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Peer Review File

Coupled earthquakes and resonance processes during the uplift of Campi Flegrei caldera

Corresponding Author: Mr Giacomo Rapagnani

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Mr Rapagnani,

Your manuscript titled "Coupled earthquakes and resonance processes during the uplift of Campi Flegrei caldera" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

The following two thresholds, in particular, should be met in the new version of the paper:
1) please take into account the structural complexity of the caldera;
2) please explain how the frequency of the signals can be fixed, considering the stiffness dependence on fluid flux changes, justifying why only the strongest events are taken into account.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Domenico M. Doronzo, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-6866-8870

Carolina Ortiz Guerrero, PhD
Associate Editor
Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Dear Editor,

I have now completed the revision of the manuscript entitled “Coupled earthquakes and resonance processes during the uplift of Campi Flegrei Caldera” by Rapagnani and colleagues.
This article deals with the analysis of VT seismicity from 2014 onwards, which has been a very hot topic in the last few years in the literature of Campi Flegrei. The authors have analyzed a large dataset (>14000 events) and extracted the largest one (136 events). For these selected events, they have calculated the focal mechanism based on the moment tensor inversion. I underline that this is a remarkably high number of focal mechanisms, and above all, they are very consistent with each other. Based on the similarities among the waveforms, the authors have been able to identify different clusters of events whose moment tensor solutions are remarkably consistent. Apart from this, there is a new and relevant element of novelty introduced in this work by the authors. As far as I am concerned, the authors report for the first time the occurrence of VLP (Very Long Period) events superimposed on the VT earthquakes. While LP events are not a novelty (these are even reported in the surveillance bulletins), this is the first report of VLPs. This VLP signal is monochromatic and overlaps with the seismic signal of the largest VT events, regardless of their origin time and hypocentral location, and it is well evident when the raw signal is filtered with a low-pass filter. Their interpretation is that this signal is produced by the resonance of pressurised fluid-filled cavities located above the most uplifted area, whereas these signals are often associated with magma movements at greater depths. Therefore, the VLPs would represent a by-product of the VT events. Hence, this work might represent a significant advancement in the comprehension of interconnected processes occurring in this escalating phase of unrest at Campi Flegrei.
The manuscript is well-written and concise, the figures are of high quality and informative. The authors should only ensure that the minimum font size per journal prescription is employed, as it is too small in most of the figures. The supplementary material is pertinent, comprehensive, and adequately recalled in the text. My overall judgment is positive, although I have some minor/moderate concerns highlighted in the manuscript file, especially about the geometry of the resonator. For instance, why attempt to approximate the centroids of VLPs to a single, large crack instead of thinking of a network of fractures? I state this considering the very complex volcano-tectonic structure of the caldera. On the same line, I am also convinced that the literature referencing the structure of the volcano should be expanded, and the differences/improvements with the previously published papers should be highlighted. I have found that there might be too little reference to previous works and that those dealing with the geology and structure of the volcano are too scarce too. This is an important point because there is an outstanding correspondence between mapped volcano-tectonic structures and computed focal mechanisms, in terms of strike, dip angles and kinematics. Hence, it might be worth it for the authors to add in Figure 3, for instance, the comparison with caldera and VT structures, which have been already proven to match remarkably with relocated seismicity. I have proposed some suggestions in this regard.
I have annotated some constructive comments and suggestions to improve the text and the figures, which can be found in the attached PDF file.
Finally, the paper shows promising potential to represent a significant advancement in the interpretation of seismicity associated with the current unrest.
Based on my review, I suggest that the article be considered for publication pending minor/moderate revision.
Best regards

Reviewer #2 (Remarks to the Author):

Dear Editor, please find here my review of the research manuscript entitled “Coupled earthquakes and resonance processes during the uplift of Campi Flegrei Caldera” submitted by Rapagnani and co-authors for possible publication in Communications Earth & Environment.
The research paper targets Campi Flegrei, one of the best studied calderas worldwide, source of major risk at local, regional and global scale. Their study fits in a very rich and complex set of multidisciplinary researches aiming at better constraining the source(s) and the evolution of the current unrest. The authors perform an analysis of the earthquake source mechanisms and highlight the spatial distribution of volcano-tectonic events associated with brittle failure of the caldera faults and propose for the first time the occurrence of very long period signals (VLP). They suggest that the source of VLP events is located a ca 4 km depth and corresponds to a single oscillating fissure with constant volume and physico-chemical properties of the filling fluids. The authors propose that the vibration of the resonant source is excited by energetic VT events.
As the study is focused on the most energetic double couple VT events and weaker events or non-double couple component VT are not studied, the correlation is in some way biased.
Signal analysis suggest that the start of VT and VLP event is synchronous; as the location of the VT is variable with respect to the resonant source, the authors should discuss if a variable time shift is expected and if this time shift is observed on stations at increasing distance from the oscillating source.
The focus on the strongest VT events does not permit to assess if an energy threshold exist to trigger the VLP events. Most important, one could argue the reverse, that is that fluid flux variation induce change in the pressure source that in turns triggers the VT seismicity……..ideally, the link between VLP and LP should be discussed and with non-double couple events.
On the high intensity side of the spectrum, are regional eartquakes able to trigger the same resonance?

The authors could therefore show some examples of VT which are not associated with VLP.
A second and main concerns is the interpretation of the fixed frequency in the amplitude spectra of the signals. For a given vibration mode, the frequency depends not only on the crack geometry (length L and width d) but most important on the crack stiffness C = bL/ d (b= bulk modulus of the fluid, and shear modulus of the solid. The unrest phase is associated with an increase in flux of fluids with increasing equilibrium temperature (temperature at depth). A change in both shear modulus (because of heating) and most important a major change in bulk modulus of the fluid (because of the change in temperature, density and sound velocity of the fluid) is expected. As bulk modulus depend on the square of fluid sound velocity, even moderate increase in temperature and pressure of the fluid translate in large change of the crack stiffness (see for instance Maeda et al., 2017 or Journeau et al., 2024 for similar applications).
This is in my opinion the main part to be addressed in the date interpretation, how can the frequency remain the same over years if the properties and the flux of the fluid change? Conversely, should we conclude that the change observed in the fluid properties are not associated to modification of the fluid properties and flux in the oscillating fissure?
In conclusion, I consider the topic very relevant and the study important, but it deserves a set of clarification before final publication.
Best regards,

Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Mr Rapagnani,

Your manuscript titled "Coupled earthquakes and resonance processes during the uplift of Campi Flegrei caldera" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Domenico Doronzo
Editorial Board Member
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Joe Aslin
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Communications Earth & Environment

Consulting Editor,
Communications Sustainability

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Dear Editor,

I have now completed the second revision of the manuscript by Rapagnani and co-authors, “Coupled earthquakes and resonance processes during the uplift of Campi Flegrei Caldera.”
The Authors have satisfactorily addressed most of the concerns raised in the previous round of revision. I have appended below just a few minor suggestions to the manuscript, figures, and supplementary material. The determination of the reconstruction of the geometry of the resonator still seems unclear to me and needs further improvement. I endorse the publication of this article following these minor interventions.
Best regards

Line-by-Line comments:
Line 40: I suggest rephrasing as follows: “After the last eruption in 1538 CE, the state of the volcano has been characterized by ground deformation […]”
Line 68: I suggest rephrasing “were never reported before” to “are yet to be reported”.
Line 74: brittle failure occurring along <the several activated structures, including the ring fault system> that borders […].
Line 94: I suggest rephrasing as follows: “with depths ranging from 2.3 to 4.2 km.”
Figure 2a: I suggest the Authors add here the supplementary Figure 10, which is very informative and would help the reader to clearly appreciate the difference between VT and VT+VLP signals.
Line 177: add within brackets the corresponding Md of the May 20th event.
Line 141-142: add within brackets the acronym “CLVD”.
Line 143: This description seems contradictory to what is shown in Figure 5. If you are referring to the resonator as a crack defined by the VLP event locations, with "oriented NNW-SSE" a reader can easily understand that this is the azimuth of the major axis of the ellipse. However, looking at Figure 5, the major axis seems perhaps WSW-ENE. Please clarify and add in

the figure the surface projection of the inferred resonator.
Line 222: Add information about the inferred width of the resonator, e.g., “~ xxx m wide, ~1000 m and a thickness of ~0.35 m; this corresponds to crack […].
Line 236: General comment: the very short delay between VT onset and VLP onset does suggest that it is specifically the P wave arrival that perturbates the resonator?
Line 241: General comment: from lines 223-224, it seems that the spatial extent of the crack is rather small and not sub-vertical. That recalls my comment in the previous round of revision to which the Authors have responded stating that “the spread of VLP locations as a measure of the resonator size, but rather we average the results to estimate the source location and geometry.” Hence, if the spatial distribution of the VLP events is not used to constrain the geometry, the Authors should clarify how they constrain the location and geometry of the resonator.
Line 249: change from “gases” to “fluids”.
Figure 5: Two comments on this figure, which depends on the completeness of the supplementary material. In particular, the authors should add a tag/note on each of the reported events indicating the cluster to which the event belongs. For completeness, the hypocentral locations of the VLP events, eventually with associated uncertainties, should be reported. In Figure 5a, the ellipse embraces the VLP events, but the geometry of the resonator reported in Line 211 is not shown. In Figure 5b, the VLP hypocenters should be shown following their display in Figure 5a.
Lines 340-341: “cm3”. Use superscript for “3” instead of “^”.
Line 342: How has the value of ~20 GPa been estimated? Shear modulus strongly depends on Vs and density.
The caption of Supplementary Figure 9: CO2, 2 subscript.

Reviewer #2 (Remarks to the Author):

Dear Editor, I consider that the authors provided a detailed set of answer to all remarks and suggestions I submitted during the first review round.
However, some (minor) clarification is still needed about the choice of parameters adopted for crack modelling and their implications for the crack geometry. The assumed density of the rock matrix (3 g/cm3) is quite high with respect to the lithotypes expected at Phlegrean fields (tuff, carbonate); could the authors please provide a reference and explanation for this choice?
The selected density of the fluid (0.56 g/cm3) correspond to a temperature of 430 °C for a pressure of 1 kbar (about the depth of the resonant crack); however, the choice of different temperature will correspond to a different density; how did the author constrain the chosen set of P/T to calculate the fluid density?
Moreover, at a density of 0.56 g/cm3 (and in the reported pressure range), the expected sound speed is 0.64 km/s and not 0.46 km/s (a typo?), as reported by the authors.
I consider the current version of the manuscript can be considered for publication, after the minor clarifications here proposed;
Best regards

Coupled earthquakes and resonance processes during the uplift of Campi Flegrei caldera

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Abstract

The Campi Flegrei caldera is a large volcanic complex, with a long history of volcanic activity, located beneath the metropolitan area of Naples, Italy. It is characterised by an intense hydrothermal activity, episodes of localised ground deformation and earthquake swarms. The ongoing unrest, which began in 2005, triggered by a degassing magma source and subsequent magmatic-hydrothermal interactions, reached an uplift of ~1.4 m. The seismicity increased exponentially, with a maximum magnitude Md 4.4 in 2024-2025, the largest ever recorded. Here, we perform a comprehensive analysis of earthquake source mechanisms and waveform similarity. Alongside the abundant shallow volcano-tectonic (VT) earthquakes, associated with brittle failures along the rim of a former caldera structure, we analyse newly observed very long-period (VLP) signals. The VLP source is located at a depth of ~3.6 km between the proposed inflation source and the Solfatara tuff cone, a massive volcanic degassing centre with an increasing CO_2 flux. The resonant source, excited by VTs at different locations, illuminates a sub-vertical, gas-filled fracture that has been emplaced over at least 6 years, connecting the inflating reservoir with the shallow brittle processes and surface fumaroles.

Introduction

Calderas are among the most cryptic volcanic environments, with prolonged unrest episodes that might span decades without necessarily ending in an eruption[1,2]. Eruptive centres from previous activities may be scattered over large areas, challenging the prediction of future event locations[3]. The location and state of magmatic reservoirs beneath calderas are often hard to detect due to the presence of shallower hydrothermal systems that hold heated and pressurized fluids of magmatic and non magmatic origin. Hydrothermal fluid changes in composition, flow-rate and pressure may be an efficient driver of geophysical and geochemical signals, masking the contribution from a deeper primary magmatic source[4]. Located in southern Italy, the Campi Flegrei (CF) caldera is a prominent example of such complexities. With a diameter of approximately 12 km, CF extends to the west of Naples and is home to ~500,000 residents. CF features a complex, nested caldera structure formed by the repeated collapse of shallow magmatic reservoirs which fed more than 70 eruptions over the past ~15,000 years[5].

After the last 1538 eruption, the primary volcanic activity has been ground deformation, so-called bradyseism. This involves rapid uplift accompanied by vigorous seismicity, followed by slower, aseismic deflation. After the major 1982-1984 bradyseismic crisis[6], CF entered a prolonged quiet phase with slow deflation and minimal seismicity. Ground inflation resumed in 2005, progressively increasing until reaching a net uplift of ~1.4m by early 2025[7]. Simultaneously, seismicity has intensified, with a peak in event rate and magnitude in 2024-2025, featuring over 1000 events/month and a maximum magnitude Md=4.4[8]. The current ground deformation exhibits radial symmetry, with the greatest uplift centred in the coastal area of Pozzuoli, ~2 km west-southwest of the most active seismic zone (*Fig. 1*). An exponential correlation between uplift and earthquake frequency indicates a causal relationship[9]. Given the increased seismicity, the seismic hazard has been recently re-assessed, considering magnitudes reaching Mw 5.1[10].

Ground deformation in volcanic environments is caused by changes in pressure within a subsurface reservoir that hosts magmatic and/or hydrothermal fluids[11]. At CF, the deformation source of the current unrest has been located at ~4 km beneath the centre of Pozzuoli, where the largest uplift is measured[12]. Although the nature of the fluids contained therein remains debated[12-15], seismic tomography reports a low Vp, low Vp/Vs anomaly[16], suggesting the presence of non-magmatic fluids in supercritical state[17]. Tomographic images of seismic velocity[16,18] and attenuation[19] also image a low permeability, high-strength caprock layer at 1.5–2 km depth. That layer would inhibit the upward propagation of fluids, causing the over-pressurization of the underneath formations which constitute the main deformation source. The peculiar mechanical properties of the caprock layer would allow the system to accommodate large strain[20], while the temporal succession of fracturing and self-sealing would regulate the fluid transfer to the shallower hydrothermal system, thus explaining the alternance of inflation and deflation episodes[21].

Shallow seismicity below 5 km depth at CF is characterized by volcano-tectonic (VT) events, representing brittle failure of faults and fractures in response to ~~tectonic stress, superposed to the~~ local stress perturbation introduced by the deformation source. Until now, focal mechanisms were estimated for a few tens of VTs only[22,23]. Long-Period (LP) signals (dominant period within the range 0.2 - 2 s)[24] were rarely observed at CF[25], and interpreted as the response of the shallow hydrothermal system to the injection of hot fluids from below[26], while Very-Long-Period (VLP) signals (period > 2 s)[27] were never reported before. LPs and VLPs, observed at many volcanoes globally[27], are generally attributed to the dynamics of buried cavities filled by magmatic or hydrothermal fluids and represent a formidable tool for understanding the processes at play within a volcano. The latest seismicity crisis provides an unprecedented wealth of VT earthquakes. Their source analysis offers new insights into the geometry of active seismogenic structures. Furthermore, we report for the first time VLP oscillations accompanying VT earthquakes. In our interpretation, these signals represent the dynamic response of a fluid-filled fracture to the transit of seismic waves generated by brittle failure occurring along the ring fault system that borders the inner caldera structure.

VLP signals at Campi Flegrei

The seismic signals of the 136 largest earthquakes at Campi Flegrei are characterised by clear P and S onsets, corresponding to so-called VT earthquakes. However, we observed that many of these VTs, regardless of their epicentral location, depth and origin time, are accompanied by a clear, low frequency signal (*Fig. 2a*). This signal, to which we refer here as very long period (VLP), is monochromatic, with a dominant frequency of ~0.1 Hz, and smoothly decay in amplitude with a duration of 1-2 minutes. This type of seismic signals, often recorded at volcanoes and interpreted as the result of resonance processes, involving cracks, sills or reservoirs with different geometries, were never observed at Campi Flegrei. The analysis of their focal mechanisms and dominant frequency can help to investigate the geometry, size and fluid composition of the reservoir. The VLP signals are well visible in the frequency domain (*Fig. 2b*), showing a clear spectral peak at ~ 0.1 Hz, and best recorded at stations located less than 10 km from Pozzuoli and, in a few cases, at larger distances. The VLP signals are emergent, lacking clear P onsets and overlapping with the VT signal, which makes it difficult to locate their source. However, the maximal amplitude of VLPs is consistently observed at stations located in Pozzuoli (*Suppl. Fig. 1*), this observation, as well as the high waveform similarity among VLPs (*Suppl. Fig. 2*), suggests they are produced by a common source, independently of the corresponding VTs, which have different locations. In this work, we analysed 14 VLP signals showing highly similar dominant frequencies and durations. They occurred from 2018 to 2025, taking place in different areas of the caldera.

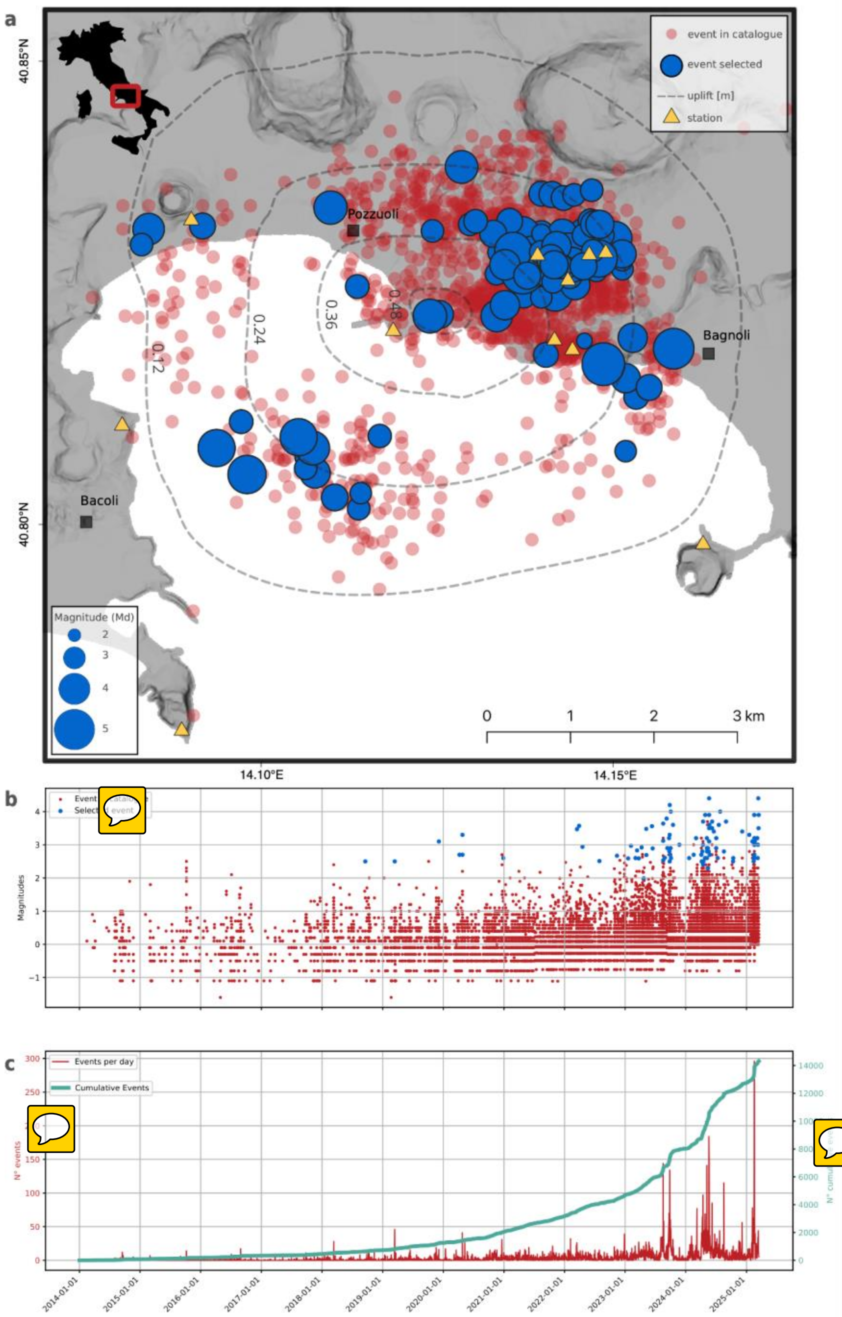

Fig. 1: Map and timeline of seismic activity (2014-2025) in the Campi Flegrei area. a, *Map of the study area, showing earthquake location according to the Osservatorio Vesuviano catalogue (earthquakes with Md > 1 in red, studied earthquakes in blue, with circle size scaling to the duration magnitude); the dotted lines show the uplift's contour lines between 2020 and 2023[44].* ***b,*** *Temporal evolution of duration magnitudes for all the events in the catalogue (red dots) and the selected ones (blue dots).* ***c,*** *Temporal evolution of the daily seismicity rate (red line) and cumulative number of events (green line).*

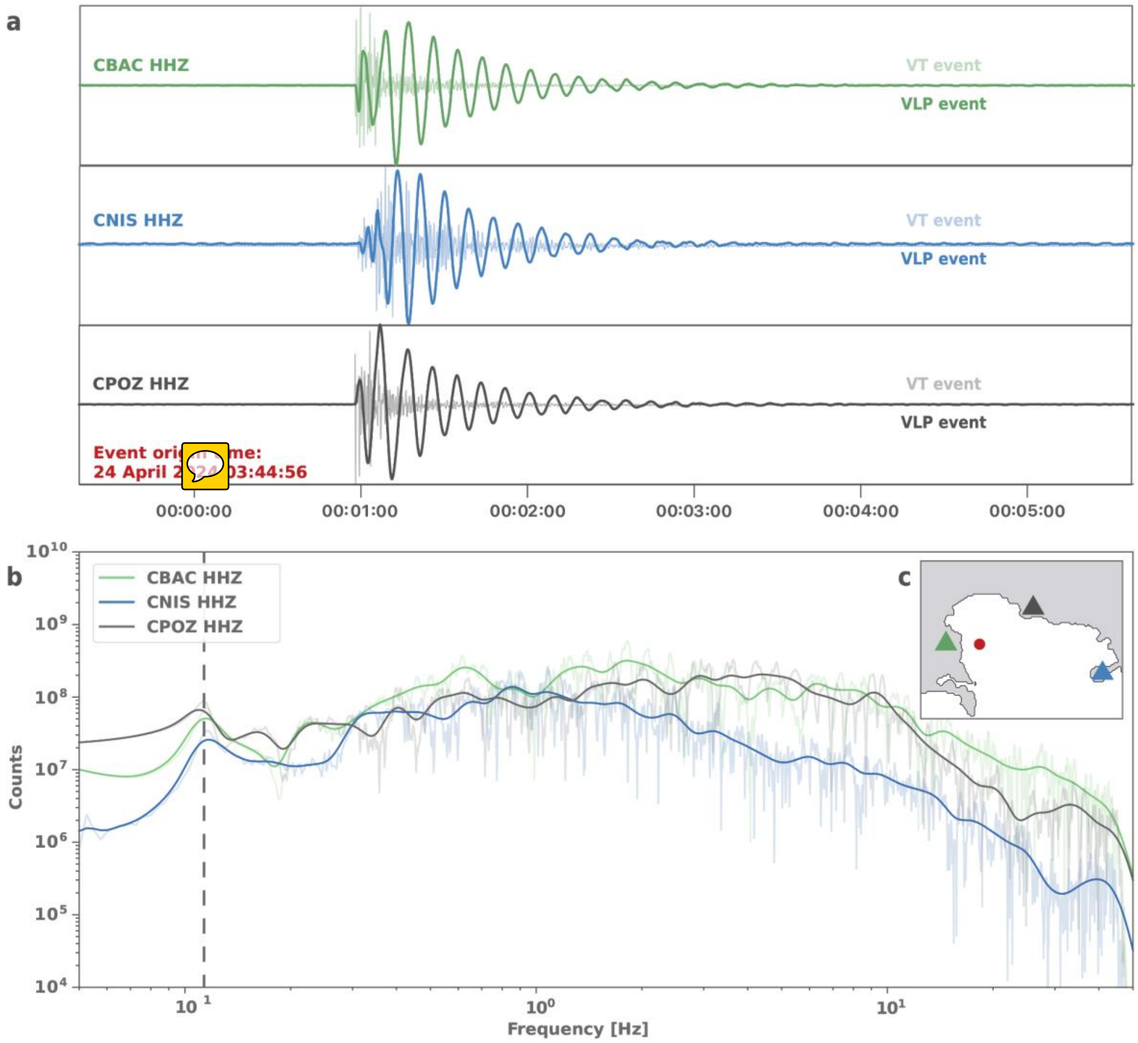

Fig. 2: Comparison of VT and VLP waveforms. a, *Signal recorded during the event of 27 April 2024 at stations CBAC, CNIS, and CPOZ. The unfiltered traces show the VT signals (light-coloured lines), while the VLP signals (dark-coloured lines) are best seen after bandpass filtering in the range 0.075-0.125 Hz. Amplitudes are normalized per trace.* ***b,*** *Amplitude spectra of the signals recorded at the three stations (light-coloured lines, with dark lines showing smoothed spectra). The dotted grey line shows the peak belonging to the resonance frequency of the VLP event.* ***c,*** *Map with the event location (red dot) and the three stations (green, blue and grey triangles).*

Results

VT earthquakes

The 104 best quality moment tensor (MT) solutions (*Suppl. Fig. 3*, *Suppl. Dataset 1*) are mostly located onshore, in the area of the hydrothermal system of Solfatara, east of Pozzuoli, and offshore, along a WNW-ESE band in the western side of the Pozzuoli Gulf, east of Bacoli. Our centroid depths, in the range 0.8-4.3 km, confirm the shallow depth of VT earthquakes. The moment magnitudes range 1.7-3.9, with the largest event occurring on May 20, 2024. Focal mechanisms [*Fig. 3*] are predominantly normal faulting, with few cases of oblique and strike-slip mechanisms. Normal fault orientations are in most cases WNW-ESE offshore and WSW-ENE onshore. We refer here to deviatoric MTs (*Suppl. Dataset 1*); inversion results assuming other MT constraints (*Suppl. Datasets 2, 3*) provide similar results regarding depths, magnitudes and focal mechanisms (*Suppl. Fig. 4,5,6*). Double-couple, deviatoric and full MT inversions show consistent double-couple components. Non double-couple components of VTs are present (*Suppl. Datasets 1, 3*), but affected by larger uncertainties and scatter, and thus not interpreted.

A waveform-based clustering analysis[28] resolves 6 clusters *(Fig. 3)*: the high waveform similarity within each cluster provides an independent confirmation of similar locations and MTs. Offshore events East of Bacoli form one cluster with depth 3.4 ± 0.5 km and WNW-ESE orientation. Onshore events were classified into four neighbouring clusters at Solfatara, plus a fifth near Bagnoli. The Solfatara's clusters have shallow depths in the range 1.6-3.0 km, shallower towards the region of maximum uplift and deeper to the NE (*Suppl. Table 2*). Here, focal mechanisms are mostly WSW-ENE normal faulting. The weak, most shallow cluster has normal faulting with a SSW-NNE orientation (*Fig. 3*). The largest magnitudes are reached at Pozzuoli (Mw 3.5-3.9), at the offshore cluster (Mw 3.5), and close to Bagnoli (Mw 3.3) [*Suppl. Table 2*].

VLP signals

We can model the monochromatic, slowly decaying amplitude of VLP signals with a damped resonating source (*Fig. 4*, *Suppl. Dataset 4*). The studied VLPs occur quasi-simultaneously to energetic VTs, which have very different locations, both onshore and offshore. Despite the heterogeneous location and mechanisms of the VTs, all resolved VLP sources have a similar geometry and quite similar locations and depths. The MT source has significant non-double-couple components, both in the form of compensated linear vector dipoles, CLVDs, and isotropic terms, whose major axis is dipping ENE, thus consistent with an oscillating crack oriented NNW-SSE and dipping WSW. The dominant frequency of the resonator (0.114±0.002 Hz) shows no temporal modulation, remaining constant for all studied events from 2018 to 2025 (*Suppl. Fig. 7*). Altogether these results point to a single, oscillating source active over the last 7 years, that may be linked to a resonating fluid-filled cavity in the shallow hydrothermal system beneath Solfatara, where the massive CO_2 flux between 2000 and 2019 increased from 750 to more than 2000 t/day[29]. Its average location is roughly beneath Pozzuoli and the Solfatara area at a depth of 3.6±0.6 km, positioning it below the VT clusters in the Pozzuoli area. We observed a high waveform similarity among different VLPs (*Suppl. Fig. 2*), which confirms their common source and resonation mode.

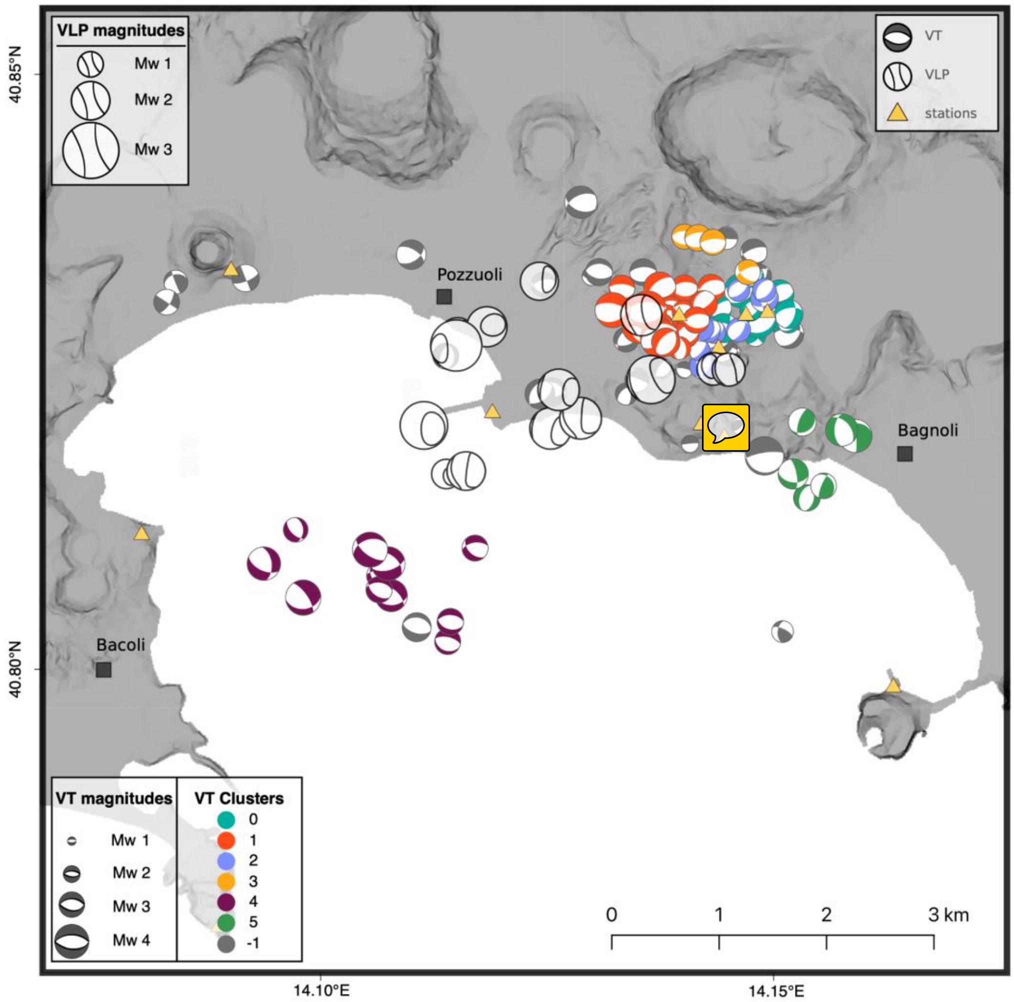

Fig. 3: Moment tensor solutions for VT and VLP events. *White focal spheres show full MTs for VLP events. VLP's magnitude scale was exaggerated to emphasize their mechanism. Coloured focal spheres (0-5) show the double couple component of deviatoric MTs for VT earthquakes, divided into 6 clusters. Grey focal spheres (-1) show the VT earthquakes not clustered.*

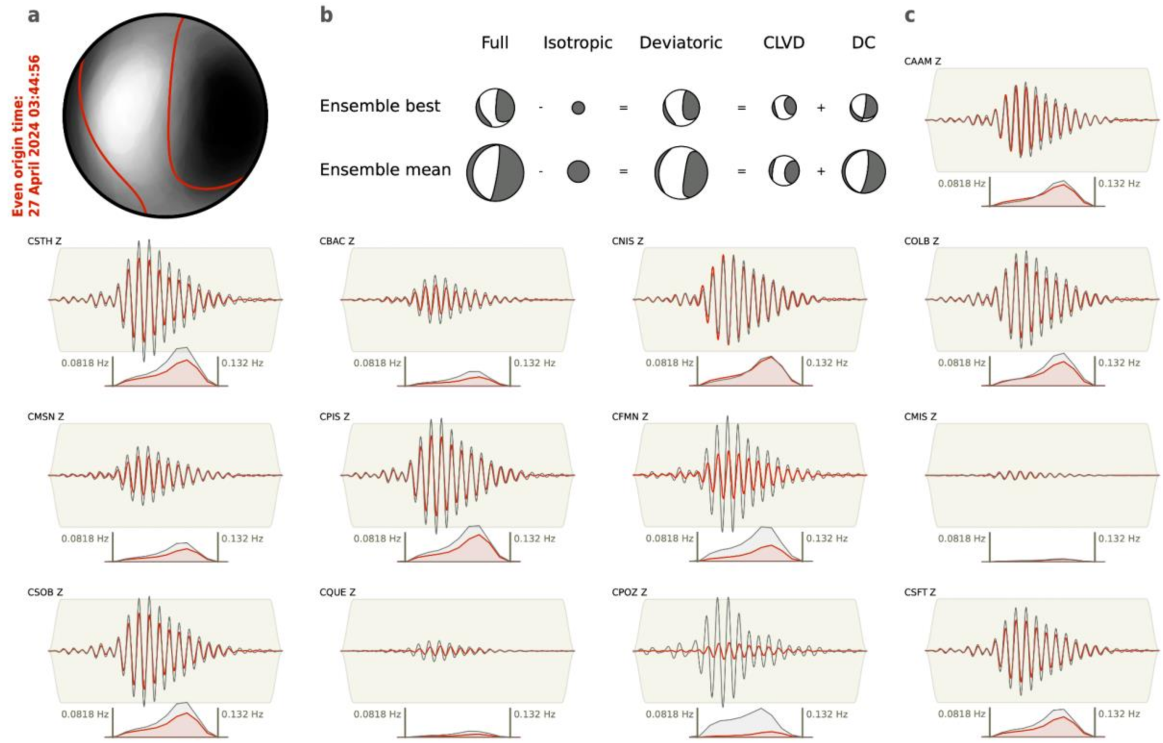

Fig. 4: Moment tensor inversion results for the VLP event on April 27, 2024. a, *Fuzzy MT, superposition of all the ensemble solutions extracted with the bootstrap method, the red line shows the best solution.* ***b,*** *full MT decomposition for the best and mean solutions, the latter obtained from the population of solutions from the data bootstrap approach.* ***c,*** *Fit between observed (red lines) and synthetic waveforms (black lines) for the best solution. The fit of vertical components is shown for all stations used; note that the inversion also relies on radial (R) and transversal (T) components, which often have smaller amplitudes. The respective amplitude spectrum is shown below each trace.*

Discussion

The joint interpretation of VT and VLP events maps in detail different shallow seismogenic structures, accommodating the current uplift, and a resonating crack, unveiling hidden structures otherwise invisible to different techniques. At CF, the source of the ongoing uplift has been ~~set~~ at ~4 km depth, based on geodetic modelling[30,31], geochemical and petrological data[12,15,32] and seismic tomography[16,33]. VTs and VLPs are here located at shallower depths, reflecting brittle and resonance responses of shallower structures, not involving the inflating body.

The large number of MTs, clustered in VT earthquake families with similar waveforms, provide information on the faults' geometry and slip motion. The studied VTs are representative of the current seismicity, including the largest earthquakes and sampling different seismogenic volumes. While earthquakes span over an elliptical region, their spatial, temporal and moment release distributions are heterogeneous, with higher activity both onshore (e.g. fumarole areas close to Solfatara east of Pozzuoli) and offshore (east of Bacoli). Earthquakes located within this elliptical region are shallower (~1.6-2.7 km) than those at its border (~3.0-3.7 km, *Suppl. Tab. S2*), likely marking very shallow faults within the caldera and faults close to its rim, or segments of the caldera rim. VT events belonging to the clusters located in the outer part of the caldera (3-5 in Fig. 3) became active only in late 2022 and early 2023, while those inside the caldera (0-2 in Fig. 3) were already active before [Suppl. Fig. 8]. Normal faulting is predominant (*Figs. 3,5*), consistent with extensional stresses above an inflating deep reservoir. Normal faultings at the deepest (~3.7 km) offshore cluster (*4 in Fig. 5*) strike WNW-ESE. Seismicity here deepens towards NE, suggesting the activation of an inward dipping caldera rim segment[34]. Similarly, seismicity and mechanism orientations map a NS-oriented structure at the Bagnoli cluster (*5 in Fig. 5*), at ~3.4 km depth. The four onshore clusters (*0-3 in Fig. 5*) are located close to the fumaroles and the region of maximum uplift. The outermost (3) is also the deepest (~3 km), while the innermost (2) is the shallowest (~1.6 km). The remaining two clusters (0 and 1) are the most seismically active and host the largest recorded magnitudes (3.9 Mw); they are located just below the fumaroles, at a depth of ~2.7 km. The predominant fault orientations in these inner clusters are E-W to SSW-ENE. Clusters' locations and depths are in agreement with the volumes outlined by b-value anomalies[35]. Our ~~abundant~~ VT catalogue confirms the general focal mechanism trends from previous studies[22,23], especially in the onshore areas, but resolves new geometries and faulting styles for the offshore seismicity, East of Bacoli.

VLP signals are observed at Campi Flegrei for the first time, where we have identified them since 2018. We were able to isolate VLPs with a dominant frequency of 0.114 Hz and to model their source geometry by moment tensor inversion. Their monochromatic signature, long duration and slowly decaying amplitudes suggest they are generated by a damped, resonating source; indeed, VLP signals last substantially longer (up to 2 minutes) than VT signals (*Fig. 2*). A high waveform similarity and coherent relative amplitudes pattern (Suppl. Fig. 2), with the highest VLP amplitudes recorded at station CPOZ (Suppl. Fig. 1), suggest a common source for all VLPs. While their emergent onsets hinder an accurate source location, their centroids were found roughly between the zone of maximum uplift and maximum seismic activity (*black ellipse in Fig. 5a*), with a depth of ~3.6 km, thus well below the VT earthquakes in that area. The MTs point to a resonating, planar crack, oriented NNW-SSE and dipping ~60° WSW, whose geometry links the deeper inflating reservoir and the shallower brittle structures (VT clusters), offering a path for the fluids to reach the surface at Solfatara and Pisciarelli regions, where massive degassing has increased since 2000. The constant dominant frequency of VLPs rules out substantial changes in the extent or properties of the resonator (Suppl. Fig. 7). The resonance frequency provides constraints on the source dimensions[36,37] (Suppl. Fig. 9), under the hypothesis of different fluids, such as magma or supercritical CO_2. The depth of the inflating reservoir and the shallow VT clusters provide an upper boundary for the possible crack length, and the seismic moment of the largest VLP a lower boundary for the required volume of the resonator. Jointly, this constrains the crack length between ~250 m and ~1200 m. Indeed, the asymmetric distribution of shallow seismicity (Fig. 5b), with highest activity beneath Pozzuoli, could be driven by the stress accumulation at the crack tip. Hypothesising that VT cluster 1 marks the upper tip of the crack, we suggest a crack length of ~1000 m and a thickness of ~0.35 m; this corresponds to a volume of ~220.000 m^3, equal to ~1/7 of the daily CO_2 surface emission[29]. VLP Signals with similar dominant periods[38,39] were attributed to cracks of comparable length and thickness. While the resonance fracture model cannot distinguish between magmatic and supercritical CO_2 scenarios, gas chemistry suggests that relatively oxidised, hot magmatic fluids are flushing the system[29].

The joint analysis of VT and VLP reveals seismological processes and their interactions in the Campi Flegrei caldera. The aseismic inflation, generated by a deeper magma reservoir, whose maximum is centred in Pozzuoli, causes brittle failures along the rim or fault segments and inside the caldera structure in the form of VT earthquakes. These VTs trigger almost coseismically the resonator, which oscillates and generates the VLP signals. The resonator is thus excited by the passage of seismic waves generated by the VT events, as proposed for other reservoirs[40], rather than by fluid transfer or pressure perturbations, as proposed for LPs[25]. We attribute VLPs to a previously unknown crack-like structure and exclude that they are generated at the deeper reservoir. The stable resonance frequency implies that the geometry and fluid content have not changed between 2018 and 2025: this also contradicts the hypothesis of the VLPs being generated by the deeper reservoir, which evolved over that time, accompanying the increased uplift[12,41]. While such structure can hardly be detected by tomographic techniques, a recent decrease of Vp/Vs ratio at its location has been interpreted as a path for uprising pressurised gases[42]. A magnetotelluric survey[43] indicated an elongated, high-resistivity vertical structure ~2 km in length beneath the Solfatara region, supporting our VLP fracture model as a transport channel of supercritical gases.

In conclusion, the VLP source correlates with the shallow, elongated, sub-vertical high resistivity structure, which we interpret as a high permeability zone that allows hot fluids to ascend from depth. Our study demonstrates that the analysis of seismological data can detect and characterise crack-like structures and gas pathways. Monitoring the future evolution of VLPs and their resonance frequency will help to promptly detect structural changes in the shallow underground.

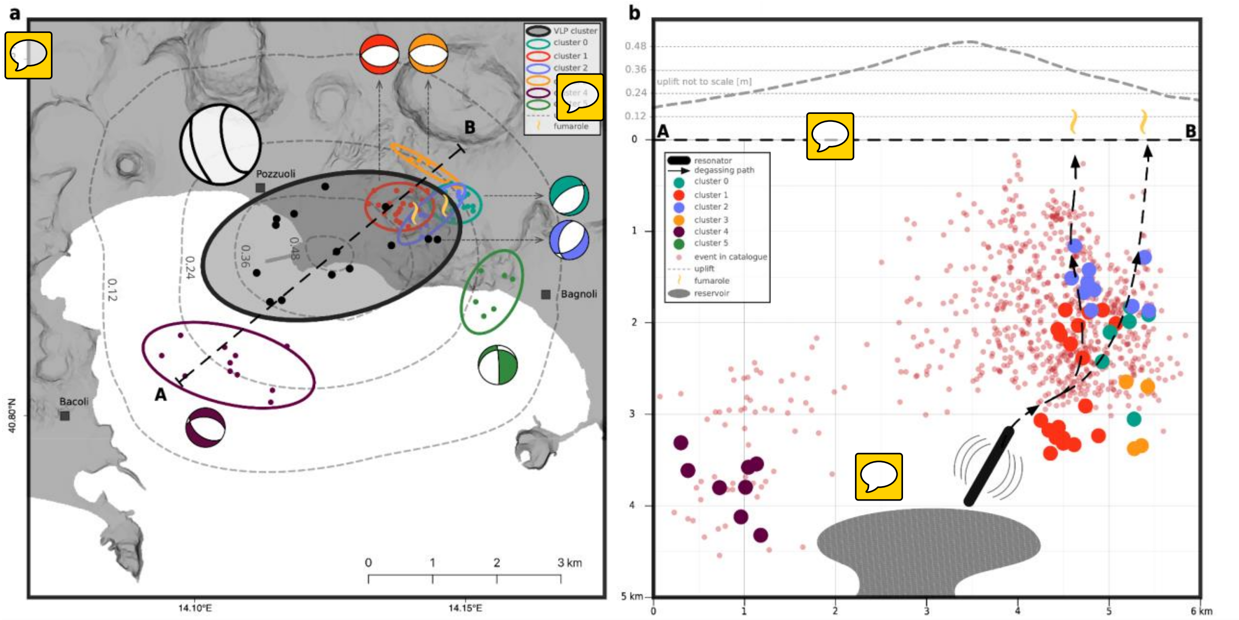

Fig. 5: ***a,*** *Map showing the six VT clusters (coloured clusters 0-5) and the VLP cluster (black ellipse) with their respective representative MT solutions.* ***b,*** *Sketch of seismicity and path of gas ascent along a vertical cross-section (black dotted line in panel a) showing: the deep reservoir, the resonating crack and VT seismicity (small dots are events of Md>1, circles mark the locations of studied VT, coloured according to their clusters).*

Methods

Data used for seismological analysis

We rely on seismic catalogues by INGV[45] and Osservatorio Vesuviano (OV)[46], considering a timespan of 11 years, from January 2014 to March 2025 (Fig. 1). The OV catalogue contains more than 14,000 events with minimum duration magnitude Md -1.6, while the INGV catalogue has ~1,800 events with minimum moment magnitude Mw 0.1. We merge the two catalogues and extract all earthquakes with reported magnitude equal or larger than 2.5, totalling 136 events. At the same time, we collected all open seismic waveform data within a distance of 50 km from Pozzuoli, run by the Italian National Seismic Network[47]. These stations offer a large number of observations with good signal-to-noise ratio (SNR) and azimuthal coverage. Since the stations' spatial distribution is inhomogeneous, with two clusters in the areas of Vesuvio volcano and Ischia island, we only considered one station per cluster, choosing stations with continuous recordings and high SNR, in this way avoiding redundant data. In conclusion, we could rely on data from 20 3-component broadband seismic stations (Suppl. Table 1). For each of these stations, we carefully verified the quality of both the seismic data and the reported instrument responses. To verify the instrument transfer functions, we compared the waveforms of teleseismic recordings through the network, considering earthquakes with different timing and azimuths. In this way, we could identify and correct a few wrong response functions. To verify the quality of seismic data, we visually revised all recordings of the 136 earthquakes, to identify problematic traces, with data gaps, saturated or tilted signals (usually after the occurrence of a strong event), or with low SNR.

Methods

We used two open source seismological software packages. We performed Moment Tensor (MT) inversion for VTs and VLPs using Grond, a tool for robust characterization of earthquake sources, which delivers meaningful model uncertainties through a Bayesian bootstrap-based probabilistic joint inversion scheme[48]. The Grond software was extensively used for both VLP[40] and VT analysis of low-magnitude earthquakes in volcanic settings[49,50], proving it to be suitable for our type of study. We also used Clusty, a waveform-based network similarity clustering toolbox[28], to identify families of events with similar waveforms, and thus similar locations and source geometries.

Moment Tensor inversion

We tuned the MT inversion of VT events depending on their catalogue magnitudes. For the largest events, the Md 4.4 of 20 May 2024 and 13 March 2025, the dataset was enhanced to include seismic stations up to 120 km, being the event more energetic. For the events with magnitude from Md 4.25 to Md 4.45 we used data up to 50 km. For smaller VT events, as well as for VLPs, we used local data only (less than 10 km). We use different velocity models to compute synthetic seismograms at local[17] and regional[51] (https://igppweb.ucsd.edu/~gabi/crust2.html) distances[52,53]. All three trace components were used, reoriented as radial, transversal and vertical. The inversion for each VT or VLP event is carried out in one global chain and 100 bootstrap chains with variable random weights on the inputs (waveforms, spectra at all stations and components). The resulting ensemble of solutions provides the opportunity to evaluate the stability of the results.

For the VT events, local data were inverted using a frequency band of 0.5-2.0 Hz, with a time interval starting 0.5 s before the P-wave and ending 1.5 s after the S-wave arrival, both computed with the local velocity model. Regional data were inverted using a frequency band of 0.05-0.1 Hz (0.03-0.08 Hz for the largest event), with a time interval starting 5 s before the P-wave and ending after the arrival of an S-wave with fixed velocity at 2 km/s, calculated with the regional velocity model, to ensure that the entire length of the waveform was selected. We inverted the signals in the time domain. The source time function applied was an instantaneous slip, used for earthquakes of short duration that can be approximated as a point source. Each event was inverted three separate times to obtain the double couple (DC), deviatoric and full moment tensor. Grond's full waveform MT inversion retrieved the focal mechanism, centroid location, depth and moment magnitude.

For the VLP events, only local data were inverted using a frequency band of 0.09-0.12 Hz, with a time interval starting 60 s before and ending 120 s after the P-wave computed arrival, based on the local velocity model. We inverted the signals in the time domain and in the frequency domain by fitting the amplitude spectrum. Since we had to simulate the signal generated by a resonating source, we used a periodic source time function, such as a damped oscillator. Grond's full waveform MT inversion retrieved the full MT components, the focal mechanism, centroid location and depth, plus the damping constant and dominant frequency of the resonator.

Waveform similarity clustering

Clusty's algorithm[28] was applied to both VT and VLP to classify the events based on their waveform similarity. The resulting clusters were then used as an independent way to confront and compare the MT solutions. The same subset of nine stations was used, selecting the ones that recorded the highest number of events. For the VT earthquakes the frequency band was 0.5-2.0 Hz, and the time windows were two: the first, starting 2 s before the P-wave computed arrival and ending 2 s after, and the second, starting 1 s before the S-wave computed arrival and ending 5 s after. We used all three trace components with a 0.5 weight on the vertical and a 0.25 weight for both East and Nord. The similarity radius values were: 0.15, 0.20, and 0.25 with a minimum number of connections between events to form a cluster of 3. For the VLP events, the frequency band was 0.075-0.125 Hz and the time window started 60 s before the P-wave computed arrival and ended 120 s after. We used all three trace components with the same weights, similarity radius values and minimum number of events per cluster as for the VT earthquakes' setup.

Crack Modelling

We obtained an estimation of the resonator's dimensions using a model for the resonance of a rectangular fluid-filled crack[36,37], frequently applied to model long-period events at volcanoes. We made two different setups for magma and supercritical CO_2 filled crack[54]. We considered the fundamental mode (= 2) and used a Vp velocity of 5 km/s for the rock matrix, 2.5 km/s for the magma and 0.46 km/s for the supercritical CO_2.

Additionally, we used a density value of 3 g/cm^3 for the rock matrix, 2.4 g/cm^3 for the magma and 0.56 g/cm^3 for the supercritical CO_2. As a constraint on the volume of the crack, we took the seismic moment of the largest VLP and divided it by the shear modulus (~20 GPa, derived using the local velocity model[17]). We considered the obtained value as the portion of volume which oscillates during the VLP, and therefore used as a minimum estimate of the total volume of the crack.

Data availability

The seismic waveform data on which this article is based is freely available through the EIDA node[55]. Earthquake parametric data has been retrieved from ISIDe[45] and GOSSIP[46] open-access catalogues.

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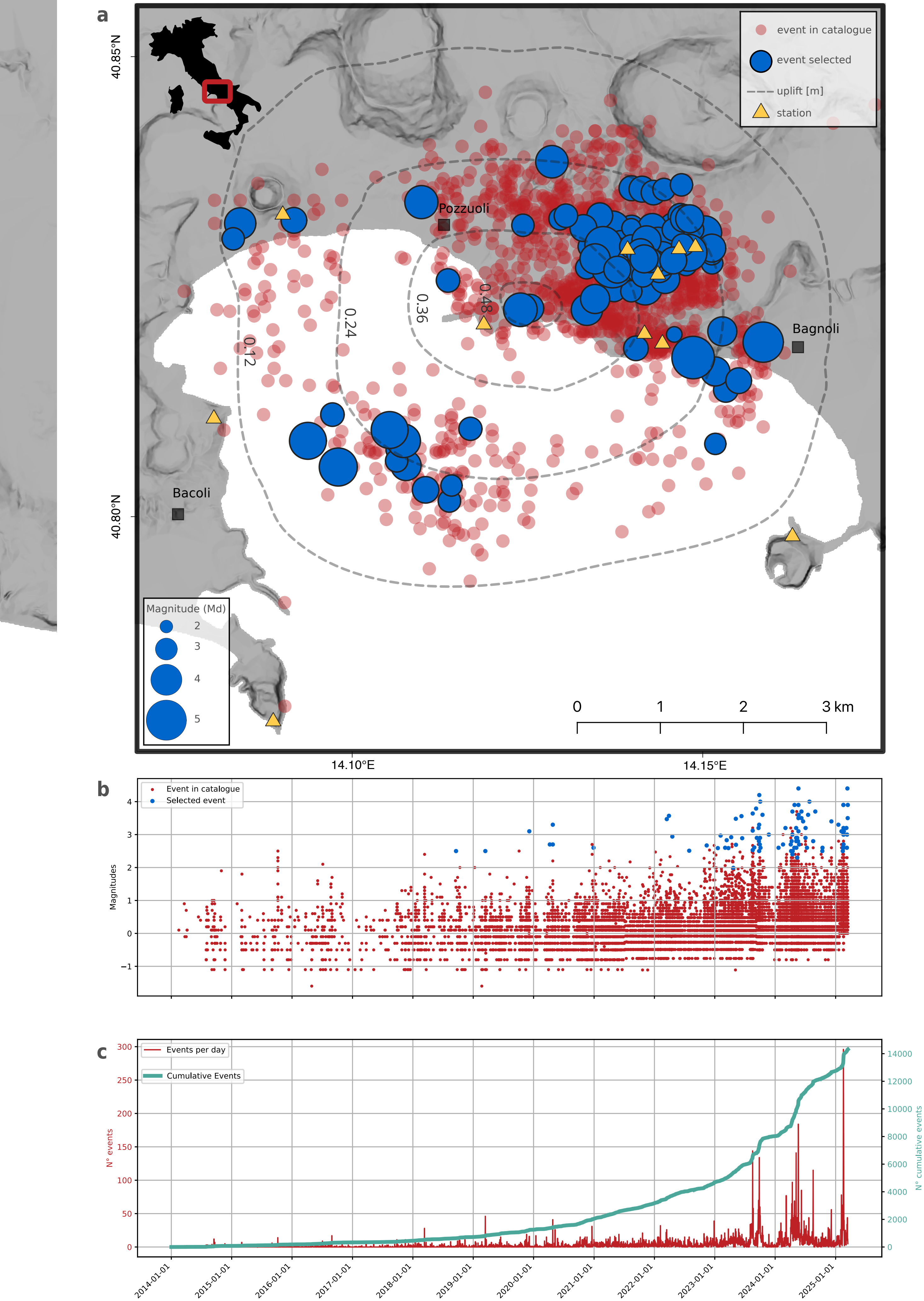
Author contributions

G.R. and S.C. coordinated this project and conceived the manuscript and figures. G.R. and S.C. performed the MT inversion for VT and VLP events. G.R. and G.P. performed the waveform based clustering analysis. G.R., G.S. and T.D. performed the crack modelling. G.R., S.C., F.G., G.S., T.D. and F.B. contributed to the interpretation of the results and discussion section. G.R., S.C. and G.S. drafted the manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.



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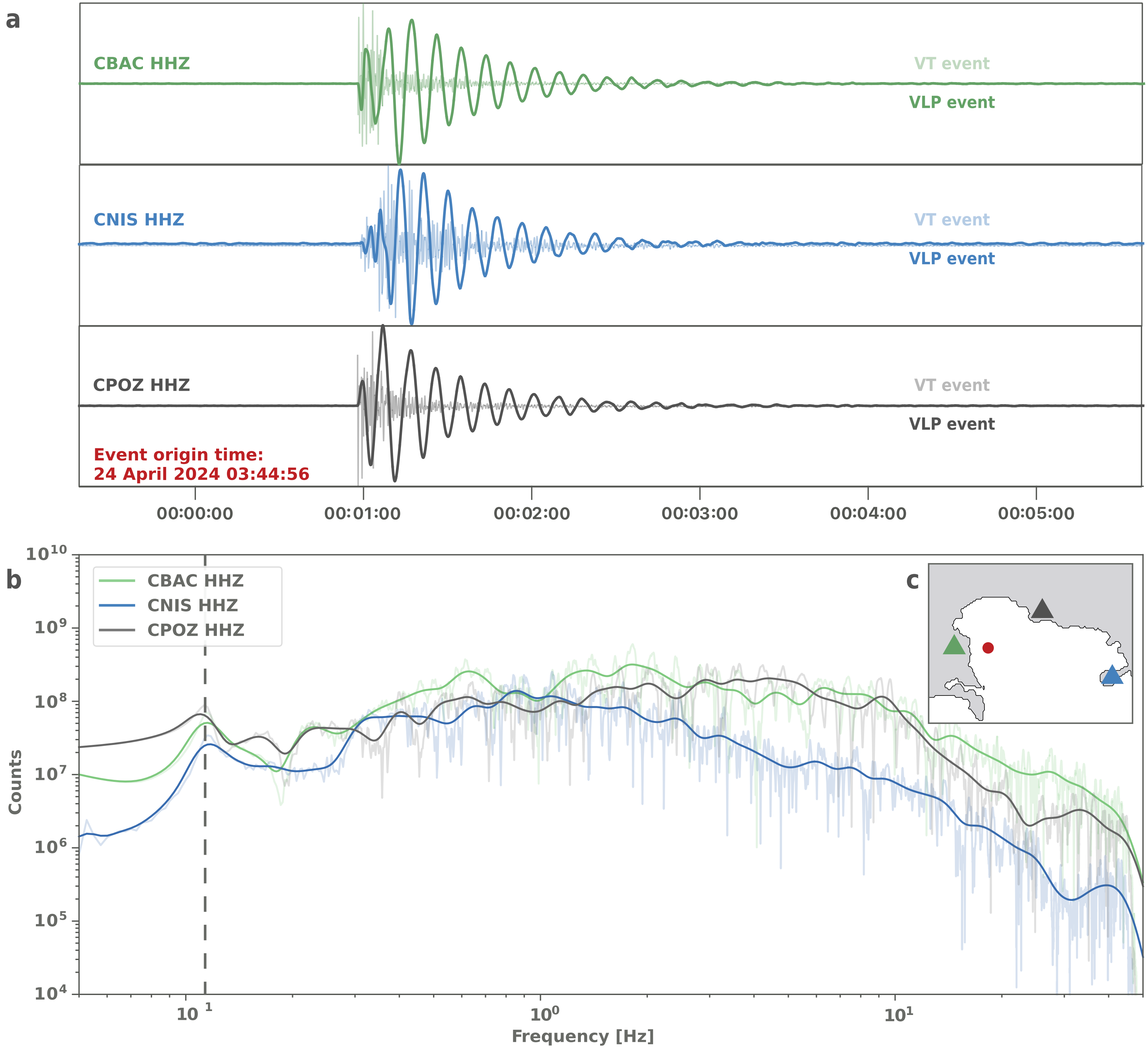
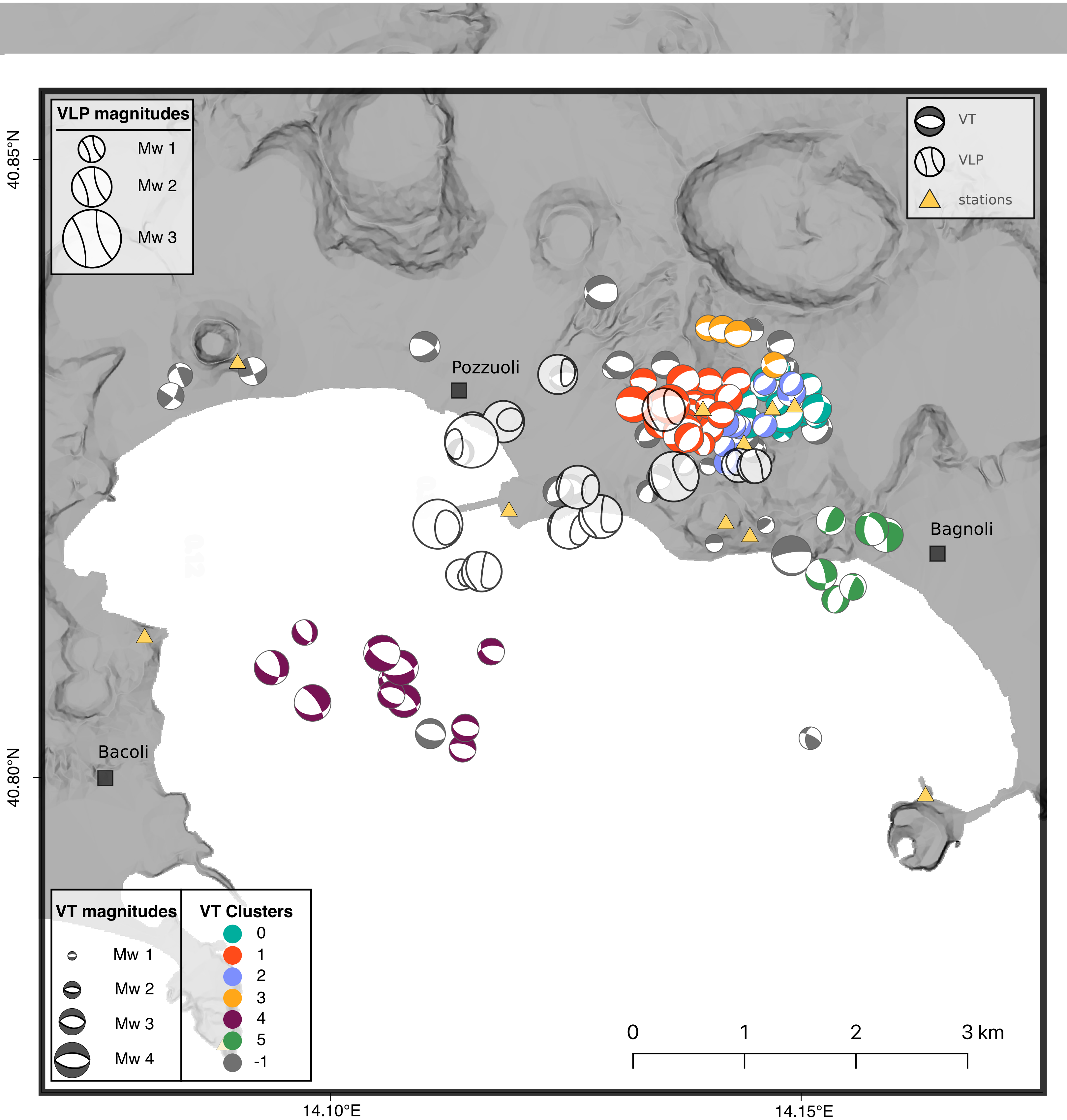
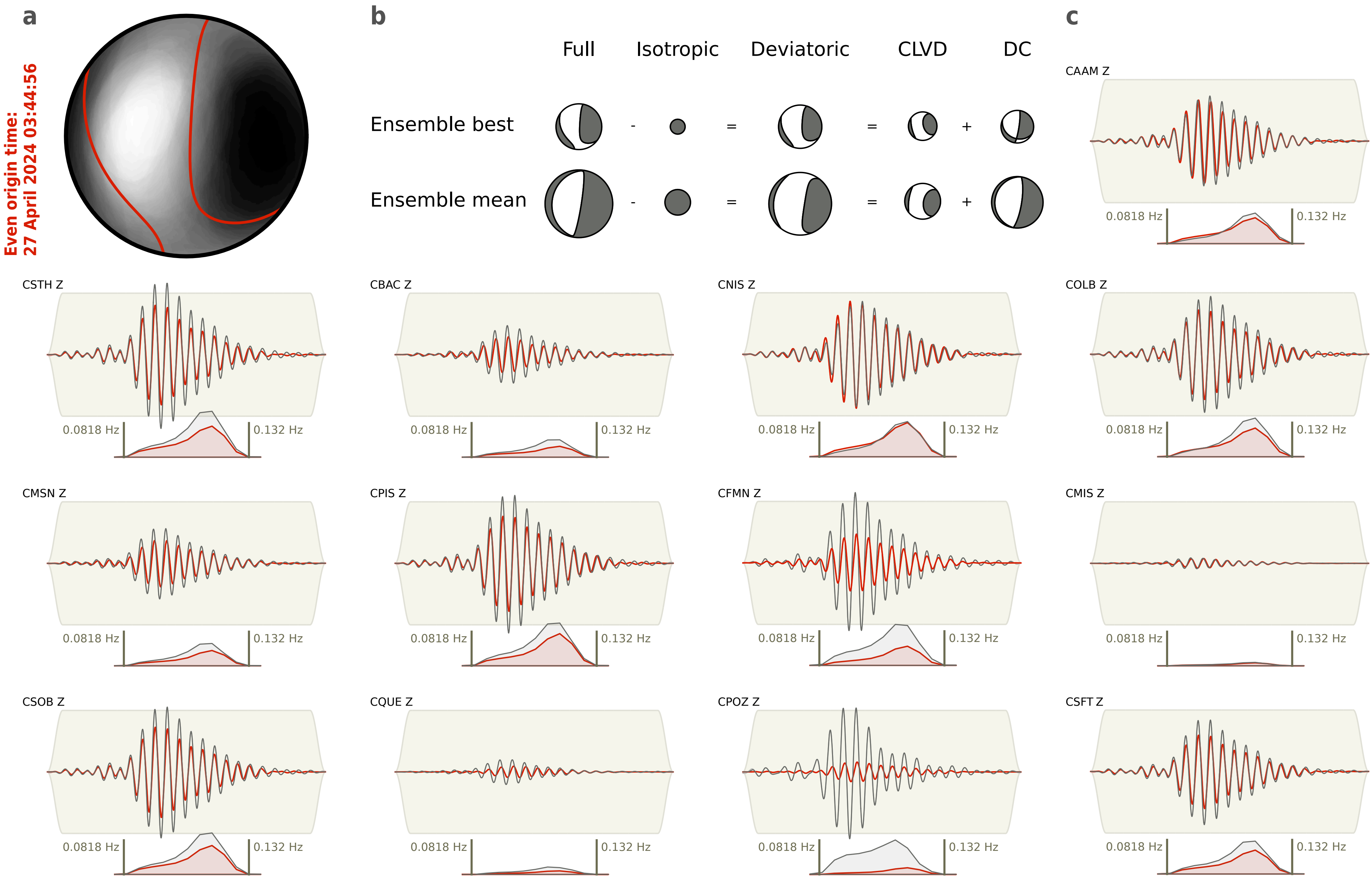
3 km
b
Event in catalogue
Selected event
Magnitudes
c
Events per day
Cumulative Events
N° events
N° cumulative events
2014-01-01
2015-01-01
2016-01-01
2017-01-01
2018-01-01
2019-01-01
2020-01-01
2021-01-01
2022-01-01
2023-01-01
2024-01-01
2025-01-01

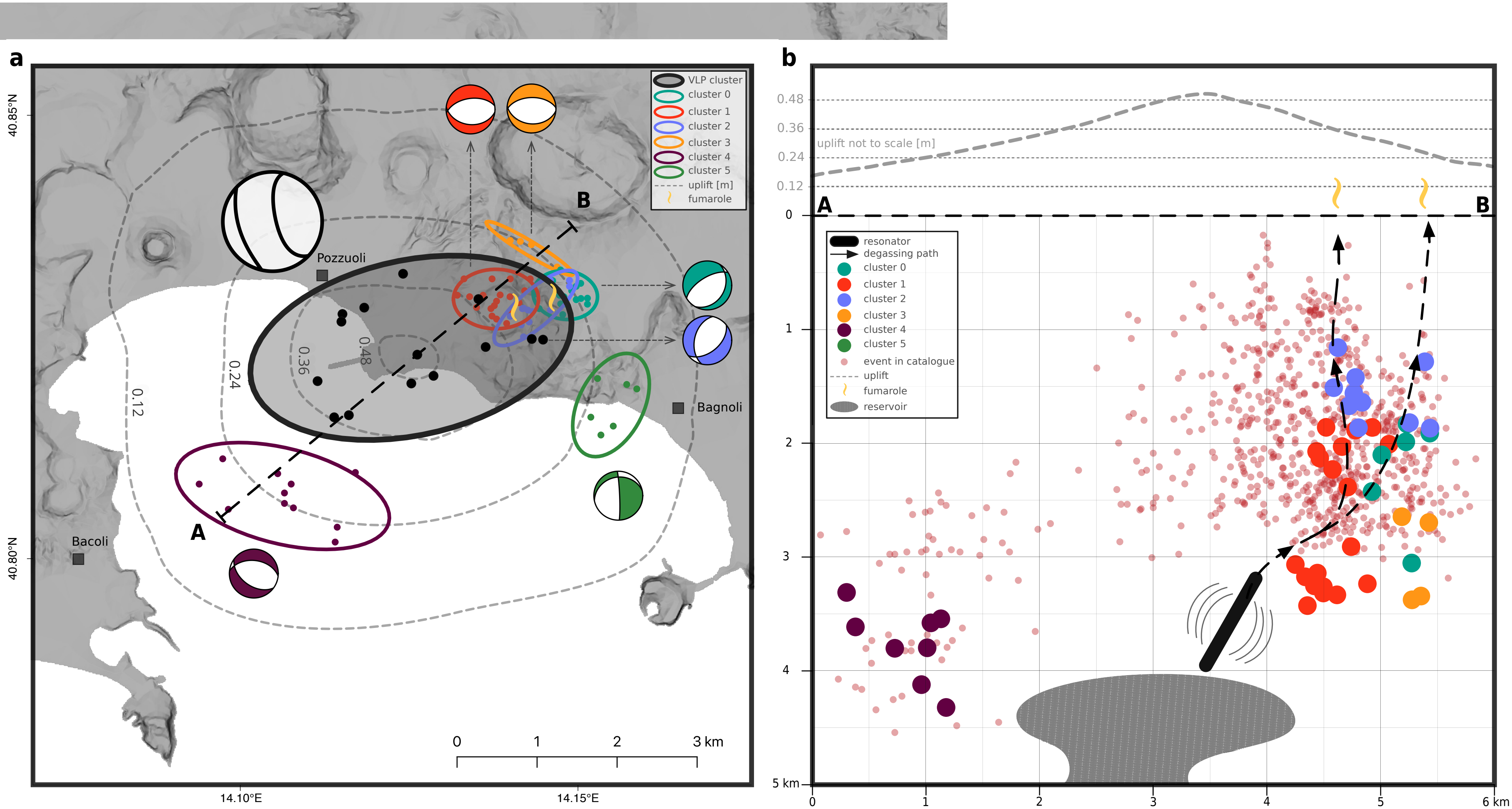


a
CBAC HHZ
VT event
VLP event
CNIS HHZ
VT event
VLP event
CPOZ HHZ
VT event
VLP event
Event origin time:
24 April 2024 03:44:56
00:00:00
00:01:00
00:02:00
00:03:00
00:04:00
00:05:00
b
CBAC HHZ
CNIS HHZ
CPOZ HHZ
c
Counts
Frequency [Hz]



VLP magnitudes
Mw 1
Mw 2
Mw 3
VT
VLP
stations
Pozzuoli
Bagnoli
Bacoli
40.85°N
40.80°N
14.10°E
14.15°E
VT magnitudes
Mw 1
Mw 2
Mw 3
Mw 4
VT Clusters
0
1
2
3
4
5
-1
0
1
2
3 km


a
Even origin time:
27 April 2024 03:44:56
b
Full
Isotropic
Deviatoric
CLVD
DC
Ensemble best
Ensemble mean
c
CAAM Z
CSTH Z
CBAC Z
CNIS Z
COLB Z
CMSN Z
CPIS Z
CFMN Z
CMIS Z
CSOB Z
CQUE Z
CPOZ Z
CSFT Z
0.0818 Hz
0.132 Hz


a
40.85°N
40.80°N
14.10°E
14.15°E
VLP cluster
cluster 0
cluster 1
cluster 2
cluster 3
cluster 4
cluster 5
uplift [m]
fumarole
Pozzuoli
Bagnoli
Bacoli
A
B
0.12
0.24
0.36
0.48
0
1
2
3 km
b
uplift not to scale [m]
0.48
0.36
0.24
0.12
0
1
2
3
4
5 km
6 km
resonator
degassing path
event in catalogue
uplift
fumarole
reservoir

Dear Editor,
We are thankful to the editor and reviewers for considering our manuscript, for the overall appreciation of our work and for the constructive suggestions.
In this rebuttal letter, we report the original review in black, and our reply in blue.

We identified two major aspects for improvement, which have been identified in both reviews. We discuss these aspects first, and later report all original reviewers' comments and a complete point-to-point reply to all comments.

1. Link between VT and VLP

Reviewer 2 suggested to extend the investigation and discussion of the link between VT and VLP. In particular, the reviewer raises the question of the triggering process (i.e. if VT triggers the resonance or vice versa) and whether there is a magnitude threshold for VT to trigger a VLP.

VT and VLPs are almost synchronous, but local data show that VTs occur first. We can thus exclude scenarios where VLP trigger VT. We prepared a figure for this letter to show it (see reply to reviewer 2).

As for the triggering threshold, we improved the discussion of our findings. On one side, a specific threshold does not exist, as we have examples of weaker events triggering VLPs and other, larger, without such signal (see new Suppl. Fig. 10 for an example of VT without VLP). On the other side, the magnitude of VTs generating VLPs seems correlated with those of the corresponding VLPs (Suppl. Fig. 8). This implies that, if the conditions for the resonation are met, larger VTs trigger larger VLPs.

As for the comment on whether regional events could trigger the resonator, we checked the waveforms of 19 selected regional earthquakes (M4.5+, distance <450km, time period 2020-2025). Based on the spectral analysis at seismic stations at Campi Flegrei, we found no evidence for resonance triggering.

2. Resonator model

Some of the reviewers' comments are dedicated to the characteristics and properties of the resonator.

On one side, reviewer 1 argues that the resonator could correspond to a network of fractures, instead of a single one. While we do not exclude such option, the repetitive waveform and spectral characteristic of all VLPs suggest a common source, which could be composed of a planar crack or distributed structure in a volume. The geometry of the crack/volume and its location were estimated from the average of the source parameters calculated for all the VLP events.

Reviewer 2, instead, highlights that changes in temperature and pressure would affect the fluid properties and thus change the dominant frequencies. We agree with this consideration. According to the original formulation by Maeda, the dominant frequency can be expressed as a function of the fluid velocity and density (neglecting changes in the properties of the hosting solid).

The constant dominant frequency is a result of our inversion and a clear, robust observation, with a very small uncertainty.
Given this observation, we can conclude that neither the resonator geometry and size, nor the fluid properties inside of it vary considerably during the long observational period. Fluctuations of flow and temperature at the surface may reflect shallower processes, but be associated with minor variations at the depth of the resonator.

We improved the discussion of the resonator in reply to both comments.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Dear Editor,

I have now completed the revision of the manuscript entitled "Coupled earthquakes and resonance processes during the uplift of Campi Flegrei Caldera" by Rapagnani and colleagues.
This article deals with the analysis of VT seismicity from 2014 onwards, which has been a very hot topic in the last few years in the literature of Campi Flegrei. The authors have analyzed a large dataset (>14000 events) and extracted the largest one (136 events). For these selected events, they have calculated the focal mechanism based on the moment tensor inversion. I underline that this is a remarkably high number of focal mechanisms, and above all, they are very consistent with each other. Based on the similarities among the waveforms, the authors have been able to identify different clusters of events whose moment tensor solutions are remarkably consistent. Apart from this, there is a new and relevant element of novelty introduced in this work by the authors. As far as I am concerned, the authors report for the first time the occurrence of VLP (Very Long Period) events superimposed on the VT earthquakes. While LP events are not a novelty (these are even reported in the surveillance bulletins), this is the first report of VLPs. This VLP signal is monochromatic and overlaps with the seismic signal of the largest VT events, regardless of their origin time and hypocentral location, and it is well evident when the raw signal is filtered with a low-pass filter. Their interpretation is that this signal is produced by the resonance of pressurised fluid-filled cavities located above the most uplifted area, whereas these signals are often associated with magma movements at greater depths. Therefore, the VLPs would represent a by-product of the VT events. Hence, this work might represent a significant advancement in the comprehension of interconnected processes occurring in this escalating phase of unrest at Campi Flegrei.

We are thankful for the appreciation of our work. Specifically, we would like to thank the reviewer for the careful review and the suggestions in the annotated PDF.

The manuscript is well-written and concise, the figures are of high quality and informative. The authors should only ensure that the minimum font size per journal prescription is employed, as it is too small in most of the figures.

We checked and improved the figure according to the suggestion.

The supplementary material is pertinent, comprehensive, and adequately recalled in the text. My overall judgment is positive, although I have some minor/moderate concerns highlighted in the manuscript file, especially about the geometry of the resonator. For instance, why attempt to approximate the centroids of VLPs to a single, large crack instead of thinking of a network of fractures? I state this considering the very complex volcano-tectonic structure of the caldera.

We agree and reformulated the text. Our results do not allow us to discriminate among a single crack or an extended seismogenic volume including a network of fractures. However, the high waveform similarity of VLP signals and their constant dominant frequency clearly indicate a common source, which has been emplaced over years. The relatively sparse distribution of VLP centroids is the consequence of significant location uncertainties, which are intrinsic due to the long wavelengths and the lack of clear P and S onsets. Therefore, we do not interpret the spread of VLP locations as a measure of the resonator size, but rather we average the results to estimate the source location and geometry. This aspect has also been discussed above in our reply to main comment 2.

On the same line, I am also convinced that the literature referencing the structure of the volcano should be expanded, and the differences/improvements with the previously published papers should be highlighted. I have found that there might be too little reference to previous works and that those dealing with the geology and structure of the volcano are too scarce too.

We improved the manuscript as suggested to discuss more recent knowledge of the caldera structure, adding a few additional references, but taking into account the limitation in the number of references.

This is an important point because there is an outstanding correspondence between mapped volcano-tectonic structures and computed focal mechanisms, in terms of strike, dip angles and kinematics. Hence, it might be worth it for the authors to add in Figure 3, for instance, the comparison with caldera and VT structures, which have been already proven to match remarkably with relocated seismicity. I have proposed some suggestions in this regard.

We tried to follow the suggestion, but the figure resulted overcrowded. Therefore, we preferred to only insert the inner caldera boundary in Fig. 3, and add the references to the mentioned paper in the text.

I have annotated some constructive comments and suggestions to improve the text and the figures, which can be found in the attached PDF file.

We followed most of the suggested changes, but tried to reformulate some of the suggestions given the word limitations and avoiding repetitions.

Finally, the paper shows promising potential to represent a significant advancement in the interpretation of seismicity associated with the current unrest.
Based on my review, I suggest that the article be considered for publication pending minor/moderate revision.
Best regards

Reviewer #2 (Remarks to the Author):

Dear Editor, please find here my review of the research manuscript entitled "Coupled earthquakes and resonance processes during the uplift of Campi Flegrei Caldera" submitted by Rapagnani and co-authors for possible publication in Communications Earth & Environment.
The research paper targets Campi Flegrei, one of the best studied calderas worldwide, source of major risk at local, regional and global scale. Their study fits in a very rich and complex set of multidisciplinary researches aiming at better constraining the source(s) and the evolution of the current unrest. The authors perform an analysis of the earthquake source mechanisms and highlight the spatial distribution of volcano-tectonic events associated with brittle failure of the caldera faults and propose for the first time the occurrence of very long period signals (VLP). They suggest that the source of VLP events is located a ca 4 km depth and corresponds to a single oscillating fissure with constant volume and physico-chemical properties of the filling fluids. The authors propose that the vibration of the resonant source is excited by energetic VT events.

As the study is focused on the most energetic double couple VT events and weaker events or non-double couple component VT are not studied, the correlation is in some way biased.

Thank you for the helpful comments to our submitted manuscript.

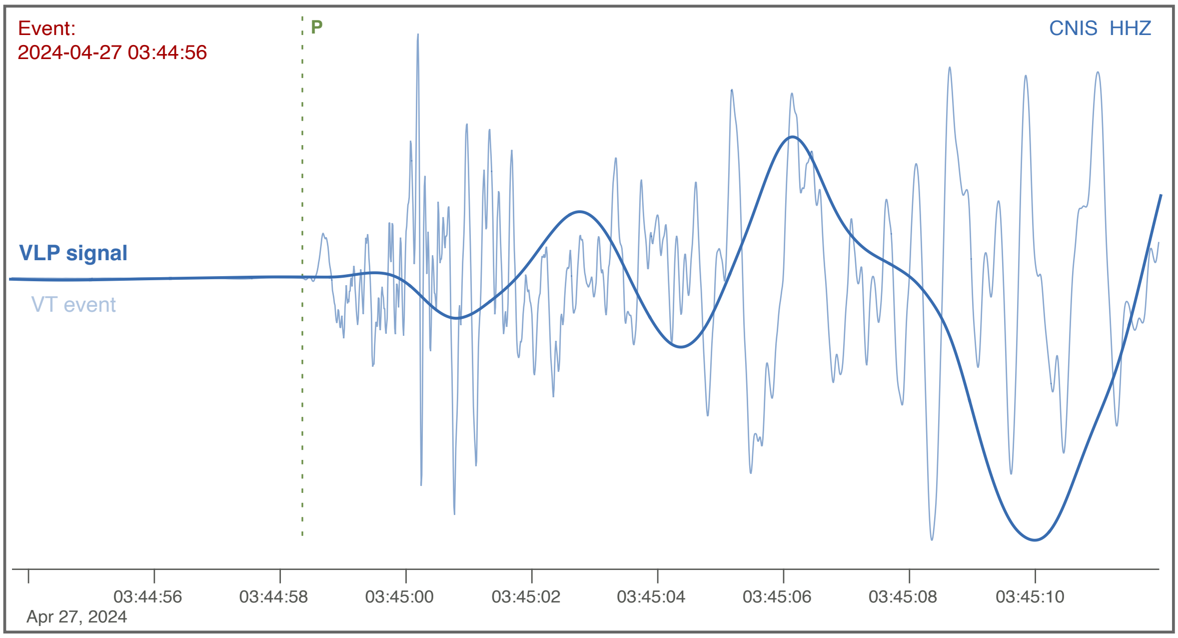
The aim of our VT analysis was to obtain the moment tensor for the largest possible number of events. With this goal, we started with the most energetic VTs and progressively processed smaller ones. In the end, we were able to analyze VT events of magnitude as low as Md 2.5. We obtained a wealth number of VTs, as also stated by reviewer 1, which represents a substantial improvement against previous studies. Unfortunately with the given network and complex geometry, it is not possible to study smaller magnitude events based on our state-of-the-art methodology.

Non-double couple components were calculated for all the events (using deviatoric and full moment tensor inversions – they are reported in Suppl. Figs. 4, 6). However, since they were subjected to significant uncertainties, we preferred not to discuss or interpret them. Non-double couple components can be strongly biased by imperfect, simplyfied 1-D velocity models, non-modeled site or path effects, and always require thorough analysis of the uncertainties. On the other hand, the events' double couple components were consistent between the different inversions, and their similarity was confirmed by the waveform similarity clustering. Therefore we decided to only analyse and interprete those well resolved double-couple components further.

Signal analysis suggest that the start of VT and VLP event is synchronous; as the location of the VT is variable with respect to the resonant source, the authors should discuss if a variable time shift is expected and if this time shift is observed on stations at increasing distance from the oscillating source.
The focus on the strongest VT events does not permit to assess if an energy threshold exist to trigger the VLP events. Most important, one could argue the

reverse, that is that fluid flux variation induce change in the pressure source that in turns triggers the VT seismicity……..ideally, the link between VLP and LP should be discussed and with non-double couple events.

The low frequencies of the VLPs (~0.1 Hz) hinders the identification and picking of a sharp onset, also because the VTs generate low frequency signals as well, overlapping with the long-lasting VLP.
What we can state is that, in all cases when a VLP signal was observed, it never arrived before the VT signal. An example of VT and VLP onsets is shown in the attached figure below.



On this basis, we can state that the VLP does not precede the VT and that a time delay between VT and VLP can not be accurately estimated.

We can also observe that the low frequency seismic signal shows the overlap of a shorter duration signal, the direct VT contribution, and a longer duration, monochromatic, and smoothly decaying signal, which we refer as VLP. Waveforms recorded at stations with increasing distance from the resonating source present a superposition of the low-frequency band of the VT signal and the VLP, rendering them indistinguishable.

All these aspects heve also been discussed in our reply to main comment 1.

On the high intensity side of the spectrum, are regional eartquakes able to trigger the same resonance?
The authors could therefore show some examples of VT which are not associated with VLP.

We tested this hypothesis for about 20 regional earthquakes (see reply to main comment 1): we found no evidence regarding the triggering of the resonator by regional events, but we cannot fully exclude the process. We clarified in the article the fact that we did not observe a magnitude threshold for the occurrence of the

VLPs events. Furthermore, we add a supplementary figure where we show waveforms recorded at one station for two events having very similar hypocenters and magnitudes: one has a very clear VLP signal and the other does not.

A second and main concerns is the interpretation of the fixed frequency in the amplitude spectra of the signals. For a given vibration mode, the frequency depends not only on the crack geometry (length L and width d) but most important on the crack stiffness $C = bL/\mu d$ (b= bulk modulus of the fluid, and μ shear modulus of the solid. The unrest phase is associated with an increase in flux of fluids with increasing equilibrium temperature (temperature at depth). A change in both shear modulus (because of heating) and most important a major change in bulk modulus of the fluid (because of the change in temperature, density and sound velocity of the fluid) is expected. As bulk modulus depend on the square of fluid sound velocity, even moderate increase in temperature and pressure of the fluid translate in large change of the crack stiffness (see for instance Maeda et al., 2017 or Journeau et al., 2024 for similar applications).
This is in my opinion the main part to be addressed in the date interpretation, how can the frequency remain the same over years if the properties and the flux of the fluid change? Conversely, should we conclude that the change observed in the fluid properties are not associated to modification of the fluid properties and flux in the oscillating fissure?

We agree with the reviewer that the crack stiffness is $C = bL/\mu d= 3(\rho f/\rho s)(a/\alpha)2(L/d)$ where ρs is the density of the solid rock matrix, ρf is the density of the fluid, a is the sound velocity of the fluid and α is the P-wave velocity of the elastic medium (from Meada et al., 2017). We also agree that the unrest process will likely cause a variation in the fluid flux and temperature which will consequently affect the density and sound velocity of the fluid.
Using Maeda's model, assuming a constant geometry and varying the density and sound velocity of the fluid by ~10%, the estimated resonance frequency would diverge by more than 3 σ from our results (0.114 +- 0.002 Hz).
We can conclude that, if there were changes in the density and velocity of the fluid, they must have been considerably small, otherwise they would have caused a drastic change in the resonance frequency, which was not observed.
With this, we are not stating that the unrest and the consequent flux changes are not affecting the resonator and the properties of the fluids inside the resonator (or at the surface). Rather, at the time when VLPs are observed (over a period of 7 years) the system conditions of the VLP source must have been very similar, given that the resonant frequency was stable with very little fluctuations.
We revised the manuscript in light of these considerations.
All those aspects have also been discussed in our reply to main comment 2.

In conclusion, I consider the topic very relevant and the study important, but it deserves a set of clarification before final publication.
Best regards,

Dear Editor,
We are thankful to the editor and reviewers for considering our manuscript, for the overall appreciation of our work and for the constructive suggestions.
In this rebuttal letter, we report the original review in black, and our reply in blue.

We report in the discussion the recent Md 4.6 earthquake, which occurred during the revision time. The event has a similar mechanism and VLP signal as previous ones and supports our interpretation.

We identified one common aspects between different comments. We discuss this aspect first, and later report all original reviewers' comments and a complete point-to-point reply.

1. Hypocentral location and geometry of resonator

We want to clarify the processes to derive the different parameters of the resonator:
- We used full waveform moment tensor inversion (GROND software) to derive centroid locations and the source parameters (such as orientation, magnitude and resonance frequency) for all VLPs.
- We used the crack model by Meada et al. (2017) to estimate the dimensions of the resonator.

All VLPs have similar waveforms, and the moment tensor inversion results show similar moment tensors and resonance frequencies. We interpret such high similarity as an indication for the repeated resonance of the same crack-like structure. In this sense, the different centroid locations obtained for different VLPs are the result of large location uncertainties, which are intrinsic to the fact that VLP signals do not show clear P or S phases. We only interpret the distribution of centroid locations to infer a rough estimate of the crack location and its uncertainty. The crack geometry, instead, can be well resolved by the result of moment tensor inversion, as solutions are similar and point to an inclined crack.
In the following step, based on the resolved crack orientation and resonance frequency, we test different, realistic rock and fluid parameters (velocity and density) to discuss the crack sizes: these dimensions fall inside the geometrical and geological boundaries of the Campi Flegrei Caldera.

REVIEWER COMMENTS:

Dear Editor,

I have now completed the second revision of the manuscript by Rapagnani and co-authors, “Coupled earthquakes and resonance processes during the uplift of Campi Flegrei Caldera.”
The Authors have satisfactorily addressed most of the concerns raised in the previous round of revision. I have appended below just a few minor suggestions to the manuscript, figures, and supplementary material. The determination of the reconstruction of the geometry of the resonator still seems unclear to me and needs further improvement. I endorse the publication of this article following these minor interventions.
Best regards

We are thankful for the endorsement.

Line-by-Line comments:
Line 40: I suggest rephrasing as follows: “After the last eruption in 1538 CE, the state of the volcano has been characterized by ground deformation […]”
Line 68: I suggest rephrasing “were never reported before” to “are yet to be reported”.
Line 74: brittle failure occurring along that borders […].
Line 94: I suggest rephrasing as follows: “with depths ranging from 2.3 to 4.2 km.”

We accepted the suggested changes.

Figure 2a: I suggest the Authors add here the supplementary Figure 10, which is very informative and would help the reader to clearly appreciate the difference between VT and VT+VLP signals.

We are thankful to the reviewer for previous suggestions, which let us to prepare *Suppl. Fig. 10*. We agree that the figure is informative to compare events with VT and VT+VLP signals. However, the purpose of *Fig. 2* is different, aiming at showing a single VT+VLP recorded at different stations. Therefore, we think that merging the two figures would be confusing for the reader and we would prefer to keep two independent figures.

Line 177: add within brackets the corresponding Md of the May 20th event.
Line 141-142: add within brackets the acronym “CLVD”.

We accepted the suggested changes.

Line 143: This description seems contradictory to what is shown in Figure 5. If you are referring to the resonator as a crack defined by the VLP event locations, with "oriented NNW-SSE" a reader can easily understand that this is the azimuth of the major axis of the ellipse. However, looking at Figure 5, the major axis seems perhaps WSW-ENE. Please clarify and add in the figure the surface projection of the inferred resonator.

We thank the reviewer for the comment. We clarified this question in our answer to the *main comment 1* and in the revised manuscript. The crack location is inferred from the centroid locations (which have intrinsically large uncertainties), while its orientation and dip angle are inferred from the moment tensors. We think that adding the surface projection of the resonator would be confusing and, in any case, redundant, given that the representative focal mechanism for the VLP cluster is shown.

Line 222: Add information about the inferred width of the resonator, e.g., "~ xxx m wide, ~1000 m and a thickness of ~0.35 m; this corresponds to crack […].

We added the the extimated width of the resonator.

Line 236: General comment: the very short delay between VT onset and VLP onset does suggest that it is specifically the P wave arrival that perturbates the resonator?

Since it is not possible to pick the VLP onset, we cannot prove that the resonator is triggered by the P-wave arrival, but that could be the case because the VLP seems to anticipate the S phase.

Line 241: General comment: from lines 223-224, it seems that the spatial extent of the crack is rather small and not sub-vertical. That recalls my comment in the previous round of revision to which the Authors have responded stating that "the spread of VLP locations as a measure of the resonator size, but rather we average the results to estimate the source location and geometry." Hence, if the spatial distribution of the VLP events is not used to constrain the geometry, the Authors should clarify how they constrain the location and geometry of the resonator.

We improved the text and clarified how we constrained the location and geometry (see reply to *main comment 1* and reply to *comment line 143*).

Line 249: change from "gases" to "fluids". Done

Figure 5: Two comments on this figure, which depends on the completeness of the supplementary material. In particular, the authors should add a tag/note on each of the reported events indicating the cluster to which the event belongs. For completeness, the hypocentral locations of the VLP events, eventually with associated uncertainties, should be reported. In Figure 5a, the ellipse embraces the VLP events, but the geometry of the resonator reported in Line 211 is not shown. In Figure 5b, the VLP hypocenters should be shown following their display in Figure 5a.

We added a catalogue file in the supplementary material in which all the events are associated with their respective cluster.
As mentioned in the *main comment 1*, we derived the location and depth of the resonator by averaging the results from the VLP waveform inversions, under the assumption that all VLP signals are produced by the same structure(s). The location uncertainty of the single events is comparable with the ellipse dimensions (in the order of ~1.4 km). In the sketch *Fig. 5b*, instead of showing the hypocentral locations of the single VLP events, we show the schematic representation of the

crack(s), with the orientation inferred by the focal mechanism and the length estimated from the resonance model.

Lines 340-341: "cm3". Use superscript for "3" instead of "^". Done

Line 342: How has the value of ~20 GPa been estimated? Shear modulus strongly depends on Vs and density.

Shear modulus was estimated using the formula $\mu = Vs^2 * \rho$,
The velocity *Vs* was taken from the model of Vanorio et al. (2005) at the depth of the resonator (~3.6 km), and the density ρ was calculated using Gardner's relation (https://doi.org/10.1190/1.1440465).
Vs = 3000 m/s, $\rho = 2600\ kg/m^3$ so $\mu = 23.4$ *GPa. We have updated the text reporting* $\mu \sim 23$ *GPa.*

The caption of Supplementary Figure 9: CO_2, 2 subscript. Done

Reviewer #2 (Remarks to the Author):

Dear Editor, I consider that the authors provided a detailed set of answer to all remarks and suggestions I submitted during the first review round.
However, some (minor) clarification is still needed about the choice of parameters adopted for crack modelling and their implications for the crack geometry.

The assumed density of the rock matrix (3 g/cm3) is quite high with respect to the lithotypes expected at Phlegrean fields (tuff, carbonate); could the authors please provide a reference and explanation for this choice?

We agree with the reviewer and changed the density value to 2.6 g/cm^3, which is equal to the one calculated using Gardner's relation with the velocity Vp = 5000 m/s provided by Vanorio et al. (2005) at the depth of the resonator (~3.6km).
*ρ = 0.31 * Vp^0.25 ~ 2.6 g/cm^3*

The selected density of the fluid (0.56 g/cm3) correspond to a temperature of 430 °C for a pressure of 1 kbar (about the depth of the resonant crack); however, the choice of different temperature will correspond to a different density; how did the author constrain the chosen set of P/T to calculate the fluid density?
Moreover, at a density of 0.56 g/cm3 (and in the reported pressure range), the expected sound speed is 0.64 km/s and not 0.46 km/s (a typo?), as reported by the authors.
We thank the reviewer for spotting the typo. We checked and recalculated the fluid properties. The temperature value was chosen based on the literature (Piochi et al. 2013) derived from a direct measurement in a 3000m-deep well. The pressure was calculated assuming a purely lithostatic gradient, with a constant rock density of 2,6 g/cm^3. Such T value may underestimate the actual temperature at the VLP source centroid and, by the same token, the homogenous-Earth approximation may lead to an overestimate of the real pressure conditions at the source. However, repeating the calculations for different P/T conditions, we obtained a set of densities and acoustic velocities with no relevant effects on the resonator's dimensions estimation. For values of T = 420° and P = *90 MPa, we have* ρ_{fluid} *= 0.525 g/cm^3 and Vp = 610 m/s*. The text and the resonance model were updated, along with *Suppl. Fig. 9*.

I consider the current version of the manuscript can be considered for publication, after the minor clarifications here proposed;
Best regards