the deposit, are hardly compatible with a main origin of CI in Campi Flegrei caldera. Then, the only collapse forming the caldera was likely due the Neapolitan Yellow Tuff eruption, dated back 15.000 years BP, erupting about 40 km^3 of DRE (Dense rock equivalent). However, proximal CI products, namely the Museo Breccia widely present at Campi Flegrei as well as at Procida and Ischia islands testify that some CI vent and/or coeval eruption actually was located at Campi Flegrei and neighboring islands.

Campanian Ignimbrite deposits are widespread in Mediterranean and north-eastern Europe. After this gigantic event, many large to medium scale eruptions occurred, including the mentioned Neapolitan Yellow Tuff occurred 15 ky BP, and in the past 6,000 years (Fig. 2). The most recent eruption, the only historical one, occurred in 1538 A.D. Most recent volcanic activity gave rise to unrest episodes without eruptions (1950-52, 1969-72 and 1982-84) involving ground deformation (exceeding rates of 100 cm/year in the years 1983-1984) and sometimes intense microseismicity (about 16.000 events with magnitude up to 4.0 in 1983-84) as well as marked geochemical changes in emitted gases (Berrino et al., 1984; De Natale and Zollo, 1986; Dvorak and Berrino, 1991; De Natale et al., 1991, 2001; Battaglia et al., 2006; Chiodini et al., 2015; Moretti et al., 2017).

The Campi Flegrei area is a typical example of collapse caldera, which has the highest recorded recent ground movements not immediately followed by eruptions. In this area, first colonized by Greeks and home to the largest Mediterranean military fleet during the Roman times (Baia, on the west side of caldera), there is the longest historical record of ground movements associated to volcanic activity, revealed by marine incrustations and mollusks on the Roman and medieval buildings (Troise et al., 2007). The secular deformation of this area is subsidence, at a rate of about 1.5-1.7 cm/year, with some periods of large and faster uplift. Historically, three such uplift periods are evident: the first one occurred from 80 to 230 AD, the second from 1441 to 1538, culminating in the last eruption in the area and the third, started in 1950 and still in progress. The latter period has been characterized by episodes of very fast deformation rates, followed by periods of minor subsidence; the ongoing uplift, started after 2005, is characterized on the contrary by much lower deformation rates and seismicity, but much longer lasting. The maximum total uplift since 1969 to 1984 was 3.5 m (around 4.5 m since 1950), and maximum uplift rate in the period 1983-1984 exceeded 1 m/year. After 1985 a relatively fast subsidence started until at the end of 2004; since the 2006 a new uplift phase is in progress, which caused a total uplift of 40 cm, so far.

The Campi Flegrei probably represents the most interesting example in the world of an active caldera that develops across a densely populated continental margin. As it partially develops beneath the sea water, over the inner continental shelf of Southern Italy (the caldera is partially submerged for about 60 % of its surface) the Campi Flegrei area is an ideal site to test the potential of IODP shallow water drilling on a volcanic continental margin by a multiplatform drilling program including land-sea transects, in the frame of a fully integrated IODO-ICDP Amphibious Drilling Proposal (ADP).

4. WORKSHOP OBJECTIVES

The Magellan Workshop held on 25-28 February 2017 in Napoli was meant to address a long-lived activity of various research groups that have been involved since 2006 in both onland and offshore preparatory work and fulfilment of proposal requirements towards an integrated scientific drilling proposal for the Campi Flegrei Caldera that will be submitted to IODP and ICDP Programmes according to the IODP Guidelines for joint review of “Amphibious Drilling Proposals” (ADPs) (Figs. 2 and 3).

4.1. Previous activity of research groups involved in the Campi Flegrei drilling initiative

In 2006, two scientific workshops on the CFDDP (Campi Flegrei Deep Drilling Project) (ICDP, May) and complementary marine drilling (IODP, November) were held in Naples, during which it was agreed that setting and features of the partially submerged Campi Flegrei caldera provide an ideal natural laboratory to study the mechanisms of caldera dynamics (De Natale et al., 2006).

While the ICDP drilling had been initiated several years ago and recently successfully completed the pilot hole drilling, an associated IODP drilling is still in the pre-proposal stage (671-pre/-pre2), which was first submitted in 2005 and then resubmitted after the ESF workshop in 2006.

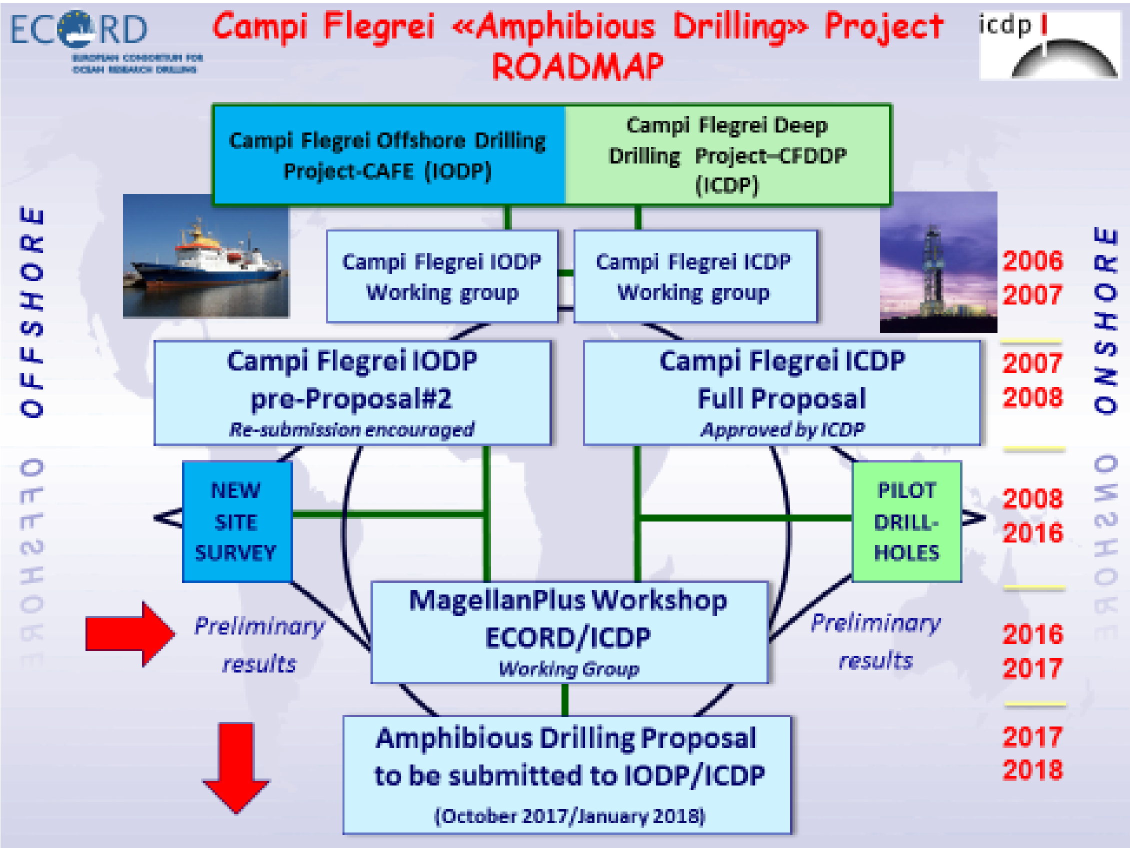

Fig.2. Roadmap of previous activity of research groups involved in the organization of the Magellan Plus workshop towards a new Amphibious Drilling Proposal of the Campi Flegrei Caldera

Since 2006, two new multichannel seismic data sets, complemented by cores and acoustic survey data for the shallow subsurface and for hydrothermal venting, had been acquired, and the basis for planning a drilling campaign has significantly improved. In 2008, a high frequency (up to 300 Hz) seismic grid was recorded at a spacing of 150 meters, and recently in January 2016, a low frequency (50 Hz) grid on 25-50 m line spacing was surveyed in the Gulf of Pozzuoli. While processing of the new data set is still to come, preliminary results have been discussed during the MagellanPlus Workshop (25-28 February 2017), to have an in-depth discussion concept drilling proposal, drilling targets, site selection and required drilling technologies.

4.2. Themes and issues addressed during the workshop

Participants were asked to present and discuss their contributions in plenary session and subgroups according to the following main themes:

<u>Explosive Volcanism and Caldera Formation</u>:
Caldera-related magmatism and eruption, pyroclastic flows, ignimbrites, fissure vs central volcano eruption, linkage between magmatic and hydrothermal systems
<u>Hydrothermal systems</u>:
Comparison between marine and terrestrial settings, pathways and flow pattern of hydrothermal circulation, structural constraints, origin of uplift (hydrothermal vs magmatic), control of small and large scale faulting on hydrothermal venting, unrest and volcanism
<u>Chronology of catastrophic eruptions</u>:
Onset, type and frequency of volcanism in Campi Flegrei region, reconstruction from sedimentary archives, caldera fill, long term sedimentary archive from a distal site
<u>Depositional Settings</u>:
Caldera fill, interaction with sea level change, terrestrial sediment fluxes, volcanic control on sediment transport pathways and accommodation space, distribution and pyroclastics and atmospheric control, characteristics of volcanoclastic deposits in a marine setting, diagenetic overprint by hydrothermalism
<u>Monitoring:</u>
Integration of boreholes into INGV-OV long-term observational network (earthquakes, tremor, micro-seismicity, temperature, pressure), lessons learned from IODP
<u>Links to land drilling;</u>
State of knowledge (cores, borehole data) and progress report from ICDP and other land drilling
<u>Technical Implementation:</u>
Constraints from MSP operational viewpoint, water depth, technology, costs

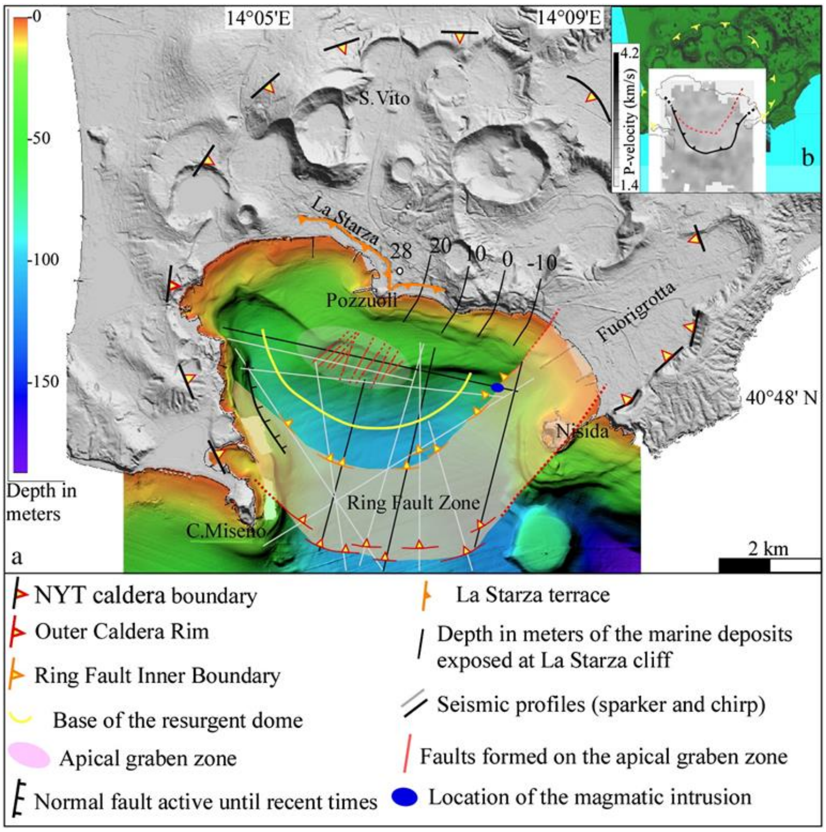

Fig.3. Map view of the main morpho-structural elements of the NYT inner caldera collapse and resurgence (from Sacchi et al., 2014).

5. WORKSHOP PARTICIPANTS

Venue: St. Domenico Maggiore Convent (Vico San Domenico Maggiore, 18 – 80134, Napoli, Italy).

	Name	Institution	Notes/expertise
1.	Volkhard Spiess	University of Bremen, Germany	Proponent
2.	Giuseppe De Natale	INGV-Napoli, Italy	Proponent
3.	Marco Sacchi	IAMC-CNR Italy	Proponent
4.	Lena Steinmann	University of Bremen, Germany	Early-career scientist
5.	Hans-Ulrich Schmincke	GEOMAR,Germany	
6.	Valerio Acocella	University Roma Te Italy	
7.	Christopher Kilburn	UCL, UK	
8.	Shanaka de Silva	Oregon State University, USA	
9.	Nobuo Geshi	Geological Survey of Japan-AIST, Japan	
10.	Fabrizio Pepe	Palermo University, Italy	
11.	Maria Jose Jurado	CSIC, Spain	
12.	Ulrich Harms	ICDP	
13.	Elisabetta Erba	Milano University, Italy	
14.	Claudio Scarpati	Napoli University Federico II, Italy	
15.	Sandro Conticelli	Firenze University, Italy	
16.	Lorenzo Fedele	Napoli University Federico II, Italy	
17.	Alfonsa Milia	IAMC-CNR, Italy	
18.	Alain Bonneville	PNNL, USA	
19.	Salvatore Passaro	IAMC-CNR, Italy	
20.	Roberto Moretti	University Luigi Vanvitelli, Aversa-Caserta, Italy	
21.	Mari Sumita	GEOMAR, Germany	
22.	Claudia Troise	INGV-Napoli, Italy	
23.	Paola Petrosino	Napoli University Federico II, Italy	
24.	Renato Somma	INGV-Napoli,Italy	
25.	Mattia Vallefuoco	IAMC-CNR, Italy	Early-career scientist
26.	Sabina Porfido	IAMC-CNR, Italy	
27.	Marta Corradino	Palermo University, Italy	
28.	Mauro Caccavale	IAMC-CNR, Italy	Early-career scientist
29.	Vincenzo Morra	Napoli University Federico II, Italy	
30.	Donatella Insinga	IAMC-CNR, Italy	
31.	Fabio Matano	IAMC-CNR, Italy	
32.	Alessandro Fedele	INGV-Napoli,Italy	Early-career scientist
33.	Flavia Molisso	IAMC-CNR, Italy	
34.	Stella Tamburrino	IAMC-CNR, Italy	Early-career scientist
35.	Luigi Ferranti	Napoli University Federico II, Italy	

6. WORKSHOP PROGRAM

The workshop included a plenary session (25 February 2017) (Fig. 4), a short field trip to the Campi Flegrei on the second day (26 February 2017), and thematic/plenary sessions on the following days (27-28 February 2017).

25 February S. Domenico Maggiore plenary session – Day 1

09:00 – 09:20 Welcome
09:20 – 09:40 **Marco Sacchi -** Aim of the "Campi Flegrei" MagellanPlus Workshop and opportunities for IODP-ICDP coordinated actions amphibious drilling proposal
09:45 – 10:05 **Giuseppe De Natale & Claudia Troise -** The Campi Flegrei Deep Drilling Project: first results and further plans
10:10 – 10:30 **Volkhard Spiess -** Challenge for a renewed IODP proposal for scientific drilling at Campi Flegrei CAFE project #2: new site survey
10:35 – 10:55 **Hans-Ulrich Schmincke & Mari Sumita -** Subaerial ignimbrites issued from large calderas and their submarine/subaqueous equivalents, with main examples from Gran Canaria ODP Leg 57 and Nemrut Caldera Anatolia
11:00 – 11:20 coffee break
11:20 – 11:40 **Nobuo Geshi -** Variation of eruption style toward caldera collapse: examples from Aso, Aira and Shikotsu calderas Japan
11:45 – 12:15 **Valerio Acocella -** Unrest and magma transfer at calderas
12:20 – 12:40 **Alain Bonneville -** The Newberry Volcano ICDP Project
12:45 – 13:05 **Shanaka de Silva -** Resurgence and unrest after catastrophic caldera forming eruptions
13:10 – 14:10 lunch
14:10 – 14:30 **Elisabetta Erba -** Priorities of the IODP Science Plan: hints and tips for implementing successful drilling proposals
14:35 – 14:55 **Ulrich Harms -** ICDP activities and Volcano Scientific Drilling
15:00 – 15:20 **Christopher Kilburn -** Progressive unrest at Campi Flegrei caldera
15:25 – 15:45 **Claudio Scarpati:** Campania Ignimbrite and NYT: products of large plinian caldera-forming eruptions and introduction to the Campi Flegrei field trip
15:50 – 16:10 **Maria Jose Jurado -** Downhole measurements and borehole images contribution to the understanding caldera evolution, structures and stress indicators. Examples from Campi Flegrei and other scientific drilling projects in volcanic rocks
16:15 – 16:40 tea break
16:40 – 17:00 **Salvatore Passaro -** A huge degassing structure between Campi Flegrei and Vesuvius: gas composition, geometry, and mechanisms of formation
17:05 – 17:25 **Alfonsa Milia** – tectono-stratigraphic setting of the eastern Tyrrhenian margin: implications for the Campi Flegrei volcanic field
17:30 – 17:50 **Sandro Conticelli -** The magmatism of the Italian Peninsula: constraints on genesis of magmas and geodynamics.
17:55 – 18:15 **Lorenzo Fedele -** A petrological overview of the Campi Flegrei volcanic district
18:20 – 18:30 Logistic information
19:00 – 20:00 wine tasting – Hotel Costantinopoli 104, Via S. Maria di Costantinopoli, 104, Napoli

26 February Field Trip to Campi Flegrei caldera - Day 2

Field trip Guides: **Paola Petrosino & Claudio Scarpati**
09:00 Bus leaves from Piazza Bovio , Napoli
09:00 – 12:00 Stop 1 (Coroglio- Nisida); stop 2 (Solfatara)
12:00 – 13:00 – Lunch lunch bags and soft drinks
13:00 – 17:00 Stop 3 (Averno); Stop 4 (Torregaveta); stop 5 (Pozzuoli)
17:30 Bus returns to Piazza Bovio, Napoli

27 February S. Domenico Maggiore introduction and working groups/plenary session - Day 3

Introduction
09:00 – 09:20 **Fabrizio Pepe -** Stratal architecture and kinematic reconstruction of the Campi Flegrei caldera during the last 15 ky based on very high-resolution single channel reflection seismics
09:25 – 09:45 **Lena Steinmann -** Post-collapse evolution of the Campi Flegrei caldera since the Campanian Ignimbrite eruption: insights from offshore multichannel reflection seismics
09:50 – 10:10 **Volkhard Spiess –** Campi Flegrei IODP proposal: new site survey data
Working groups session
10:10 – 11:00 General discussion and creation of Working groups for the preparation of a draft amphibious drilling proposal to be submitted to IODP/ICDP in October 2017/January 2018
11:00 – 11:20 coffee break
11:20 – 13:00 Plenary working groups meeting and planning
13:00 – 14:00 lunch
14:00 – 16:00 Working groups Meetings
16:00 – 16:20 tea break
16:20 – 17:00 Working groups Meetings
17:30 – 18:00 Working groups reports and plenary discussion

28 February S. Domenico Maggiore introduction and working groups/plenary session - Day 4

Working groups session
09:00 – 11:00 Working groups Meetings
11:00 – 11:30 coffee break
11:30 – 13:00 First draft of proposal by Working groups Meetings
13:00 – 14:00 lunch
14:00 – 16:00 Feedbacks to Working groups Meetings on proposal drafting
16:00 – 16:30 tea break
16:30 – 17:00 Second draft of proposal by Working groups Meetings
17:30 – 18:00 Plenary discussion

7. SUMMARY OF THE WORKSHOP ACTIVITIES

- Plenary session (25 February 2017) had the purpose of providing participants with a general framework of the scientific themes related to explosive volcanism and volcanic hazards in the context of IODP and ICDP research priorities, with examples of already existing projects based on scientific drilling.

Fig. 4. Participants in the MagellanPlus Workshop on Campi Flegrei Caldera held in Napoli, Italy (25-28 February 2017)

- Field trip (26 February 2017) consisted of 5 stops: 1) Coroglio cliff – Nisida Island; 2) Solfatara Crater; 3) Averno Crater Lake); Stop 4 (Torregaveta cliff); stop 5 (Pozzuoli).

Stop 1: Coroglio cliff – Nisida Island. The aim of the stop at Coroglio cliff was to visit a representative section of the Neapolitan Yellow Tuff Formation (ca. 15.0 ka) which unconformably overlays a remnant of the Trentaremi tuff rim (ca. 21.0 ka). Seaward, the tuff-cone of Nisida Island could be observed, as an example of late stage (ca. 3.7 ka) monogenic vent developed along the structural border of the caldera.

Stop 2: Solfatara Crater. It is a monogenic volcano resulting from the youngest phase of activity of the Campi Flegrei (ca. 4.5 – 3.6 ka), characterized by more than 15 explosive eruptions. The stop includes a visit to the inner crater of the Solfatara, where significant hydrothermal activity and active fumaroles is ongoing.

Stop 3: Averno Maar Lake. It is a small volcano of hydromagmatic origin superimposed on an older vent (Archiaverno tuff ring, ca. 11 ka). This area was morphologically shaped by a number of explosive eruptions occurred during the Holocene. The youngest event was the Averno2 (ca. 4.5 – 4.2 cal ka; Di Vito et al., 1999; Orsi et al., 2009). Due to the intense hydrothermal activity that had characterized the place over the last centuries, Lake Averno was believed to be the entrance to the hell for the Romans.

Fig. 5. Products of the Campania Ignimbrite Formation (ca.39.0 ky B.P.) exposed at the SW border of the Campi Flegrei Caldera (field trip stop 4: *Torregaveta cliff*).

Stop 4: Torregaveta cliff. Located in the WSW sector of the Campi Flegrei, Torregaveta cliff exposes some of the deposits of the CF caldera, including products from Procida and Ischia islands. Here both the Neapolitan Yellow Tuff (ca. 15 ka) and the proximal facies ("Breccia Museo") of the Campania Ignimbrite (ca. 39 ka) are exposed in outcrop (Fig. 5). The products of Campania Ignimbrite formation are spread over a large area that encompasses the whole Campania region of south Italy. Distal tephra associated with this eruption can be found as far as central Asia.

Stop 5: Pozzuoli. The stop in Pozzuoli included a visit to the old port of the modern town, nowadays uplifted at ca. 3 m above the sea-level and the Roman Macellum ("Serapis temple"). The 2000-year-old Roman complex was partially submerged after construction, and subsequently uplifted as a consequence of ground deformation following by the late stage resurgence of the Campi Flegrei inner caldera region.

- Thematic sessions (27-28 February 2017) lasted two days, each one including a first part of the program dedicated to invited presentations and a second part addressed to working groups discussion and reports.

8. OUTCOMES OF THE WORKSHOP AND FUTURE PLANS

The workshop was very successful in identifying fundamental questions, research approaches and strategies to be addressed for an Amphibious Drilling Proposal (ADP) dedicated to the Campi Flegrei Caldera. As a result of the presentations and discussion, it was also recognized that the CF-ICDP group made a significant progress between 2005 and 2012 in the understanding of the volcanic stratigraphy, rock properties and caldera formation, by the drilling of 2 pilot holes (namely 500 m and 200 m deep), whereas the CF-IODP group, between 2008 and 2016, acquired a (>5000 km) dataset of seismic profiles that provided the potential for unprecedented spatial and temporal resolution of a whole resurgent caldera system.

Following the reports of working groups, several general points has been afforded, concerning the relevance, and in some aspects, the uniqueness of the Campi Flegrei Caldera as a scientific drilling target with a significance in terms of global perspective.

8.1 Key issues for an ADP dedicated to the Campi Flegrei Caldera

- Why drilling at Campi Flegrei*?*

- *CF is the one of the best examples on Earth of a young, resurgent, highly explosive caldera located at the marine/continent interface (between a back-arc basin margins and adjacent fold and thrust belt) in shallow water (non-oceanic) settings.*
    - Best candidate to reconstruct the magmatic history, dynamic evolution and stress regimes of highly explosive volcanic systems/calderas associated with back-arc basin continental margins;
    - Best site to understand structure and evolution of caldera borders and inner caldera resurgence by integrating onland ad offshore data;
    - Best site to understand role/interaction of sea-level vs. groundwater influence/forcing for a caldera forming and evolution;
    - Primary site to discriminate magmatic vs hydrothermal forcing in the mechanism of caldera dynamics;
    - Primary site to understand the relationships between fissure vs. central vent eruptions in the genesis of ignimbrite deposits;

    - Ideal site to study mixed siliciclastic-volcaniclastic systems in coastal volcanic areas and understand depositional mechanisms of ignimbrite units over continental shelves;
    - Ideal natural laboratory for in-situ calibration of caldera analogue and numerical modeling;

- *It produced some of the largest explosive eruptions in Europe during the Latest Quaternary*.
    - Extremely high volcanic risk (densely populated area);
    - Provides unique opportunity to install long-term borehole observatories to monitor critical parameters, and precursors of volcanic unrest;
    - High potential for improving intercalibration of Quaternary chronology and ash dispersal maps based on tephrochronology of distal marine and continental deposits;
    - May provide new insights into the possible correlation between the Campanian Ignimbrite Eruption (ca. 39 ka) and human evolution (decline of Neanderthals);

- *Ground deformation and volcanic unrest at CF have been historically documented over the last two millennia*
    - Assembling the present-day location archeological indicators and markers to integrate and implement the reconstruction of the caldera dynamics over the last thousand years;
    - Understanding the causes and relations of "long-term" vs. "short-term" caldera dynamics;
    - Understanding the dynamics of past caldera eruptions to assess the hazard potential of future eruptions;

- **Why amphibious drilling at Campi Flegrei?**

- *Need of combining information on the caldera deep structure and associated magmatic-hydrothermal system, deriving from an ICDP action (deep continental drilling) with high resolution data on the shallow structural levels of the caldera and its geological record deriving from an IODP action (shallower offshore drillings)(Fig. 6).*
    - "Onshore-based" (ICDP-leg) drilling targets (3000-3500 m):
        - Physical-Chemical parameters of the Geothermal System for the whole depth;
        - Stress measurements (size and direction) at depth;
        - Mechanisms for magma-water interaction: Hydromagmatism and Control on Unrest episodes;
        - Permeability measurements at depth;
        - Extrapolation of Temperatures in the Supercritical layer to detect the depth of magmatic temperature;
        - Determination of rheological behavior of deep rocks, with main focus on viscous parameters;
    - "Offshore-based" (IODP-leg) drilling targets (200-1000 m):
        - Reconstruction of inner caldera stratigraphic architecture and depositional systems of the caldera fill, down to caldera floor;
        - Structural analysis of caldera borders;
        - Recognition of ignimbritic units offshore;
        - Reconstruction of the recent eruptive history by proximal offshore data;
        - Stratigraphic framework of distal tephra deposits;
        - Reconstruction and timing of resurgence episodes;

- Reconstruction of the deformation (and other precursory) episodes associated to the caldera forming eruptions;
- Paleoenvironmental and paleoclimatic reconstruction of the stratigraphic succession associated with the onset of volcanism;

- *Need of complementing onshore data with the high resolution and preservation potential of the offshore geological record*
  - Need of using complementary morphobathymetric indicators to constrain uplift/subsidence history;
  - Need of marine drilling to understand the significance of offshore hydrothermal vents and/or shallow degassing structures composed of mobilized volcaniclastic sediments vs. submarine monogenetic volcanoes;
  - Advantage of relative sea-level changes record in constraining caldera evolution history;
  - Need of continuous marine record to improve chronostratigraphy of volcanic events onland and unlock the evolution of the inner caldera resurgence;
  - Need of continuous marine record to understand the climatic effects and environmental impacts of large ignimbritic eruptions and recovery of life after deposition of major ignimbritic units and co-ignimbritic ash fall;

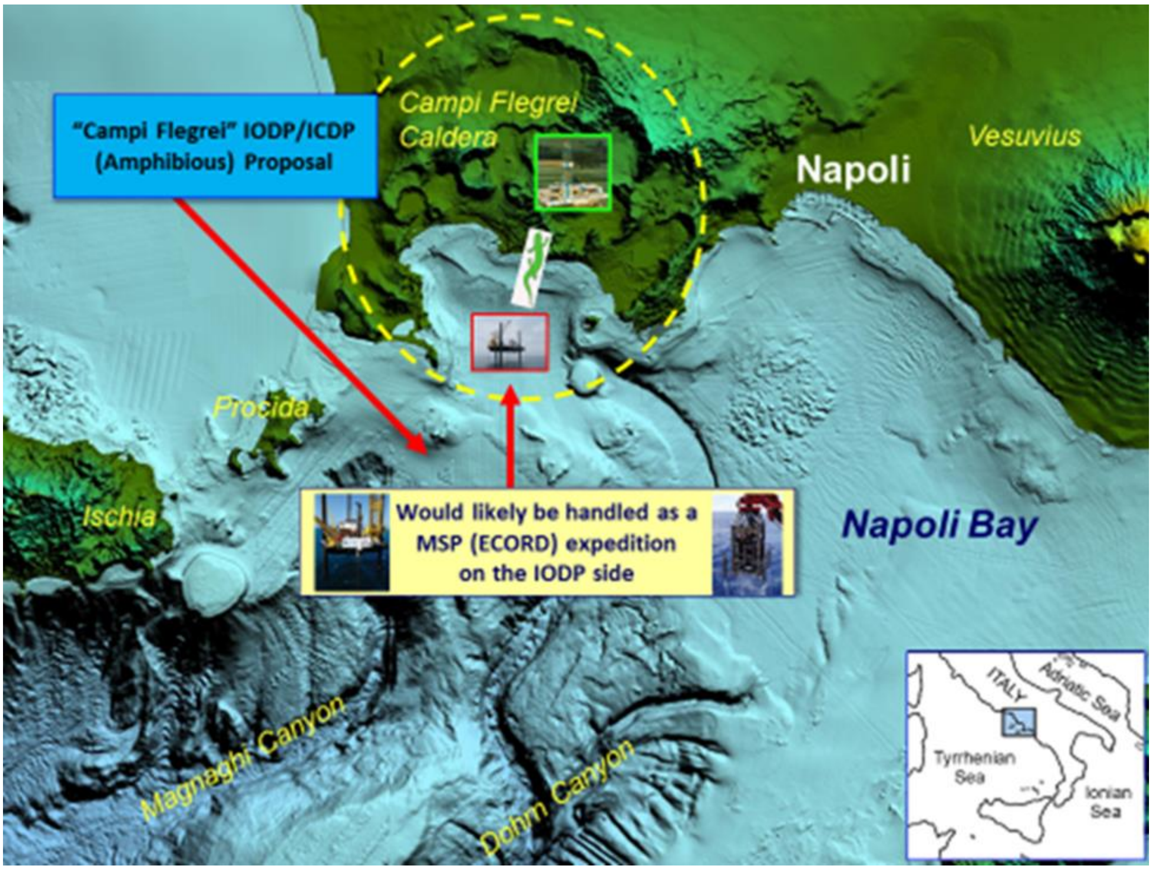

Fig. 6. Location of the planned "Amphibious Drilling Proposal" transect across the coastline of the Campi Flegrei area (NW Napoli Bay).

- Open questions

- When did the Campi Flegrei volcanic history really start?
- What is the relation between Campi Flegrei and ignimbrite volcanism earlier than the Campanian Ignimbrite?
- Did the pre-CI ignimbrites originate from Campi Flegrei?
- Where actually CI super-eruption originated, and did it form the first Campi Flegrei caldera?
- What are depositional mechanisms of ignimbrite flow units over continental shelves?
- What have been the environmental consequences of ignimbrite volcanism in Campania?
- What is the nature and significance of offshore shallow degassing structures composed of mobilized volcaniclastic sediments/submarine monogenetic volcanoes?
- What is the complete distal record of major eruption associated with the Campi Flegrei?
- Why did Campi Flegrei form a large caldera?
- Is the syn- and post-collapse surface deformation confirmed by the architecture of the ring-fault system?
- Is the existence of a subcircular caldera and associated magma at depth, a necessary and sufficient condition to explain the onset and evolution of ground deformation?
- How are magma and fluids transported to shallow depths?
- How do intrusions and hydrothermal system contribute to deformation?
- Can long-term evolution constrain evaluation of short-term hazards (an vice-versa)?
- What drives long-term resurgence?
- How does resurgence occur (times, rates, conditions)?
- What drives short-term unrest?
- Are resurgence and unrest related? If yes, how?
- How the syn- and post-collapse surface deformation is confirmed by the architecture of the ring-fault system?
- Can the fluid transportation modes (hydrothermal and also magma) from their storage to the shallow, reflect the differences between different faulting styles within the main caldera ring-fault system?

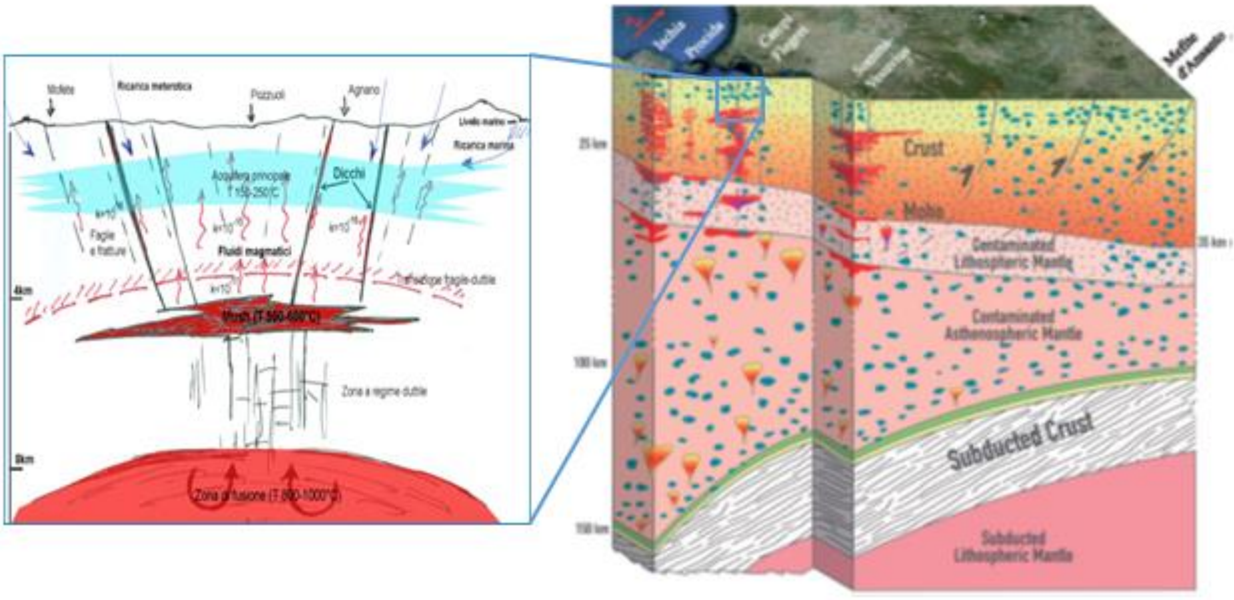

Fig. 7. Structural levels involved by the formation of the Campi Flegrei Caldera.

- <u>Main themes</u>

- *Time scales* (Tab.1)
- *Forcings – external vs internal*
- *Magmatic environment*
- *Environment impact (hazards and climate/eco system)*

Tab. 1. Conceptual frame of research themes for the Campi Flegrei ADP

Timescales	Forcings	
	Internal	External

• Active – historic
  • Unrest, restlessness
  • Eruptions
	Fluids
	Hydrothermal
	Magmatic (shallow/deep)
		Sea Level
		Tectonic

• 10^3 to 10^4
  • Post-caldera recovery, Resurgence
  • Uplift, eruptions
	Magmatic (shallow)	Sea Level
		Tectonic

• $10^5 – 10^6$
  • Volcanic, magmatic history
  • Cyclicity, Periodicity
	Magmatic (Flare-up)
	Crust/Mantle
		Tectonic
		Sea Level?

- General approach

- *Going big - probing the source at Campi Flegrei, Estaern Tyrrhenian Margin*
  - More in situ data are needed on sub-surface magmas and their surrounding hydrothermal and host-rock shells;
  - Boreholes serve as the best observatories we can develop, with far superior signal to noise of geophysical data than is available at the surface;
  - Confirm conceptual models, intensive variables, fluid compositions, and rock properties near and within the magma:
    - the spectacular inflations and deflations of calderas appear as commensurate and synchronous changes in the temperature, pressure, and flow rates of hydrothermal fluids;
    - might track changes during intrusive episodes by observing real-time seismic velocity changes in the materials in between two drill-holes (using one as a source and the other as a receiver);

- Historical support

- *Kakkonda in Japan revealed the steep permeability and lithological gradients where magmatic and hydrothermal regimes interact (Saito et al., 1997);*
- *The IDDP-1 well at Krafla in Iceland intercepted rhyolite melt in the region where geophysics had implied it would be absent (Elders et al., 2011);*
- *In the Long Valley;*
- *Exploratory Well in eastern California a maximum temperature of ~100 °C was measured where the presence of shallow magma or at least very hot rock was assumed prior to drilling;*
- *Actual solidifying magma reservoir were provided by the USGS drilling into the 1959 lava lake at Kilauea Iki, Hawaii;*

- Preliminary criteria for the selection of Cami Flegrei ADP sites

It was agreed, as an outcome of the workshop, that the best drilling strategy would include 1-2 major onshore drilling(s), complemented by an ideal amphibious drilling transect extending from the Campi Flegrei shoreline towards the offshore, as far as distal drill sites in the Adriatic and/or Ionian Seas

- *Onland (ICDP) site(s)*
    - Site CFDDP-01 – The main ICDP proposed site includes a deep drilling of the whole caldera structure throughout a deviated 3,0 -3,5 long well directed from the eastern border of the caldera towards the caldera center at depth.

- *Offshore IODP (offsite(s)*
    - site CF-01 - caldera centre, in order to sample the tectono-stratigraphic interval(s) likely involved in the late stage caldera resurgence and penetrate the structural floor of the CF caldera (ca 0.8 km);
    - site CF-02 additional, (optional, or alternate) along-transect site within the NYT caldera collapse, in order to drill the caldera fill at site of minor stratigraphic thickness (0.8 - 0.6 km approx.);
    - site CF-03 is planned to drill and understand the nature of shallow intrusion likely representing mobilized sediments mixed with fluids coming from degassing magma (Pampano-Monte Dolce structure);
    - site CF-04 intended to drill the external rim of the CF caldera and penetrate a relatively complete stratigraphic section (Monte di Procida-type, eventually including old domes or intrusions) at shallower depth (0.6 - 0.5 km approx);
    - site CF-05 drill site located outside the CF caldera collapse, in order to sample a reference stratigraphic sequence and detect all major ignimbritic units (0.8 -0.9 km)
    - site CF-06 intended to penetrate a reference Quaternary stratigraphic section at median distance and relatively undisturbed location. The site has been selected in order to drill through 0,3 km of Quaternary sediments;
    - sites CF-07/09 shallow drill holes (0.2 - 0.1 km) planned at distal site locations, in order to get the signature of major explosive events (a "high-frequency filtered" stratigraphic record of ash layers) of the entire Campania volcanic district. This drill sites would also yield information on large scale (regional) dispersal areas that are crucial for the reconstruction of the dynamics and evolution of eruptive events at regional scale;

- Future actions

1) Submission of a full IODP proposal (ADP) dedicated to the drilling of the Campi Flegrei Caldera by 1 October 2017 or 1 April 2018.

2) Update of the already approved ICDP proposal (Campi Flegrei Deep Drilling Project) to fit the requirements of ADP dedicated to the drilling of the Campi Flegrei Caldera by 15 January 2018.

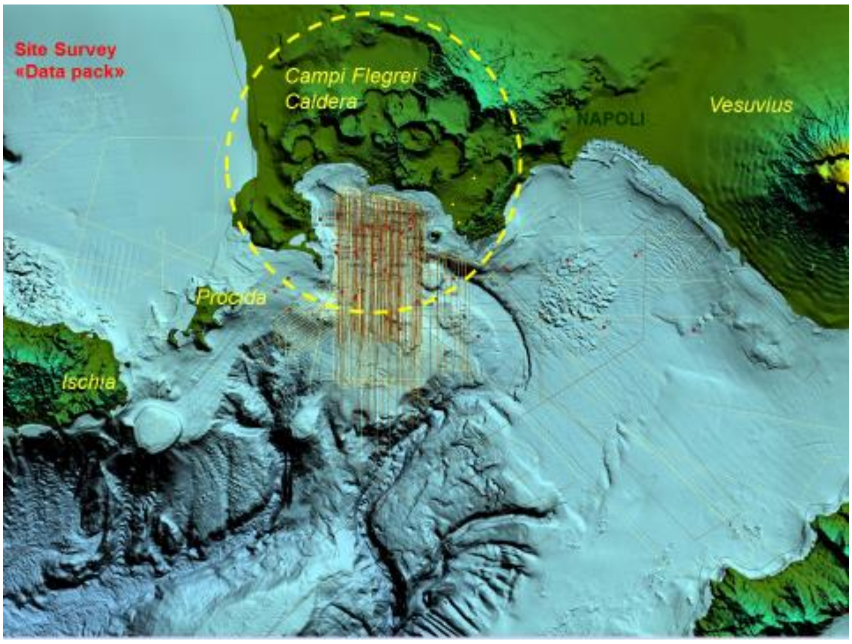

Fig. 8. Site survey pack (reflection seismic profiles and gravity core data) available to support the IODP component of the Campi Flegrei drilling proposal.

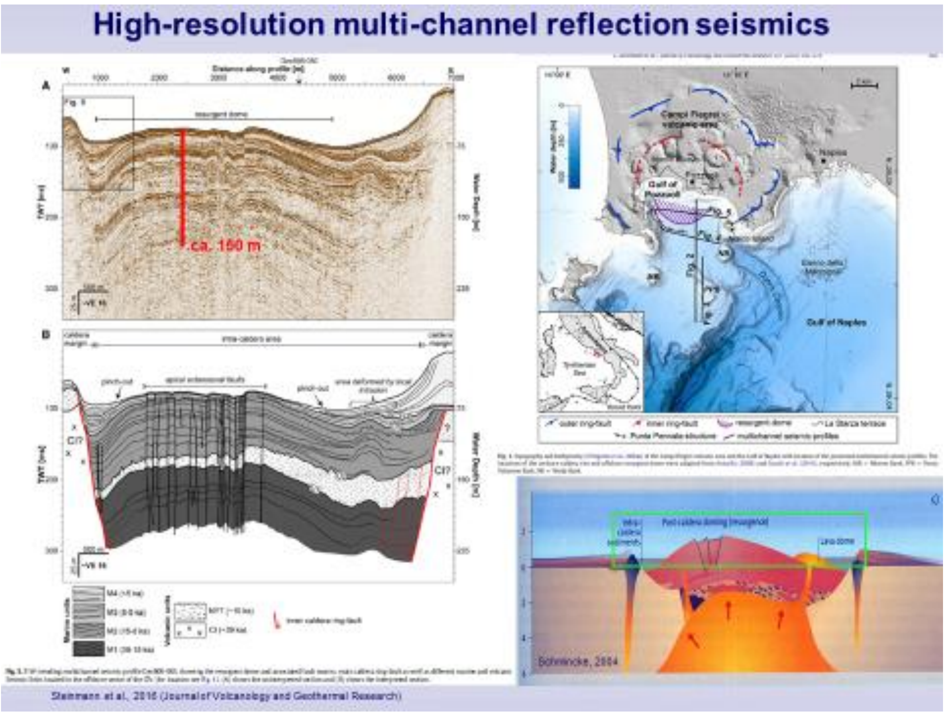

Fig.9. High-resolution multi-channel reflection profile showing the Campi Flegrei Caldera resurgent dome (from Sacchi et al., 2009 and Steinmann et al.,2016).

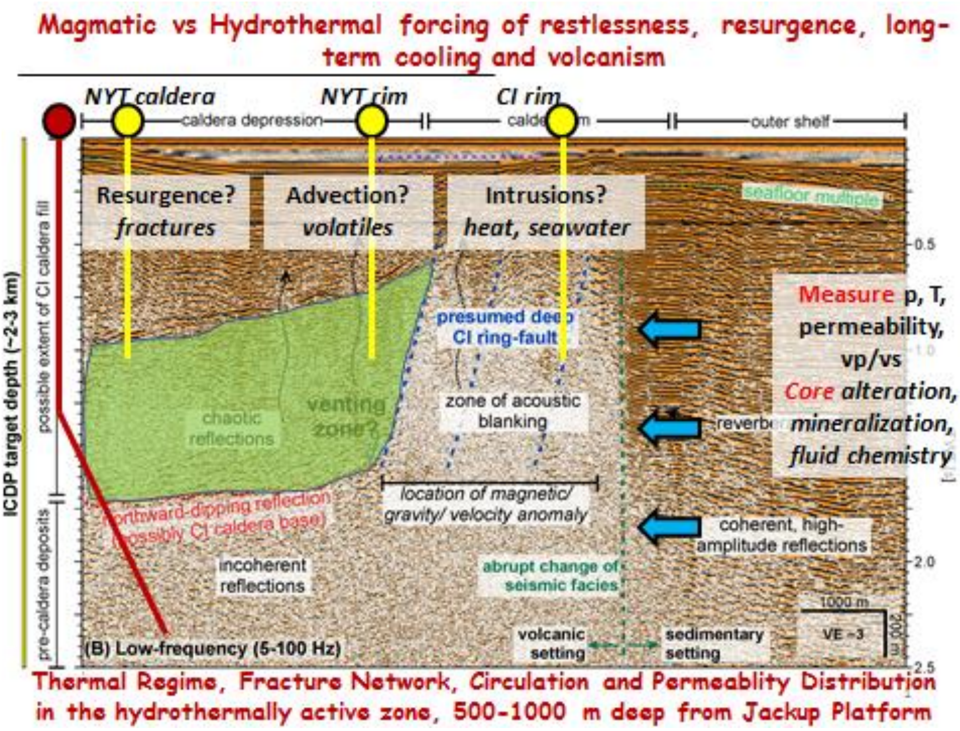

Fig.10. Structural levels and processes relevant to the offshore component of the Campi Flegrei Amphibious drilling proposal.

9. SPENDING OF THE MAGELLAN PLUS GRANT

The MagellanPlus workshop funds were € 14,952,63, with additional funding from separate Italian (INGV, Napoli and IAMC-CNR, Napoli) grants and in-kind contributions. Integrated funding enabled participation of scientists regardless of their country of origin, a wider range of scientific expertise and more participation from early career scientists (including PhD students). The table below provides details of expenditure for the organization of the event (Tab. 2).

Tab. 2. Summary of costs towards the organization of the Campi Flegrei MagellanPlus Workshop (Napoli, Italy 25-28 February 2017).

Item	Cost (€)
Catering service and wireless internet service	5.445,00
Travel Agency service and field trip bus	9.396,13
Supplementary material for the meeting room and field trip logistics	111,50
Total Magellan Plus financial support	**14.952,63**

INGV-Napoli financial support (approx.)	8.000,00
TOTAL EXPENDITURE	**22.952,63**

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