Simultaneous eruptions from multiple vents at Campi Flegrei (Italy) highlight new eruption processes at calderas

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METHODS

Nomenclature

The tephra sequence explored in this work has been divided into 5 main units (U1 to U5), mainly based on tephra sedimentological characteristics (color and grain-size variations), consisting of an alternation of accretionary lapilli-bearing, ash layers with scattered pumice fragments.

The Averno 2 tephra sequence has been divided (Di Vito et al., 2011; Fourmentraux et al., 2012), from base to top, into three Members, namely A, B and C. The lower part (Member A), has been divided in six fallout sub-members (A0 to A5) interlayered with thin, fine-grained surge deposits. A2 sub-member, which represent the climax of the eruption, has been further divided into a basal (A2b) and a top (A2t) layer. The intermediate part (Member B) consists in a complex sequence of surge bedsets intercalated with minor fallout deposits, with sample Bt representing one of the fallout bed of the upper portion of the member. Finally, Member C represents the final stage of the eruption mostly consisting in surge beds; Cmb represents a thin fallout bed within the lower portion of the member. For the sake of simplicity, we tried to preserve this existing nomenclature (Di Vito et al., 2011; Fourmentraux et al., 2012) by
modifying it only to simplify unnecessary details. We divide the Averno 2 eruption into three main phases: i) opening phase (corresponding to Member A0 in Di Vito et al., 2011), ii) intermediate phase, which includes the peak fallout deposit (A2) followed by a PDC and minor fallout phase deposits (member B); iii) final phase (PDC and minor fallout deposits of Member C).

Field data collection

Field data collection was carried out during different surveys, which allowed detailed stratigraphic reconstructions of the two eruptions. Although stratigraphic sections in which the two eruptions are clearly intercalated are few, the work benefited from the years-lasting stratigraphic and petrological work on the reconstruction of the two single eruptions. In the stratigraphic survey, about 10 natural sections were investigated. At each site, a detailed stratigraphic log of volcanic succession was measured and described. All information (global positioning system [GPS] coordinates, photos and field notes) was stored in geographic information system (GIS) format, on a digital topographic base. Several tephra sections, where the deposits of the Averno and Solfatara eruptions are interlayered, were studied with joint field activities involving all the authors. Among these stratigraphic sections, one was particularly valuable thanks to its preservation and was selected for detailed sampling (33T 425942 4520976 UTM).

Two compositional end-members emitted during the opening and final phase of Averno 2 eruption were analyzed as reference samples. A0, representing the opening phase, was collected at La Torretta (33T 420909 4520782 UTM) while sample Cmb, representing pumice clasts 19-cm thick fallout layers in the middle portion of member C were collected at La Schiana (33T 422613 4522150 UTM). The reference sample from the proximal Solfatara sequence (SF12_4) was collected on the northwestern side of the crater area (33T 426804 4520436 UTM).
Grain-size analyses

Collected samples were dry-sieved for grain-size analyses with a set of sieves with 0.5 phi (ϕ) interval from -6ϕ to fine ash particle (≤6ϕ, where ϕ=−log diameter of the particle in mm) at Dipartimento di Scienze della Terra of Pisa (Italy). The presence of a significant amount of fine ash in most of the samples required the use of a laser particle size analyser (Mastersizer 2000, Malvern; CNR-ISE Pisa) on the finest fraction (<32 µm). Grain-size data are reported in Fig. DR4.

SEM-EDS analyses

Pumice fragments (including some accretionary lapilli) were separated from the -0.5ϕ (1.4–2 mm) and -2ϕ (4–5.6 mm) grain-size fractions, mounted on double-adhesive tape on a glass slide and embedded in epoxy resin for morphological scanning electron microscope (SEM) observations and energy-dispersive spectroscopy (EDS) analyses on residual glass. From the coarsest bed at the base of the section, 13 lapilli-sized clasts (from 2 to 6 cm) and one bomb (10 cm) were also analyzed. Analytical conditions were 20 keV accelerating voltage, 0.1 nA beam current and a working distance of 10 mm. We used a raster window of about 10×10 µm² to avoid Na migration under the electron beam during analysis. The analytical error is 1% for concentrations higher than 15 wt%, 2% for 5-15 wt%, 5% for 1-5 wt%, and 30% for <1 wt%.

Before each session of analyses the quality of SEM EDS analyses was checked using CFA47 trachytic, ALV81R23 basaltic, and KE12 pantelleritic glasses as internal reference standards. Information about precision on each oxide, accuracy and standards used are reported in Table DR1, in which all EDS analyses are reported; in Fig. 2 only averaged data of multiple analyses collected on the same clast are reported.
LA-ICP-MS analyses

LA-ICP-MS analyses of the Solfatara and Averno samples were performed using a Thermo Scientific iCAP Qc ICP-MS coupled to a Photon Machines analyte 193 nm eximer laser ablation system with a Helix two-volume ablation cell at the department of Geology, Trinity College, Dublin. We used 36 and 30 µm laser spots, depending on the size of glass areas available for analysis in individual samples. The repetition rate was 5 Hz and the count time was 40s (200 pulses) on the sample and 30s on gas blank (background). Concentrations were calibrated using the NIST613 external standard with $^{29}$Si as the internal standard. Data reduction was performed manually in Microsoft Excel allowing for the removal of signal compromised by microcryst inclusions. Full details are presented in Tomlinson et al. (2010). Accuracies of analyses of the ATHO-G and StHs6/80-G MPI-DING glasses are typically <5 %, standard data is presented in the supplementary material. Relative standard Errors (% RSE) for tephra analyses are typically <5 % for Y, Zr, Nb, La, Ce, Pr, Nd, Th and U; and <7% RSE for Rb, Sr, Ba, Sm, Eu, Dy, Er, Yb, Lu, Hf, Ta. Full errors (standard deviations and standard errors) for individual samples are presented in Table DR2.
Figure DR1. Shaded relief map of the Campi Flegrei caldera with the Averno 2 and Solfatara volcanoes highlighted in red and the new studied stratigraphic section indicated by a red star. Green dots represent the locations of the reference samples for Averno 2 (1 – La Torretta; 2 – La Schiana) and Solfatara (3 – SF12_4).
Figure DR2. (A) Chronostratigraphic section of volcanism younger than 15 ka at the Campi Flegrei caldera, and a detailed section for the volcanic events younger than Agnano Monte Spina (about 4.5 ka); modified after Isaia et al. (2009). (B) Solfatara-Averno 2 stratigraphic section studied in this work. Tool on the left for scale is 30 cm. (C, D) Details of the two types of accretionary lapilli found in Unit 3.
Figure DR3. The key section where Solfatara and Averno 2 deposits are interlayered. The main characteristics of each unit are described on the left.

**Unit 5**: 7-cm thick, medium-ash bed pinkish in color, humified in its uppermost 3 cm. This bed is slightly coarser and poorly sorted at the base and well sorted at the top, and bears scattered accretionary lapilli.

**Unit 4**: 18 cm-thick alternation of greenish and light grey (in the lower part of the unit), and yellowish to pinkish in color (in the upper part) ash beds (E). The upper part is represented by a 1.5 cm-thick poorly sorted bed of fine-lapilli, pinkish in color and mostly made up of pumice fragments.

**Unit 3**: 48 cm-thick, stratified, greenish coarse- to medium-ash deposit, showing fraction structures in its middle part. The grain-size distribution is polymodal due to the presence of abundant accretionary lapilli, which represent the coarsest sub-population contained in the loose ash fraction. Accretionary lapilli either have a green ash core with yellowish rim or are composed of yellowish-green concentric layers with a light-colored core (C, D and S2).

**Unit 2**: 12 cm-thick, reversely graded yellowish ash bed, with rare lapilli fragments in the upper part.

**Unit 1**: 17 cm-thick, medium-coarse, accretionary lapilli-bearing, well-sorted greenish ash bed, interlayered in its lower part with seven light-colored, yellowish, fine-ash laminae (B). Scattered lapilli- to bomb-(oversized (up to 15 cm) pumice fragments, which cover the first two ash laminae and strongly contrast with the grain-size of the whole sequence.
Figure DR4. Stratigraphic sequence with grain-size analyses of the collected samples. Pink bars in grain-size histograms refer to classes where accretionary lapilli were clearly identified.

Table DR1. SEM-EDS major analyses of the analyzed samples. Standards are also reported.
Table DR2. LA-ICP MS trace elements of the analyzed samples. Standards are also reported.

Table DR3. Timing of eruptive events and corresponding tephra units.

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<thead>
<tr>
<th>Unit</th>
<th>Solfatara Activity</th>
<th>Averno Activity</th>
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<tbody>
<tr>
<td>U5</td>
<td>Probably the Solfatara activity ends slightly before that of Averno</td>
<td>=</td>
</tr>
<tr>
<td>U4</td>
<td>Ash fallout</td>
<td>Last phase of the eruption (Member C)</td>
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<tr>
<td>U3</td>
<td>Magmatic/phreatomagmatic phase, PDC</td>
<td>Low level activity at the end of Member B phase. Two types of accretionary lapilli</td>
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<tr>
<td>U3</td>
<td>generation, breccia and stratified ash deposits</td>
<td>Ash-laden plumes during the emplacement of PDC deposits of Member B</td>
</tr>
<tr>
<td>U2</td>
<td>Pause between first and second phase</td>
<td>Explosion mostly driven by Magmatic explosions. Eruptive</td>
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<tr>
<td>U1</td>
<td>Hydrothermal fluids. Deposits with limited dispersal. Phreatic breccias close to the vent</td>
<td>The 2 eruptions begin almost simultaneously</td>
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<tr>
<td>A2t</td>
<td>Interlayered with the upper part of U1</td>
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Additional references

