

## Birth and growth of a volcanotectonic fault during the current volcanic unrest at Campi Flegrei caldera (Italy)

Corresponding Author: Professor Guido Giordano

**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:

**\*\* 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 Professor Giordano,

Your manuscript titled "Birth and growth of a volcanotectonic fault during the current volcanic unrest at Campi Flegrei caldera (Italy)" has now been seen by 3 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.

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.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:

Link Redacted

**\*\* This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first \*\***

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,

Carolina Ortiz Guerrero, Ph.D.  
Associate Editor, Communications Earth & Environment  
Consulting Editor, Communications Sustainability

## EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

Editorial Policy: [Policy requirements](https://www.nature.com/documents/nr-editorial-policy-checklist.pdf) (Download the link to your computer as a PDF.)

For Manuscripts that fall into the following fields:

- Behavioural and social science
- Ecological, evolutionary & environmental sciences
- Life sciences

An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript

You can download the form here:

<https://www.nature.com/documents/nr-reporting-summary.zip>

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist: [Communications Earth & Environment formatting checklist](https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf)

and also in our style and formatting guide [Communications Earth & Environment formatting guide](https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf) .

\*\*\* DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (<http://www.copdess.org/enabling-fair-data-project/> ). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at <http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf>.

In particular, the Data availability statement should include:

- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at <http://www.nature.com/sdata/policies/repositories>.

If a community resource is unavailable, data can be submitted to generalist repositories such as [figshare](https://figshare.com/) or [Dryad Digital Repository](http://datadryad.org/). Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at <http://www.nature.com/authors/policies/availability.html>.

## REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author): [See attachment].

Reviewer #2 (Remarks to the Author): [See attachment].

The manuscript reports a statistical and geometric analysis of recent (2019-2024) seismicity during 'unrest' and active uplift of Campi Flegrei caldera volcano in Italy. The analysis involves the use of the least square root of distance method (LRM) to test the fit (clustering) of earthquake hypocentre locations to potential fault plane orientations. This method, as well as its pros and cons, are well explained. Overall the analysis seems carefully done and robust.

This study nicely augments several recent geophysical or geodetic studies on the ongoing unrest at Campi Flegrei. In several respects it resembles in its topic and aims the recent paper by Scott di Uccio et al. (2024, *Geophys. Res. Lett.*), which used the same or very similar datasets and presented some similar general conclusions. The present manuscript differs from that work, however, in (i) its more intricate methodology for identification of potential failure planes, (ii) the more up-to-date time span considered and (iii) its principal finding of a localization since 2023 of seismicity on a ENE-WSW striking and NNW-dipping structure.

Overall the study's results are well presented and its main findings are well supported by the data as presented. I think it represents an important contribution to our understanding of the ongoing evolution of this highly-hazardous and high-risk volcanic system.

There are nonetheless a few issues that could/should be addressed before publication:

(1) The manuscript introduction focusses heavily on the Failure Forecast Model (FFM) and its application to Campi Flegrei and elsewhere. There is only a very brief mention of the FFM in the Discussion section, however, where it is stated that the implications for the FFM from the data and analysis presented are inconclusive. This 'lack of delivery' from the introduction to the conclusions makes the manuscript seem a bit unbalanced. Probably the manuscript's Introduction section should be reorientated a bit more toward imaging/delineation of seismogenic structures and the emergence of potential magma conduits, rather than application of the FFM.

(2) The overall annular (elliptical) distribution of hypocenters at Campi Flegrei, as seen in Figure 2, is not mentioned at all in the text ('elephant in the room'). That the overall distribution is non-planar, yet the author's approach considers only planar failure surfaces initially seems a bit incongruous. At a minimum there should be a rationale provided for why the apparent overall localization (emergence) of a ring fracture system is ignored and why instead the study reduces to consideration of smaller-scale planar features.

(3) The plan view images in Figure 2 are good to show the development of seismicity in 2D, but it would be best to show also the distribution in cross-section to give a sense of the distribution in 3D. I suggest showing a map of the events colour coded for depth and perhaps scaled for magnitude. Beside this map one would ideally plot two cross-sections, one NE-SW and one NW-SE. These images could be appended to the existing Figure 2 as a third row of plots, or perhaps included as an additional figure. Either way such a visualization would be extremely helpful for the reader.

(4) Following from (1+2), links to other studies of intra-caldera seismicity at other resurgent caldera systems, specifically studies of hypocentre location and related analysis would be useful for context on the originality and wider significance of this study. In particular, a brief comparisons to the cases of unrest at Rabaul caldera, New Britain (e.g. Mori and McKee, 1987, *Science*, and other works) and Sierra Negra caldera, Galapagos (e.g. Bell et al 2021, *Nature Comms*, and other works), and Long Valley caldera, California (Hill et al 2020, *J. Volcanol. Geotherm. Res.*) and other works) would be useful. Currently the perspective of the manuscript is very focused on Campi Flegrei (naturally so), whereas a general reader may appreciate a wider context to the approach and results presented. Reducing the focus on the FFM in the introduction might facilitate this.

(5) A clearer articulation of the implications for volcanic hazards could be made. Again analogies to other geophysically well-monitored volcanic systems would be useful to illustrate to the reader what one might expect to happen in the future with continued uplift and magma accumulation. For example, the phenomenon of shear fracturing (normal and strike-slip) with magnitudes of M3-M4 preceding or accompanying dyke intrusion that feeds an eruption has been well documented at recent eruptions at Kilauea (in 2018) and Bardarbunga (in 2014) volcanoes, among others.

(6) Finally, and linked to points (3+4) above, it might be worth considering for the volcanic hazard that the seismogenic intra-caldera structures at depth may not correspond cleanly with the eventual locations of magma eruption at the surface. At both Rabaul and Sierra Negra, for instance, the vents were located at some horizontal distance (up to several km) outside the seismically-active ring structure.

I attach a marked up pdf of the manuscript with a few further, if more minor, scientific comments (pink) and editorial suggestions (yellow), which I hope the authors might find helpful to improve the manuscript before its final publication.

Sincerely,

Eoghan Holohan (Dublin, 16.05.2025)

Reviewer #3 (Remarks to the Author):

Review of Birth and growth of a volcanotectonic fault during the current volcanic unrest at Campi Flegrei caldera (Italy) by Giordano et al., submitted to *CE&E*.

Overview:

Giordano et al. present novel models of seismic clustering through time, interpreted as direct evidence of fault nucleation from 2023. These models have significant implications for the development of the current unrest at the Campi Flegrei caldera. The model is based on a novel clustering analysis using a different norm, named Least Root Squares, which necessitates a specific Monte Carlo approach to converge on the optimal solution. The primary aim of this approach is to avoid discarding data distant from the trend; under the new norm, such data has a lesser impact on the final computation. The result is the definition of a  $N249^{\circ}\pm4^{\circ}$ ,  $53^{\circ}\pm1^{\circ}$  fault plane representing a feature in the seismic-deformation response of the caldera that indicates critical failure. The location of the extended fault under the point of maximum ground uplift suggests a first condition for rise of deep materials.

The conclusions are original and of interest to the community. The manuscript is concise and well written. The definition of the PIF brings forward a novel feature that can spark debate on the nature of the current unrest. The technique is novel but requires more details and tests to support the conclusions. The interpretation needs a more thorough assessment, especially of recent results published regarding the caldera unrest. Presentation needs revision.

#### Technique

The technique employed addresses the shortcomings of the least squares approach (LSQ) by modifying the norm to a square root relative to the distance between the data and the proposed model. This approach provides a more effective means of including outliers without having to discard them qualitatively, as it does not make any assumptions about Gaussianity, and the tails of the data probability distribution are better accounted for. It requires an additional computational burden, as Monte-Carlo-like solutions are necessary to resolve the problem. I have the following comments:

1. Before approaching a square-root norm solution, the standard procedure is to attempt a total variation norm (norm L1). The square-root norm allows for increased consideration of outliers, as it differs from the exponential distribution underlying the L1 solution, which is not a standard in fitting applications (at least as far as I know). The material section lacks references that demonstrate, through theoretical and synthetic studies, the validity of the approach, which would help the expert reader assess the technique.
2. More generally, the Materials should provide an assessment of the technique, including the Monte Carlo Convergent (MCC) type search. If references are available, they will help evaluate the validity of the method in known scenarios, enhancing our understanding of the challenges this same method could face in a volcano. If they are not, such technical work should be tested within this study or through technical papers that precede the present work.
3. The developed code is currently unavailable, but it is crucial for evaluating the validity of the approach employed. It should be made fully available through open-access repositories with sample datasets, allowing reviewers and the wider community to test it. The study currently lacks the open-access features essential for publication in CE&E, despite the details provided in the materials.
4. There is no discussion of the influence of event numbers on the technique. The study began in 2019 with 536 events, and the number of events increased each year until they tripled in 2022. In 2023, the number of events is approximately seven times that of 2019 and more than twice that of the previous year. The distribution sampling in the diffusive and non-diffusive years is thus very different. The number of earthquakes should influence the analysis and should be tested by random sampling of the available earthquakes in the most numerous years.
5. The authors state that Scotto di Uccio et al. (2024) provided a qualitative interpretation of the fault planes based on correlation with geomorphology. However, these authors tested their novel locations using an updated version of NonLinLoc against those obtained with older versions, other methods, and locations provided by the Osservatorio Vesuviano. They conclude that their locations exhibit higher quality in terms of uncertainty compared to other location methods. The clustering obtained here depends on the quality of the locations routinely gathered by the Osservatorio Vesuviano. The same analysis should be conducted on more than one location dataset to demonstrate the reliability of the technique.

#### Results and presentation

The stated objective is to determine whether, when, and where seismicity has transitioned from diffuse microfracturing to localization along a well-defined fault plane. This assessment relies solely on the quantitative approach developed in the materials, without comparison to surface features, as in Scotto di Uccio et al. (2024). I have the following comments:

6. I view this lack of comparison as detrimental to the authors' inferences. Instead of stating that no fault appears to correlate with the (quite extensive) inferred deep fault, it would be much better to show surface features in a way that allows the reader to draw this conclusion. There have been numerous recent studies detailing faults at Campi Flegrei, beginning with those cited in Scotto di Uccio et al. (2024).
7. The only geomorphological features (caldera rim bounds) are presented in Fig. 1. However, the information it provides, given the short format and length restrictions, is limited to station distribution. Is this figure necessary, considering it is cited only once and not referenced for station distribution (stations are also in Fig. 2)? Why are Vesuvius and Ischia Island included, yet only mentioned in the figure caption and shown so prominently? This figure could be reworked into a single panel above Figure 2, focusing solely on Campi Flegrei.
8. Perhaps due to the final manuscript's transformation into the journal format, Figures 2-4 have low quality, with labels that are small and sometimes unreadable. Figure 2, in particular, has all its internal labels unreadable. Moreover, it would be more sensible to show a geomorphological map with the discussed geological features rather than one that shows what

looks like roads. Seismicity generally occupies less than half of the figure area, so the panel could be made smaller or, ideally, only two years per row could be shown. This figure needs to be completely redrawn.

9. I am a big fan of bird's-eye views, like those in Figs. 3-4. However, these views make it challenging to understand the exact shape and directionality of the PIF plane. A more standard WE/SN perspective on the PIF would greatly enhance understanding of its features.

10. Looking at Fig. 5, I would have guessed downthrow toward SSE; the authors should indicate the directionality of the profile, as it was intuitive for me to view it from the SSW.

#### Interpretation

I have the following comments:

11. As the author states, an increasing number of scientific works are now suggesting the direct involvement of magma at relatively shallow levels. However, there are recent papers that either discard by any means the rise of magma as the cause of the current unrest (Vanorio et al., 2025, *Science Advances*) or show the effect of pore-fluid pressure and thermoporoelastic processes as the underlying mechanism triggering the unrest (Nespoli et al., 2023; De Siena et al., 2024). Faults like those inferred from the analysis do not require, in my experience, the presence of magma: they can develop at the boundary of any thermo-poroelastic reservoir, which stresses the weaker surrounding fault. This does not mean that the PIF inference is any weaker, but the interpretation in terms of rupture should take this into account.

12. The area intersected by the PIF has been the target of several investigations, suggesting the existence of a stressed boundary, for example, through InSAR measurements via the THD method (Pepe et al., 2019 and especially Tizzani et al., 2024 – see particularly their Fig. 17). The inferred dip seems to correspond to several earthquake migrations existing at least since 2018-2019, corresponding to a change from compressive towards the central reservoirs to extensive in GPS measurements (De Siena et al., 2024, see their Figs. 2-3 and supplementary materials). These results appear to support the opening of the structure, with the deformation anomaly exhibiting similar responses prior to 2023. Deformation is expected to precede earthquakes, which involve rupture. The lack of discussion of time-dependent deformation features is detrimental to the drawn conclusions.

I finally note these two typos:

13. Line 26, page 4, (Ricciolino et al. 2024).

14. Line 29, page 15, “farer”?

References in this review, not in the text - they act as a sample to discuss uncertainties about interpretation and deformation features. The author might find others more appropriate.

De Siena, L., Amoroso, A., Petrosino, S., & Crescentini, L. (2024). Geophysical responses to an environmentally-boosted volcanic unrest. *Geophysical Research Letters*, 51, e2023GL104895. <https://doi.org/10.1029/2023GL104895>

Pepe, S., De Siena, L., Barone, A., Castaldo, R., D'Auria, L., Manzo, M., ... & Tizzani, P. (2019). Volcanic structures investigation through SAR and seismic interferometric methods: The 2011–2013 Campi Flegrei unrest episode. *Remote Sensing of Environment*, 234, 111440.

Tizzani, P., Fernández, J., Vitale, A., Escayo, J., Barone, A., Castaldo, R., ... & Camacho, A. G. (2024). 4D imaging of the volcano feeding system beneath the urban area of the Campi Flegrei caldera. *Remote Sensing of Environment*, 315, 114480.

Vanorio, T., Geremia, D., De Landro, G., & Guo, T. (2025). The recurrence of geophysical manifestations at the Campi Flegrei caldera. *Science Advances*, 11(18), eadt2067.

Best Wishes,

Luca De Siena

\*\* Visit Nature Research's author and referees' website at <a href="http://www.nature.com/authors">www.nature.com/authors</a> for information about policies, services and author benefits\*\*

Communications Earth & Environment is committed to improving transparency in authorship. As part of our efforts in this direction, we are now requesting that all authors identified as 'corresponding author' create and link their Open Researcher and Contributor Identifier (ORCID) with their account on the Manuscript Tracking System prior to acceptance. ORCID helps the scientific community achieve unambiguous attribution of all scholarly contributions. You can create and link your ORCID

from the home page of the Manuscript Tracking System by clicking on 'Modify my Springer Nature account' and following the instructions in the link below. Please also inform all co-authors that they can add their ORCIDs to their accounts and that they must do so prior to acceptance.

<https://www.springernature.com/gp/researchers/orcid/orcid-for-nature-research>

For more information please visit <http://www.springernature.com/orcid>

If you experience problems in linking your ORCID, please contact the [Platform Support Helpdesk](http://platformsupport.nature.com/).

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 Professor Giordano,

Your manuscript titled "Birth and growth of a volcanotectonic fault during the current volcanic unrest at Campi Flegrei caldera (Italy)" 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.

#### EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

\*\*\*\*\*Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. \*\*\*\*\*

Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

#### SUBMISSION INFORMATION:

In order to accept your paper, we require the files listed at the end of the Editorial Requests Table; the list of required files is also available at <https://www.nature.com/documents/commsj-file-checklist.pdf>.

#### OPEN ACCESS:

Communications Earth & Environment is a fully open access journal. Articles are made freely accessible on publication. For further information about article processing charges, open access funding, and advice and support from Nature Portfolio, please visit <https://www.nature.com/commsenv/open-access>

At acceptance, you will be provided with instructions for completing the open access licence agreement on behalf of all authors. This grants us the necessary permissions to publish your paper. Additionally, you will be asked to declare that all required third party permissions have been obtained, and to provide billing information in order to pay the article-processing charge (APC).

Please use the following link to submit the above items:

Link Redacted

**\*\* This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first \*\***

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

Best regards,

Joe Aslin

Deputy Editor,  
Communications Earth & Environment

Consulting Editor,  
Communications Sustainability

<https://www.nature.com/commsenv/>  
Twitter: @CommsEarth

#### REVIEWERS' COMMENTS:

##### Reviewer #1 (Remarks to the Author):

The authors have addressed the comments raised in the former version, supporting their analysis and significantly improve the quality of the figures.

Again, as already pointed out in the former comments, I ask the authors to correctly refer to moment magnitude and not duration magnitude when discussing about the maximum magnitude expected in the area, since this is what was inferred in Scotto di Uccio et al. (2024) and Iervolino et al. (2024)

With this final modification, I support the manuscript for publication.

##### Reviewer #2 (Remarks to the Author):

I appreciate the efforts made to address my comments on the earlier version and to revise the manuscript, which I think has been very substantially improved.

My main concern regarding the first version of this manuscript was a 'lack of delivery' (or a lack of balance) regarding how the proposed earthquake clustering method and its results relate to and improve upon the Failure Forecast Method. To rectify this imbalance, I suggested that the manuscript's Introduction section might be reorientated a bit more toward imaging of seismogenic structures and the emergence of potential magma conduits, rather than application of the FFM. The authors have responded that they prefer to maintain focus on the FFM in the introduction and to rebalance the Discussion section by better explaining the study's implications for use of the FFM. I fully respect the authors' decision; their rationale is well explained in their rebuttal letter, and they have clearly attempted to better articulate how their method can augment or improve upon the FFM approaches.

Nonetheless, the Abstract and Introduction could still be more direct about the aims and scope of the paper with respect to the FFM. I suggest a restructuring of the Introduction to facilitate focus, to eliminate some repetition and to remove some potentially redundant text. A restructured paragraph order could be (i) risk and current activity at Campi Flegrei; (ii) the principles of FFM and the past application of FFM to Campi Flegrei; (iii) the problem with FFM (iv) the contribution of the present study. I also suggest some more minor restructuring of the first few paragraphs of the Discussion section to achieve a similar streamlining. The attached document with tracked changes should help the authors to gauge the impact of this suggested editing, BUT, for clarity, please first read the suggestions with tracked changes turned off.

A second concern I raised regarding the overall annual (non-planar) distribution of seismicity and its bearing on the use of planar fault estimations has been dealt with adequately in the revised Approach section. Similarly, my major comment 3 on the original manuscript regarding the addition of cross-sections to show the three-dimensional distribution of the seismicity has been well addressed in the revised Figure 2. In general, all the figures have been greatly improved in terms of clarity and quality.

My suggestions for more comparison to other restless calderas (comments 4 and 5 on the previous manuscript version) were not adopted in the revised version, given the abovementioned decision to retain focus on the FFM. I appreciate the authors' perspective here. The short note at the start of the revised Discussion section alerting the reader to the existence of similar phenomenon at other calderas, and the note at the end of the Discussion on the transferability of the methodology proposed here, are both fine. However, I do think it important to acknowledge explicitly that other studies have similarly - if not exactly in the same way - been able to delineate the geometry and evolution of intracaldera faults systems from earthquake hypocentre locations (see suggested edits on the attached doc).

Overall, my comments/critiques of the revised manuscript are thus mainly of an editorial nature. I congratulate the authors on their fine work. I hope the above suggestions and those in the attached document will help to finalize the paper.

Sincerely,

Eoghan Holohan (Dublin, 05.08.2025)

Reviewer #3 (Remarks to the Author):

The authors correctly addressed most of the critical comments, improving the manuscript. Figures now clarify extension and depth of the PIF, and I am convinced by the authors' responses to my doubts regarding the technique and interpretation.

I report here a simple reference to the numbered point of my previous review, to show where they answered satisfactorily and where more discussion is needed.

**Technical Points 1, 2, 4, 6-10, 12 and 13:**

The additions to the paper and responses fully address my comments.

**Point 3:**

This is more of an editorial and policy matter - if CE&E accepts that the code must be asked to the authors I have no further issue. I report below regulations regarding reporting of computer codes in Nature journals (<https://www.nature.com/nature-portfolio/editorial-policies/reporting-standards>) so that the authors and editor can better resolve any matter regarding code availability:

***Availability and peer review of computer code and algorithm***

***Authors must make available upon request, to editors and reviewers, any previously unreported custom computer code or algorithm used to generate results that are reported in the paper and central to its main claims. Any reason that would preclude the need for code or algorithm sharing will be evaluated by the editors who reserve the right to decline the paper if important code is unavailable.***

***For all studies using custom code or mathematical algorithm that is deemed central to the conclusions, a statement must be included under the heading "Code availability", indicating whether and how the code or algorithm can be accessed, including any restrictions to access. Code availability statements should be provided as a separate section after the data availability statement but before the references.***

***Upon publication, Nature Portfolio journals consider it best practice to release custom computer code in a way that allows readers to repeat the published results. Code should be deposited in a DOI-minting repository such as Zenodo or Code Ocean and cited in the reference list following the guidelines described here. Authors are encouraged to manage subsequent code versions and to use a license approved by the open source initiative. Full details about how the code can be accessed and any restrictions must be described in the Code Availability statement.***

***Point 5:***

***The importance of assessing the PIF to understand Campi Flegrei current unrest is undeniable, as is a test with other location datasets that are available at the caldera. The implementation of the algorithm on the mentioned datasets still offers snapshots on the PIF, allowing the authors to evaluate technically how reliable the structure might be and consistent with that obtained so far. There are obvious problems affecting routine locations at the Osservatorio Vesuviano even above the chosen magnitude threshold that might corrupt the definition of the PIF structure. As the three mentioned datasets (Tramelli, Giacomuzzi and Scotto di Uccio) are available from repositories (one from a co-author) and the code can be swiftly implemented, I still see this lack of comparison as detrimental. The author can discuss this further in their response, but this will certainly be a question that the wider community will ask.***

***Point 11:***

***I acknowledge the work can disregard differences between interpretations and the PIF is independent of such interpretations. My comment was more about the impact that such a structure could have in the context of a magmatic or non-magmatic unrest. While it is challenging to explain the current unrest without magma for many, it has been done recently (Vanorio et al., 2025, Science Advances; De Landro et al., 2025, Nature: Communications). Explaining how the PIF would interact with this scenario could add impact and reach, but I understand if the authors believe this to be unnecessary.***

***Best Wishes***

***Luca De Siena***

***\*\* Visit Nature Portfolio's author and referees' website at <http://www.nature.com/authors> for information about policies, services and***

***Open Access This Peer Review File is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.***

***In cases where reviewers are anonymous, credit should be given to 'Anonymous Referee' and the source.***

***The images or other third party material in this Peer Review File are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.***

***To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/>***

**Review of the manuscript “Birth and growth of a volcanotectonic fault during the current volcanic unrest at Campi Flegrei caldera (Italy)” by Giordano et al.**

Dear Editor,

I hereby report my comments for the submitted version of the manuscript. The manuscript is well written overall and focuses on the identification of a novel activated structure within the Campi Flegrei area, which is undergoing a continuous ground uplift with a relatively high seismicity rate in the last years. The authors identified this structure through a refined spatio-temporal analysis, revealing the clustering of the seismicity along the mentioned structure since 2023. Despite within the manuscript the discussions support the proposed interpretation, I have identified some points which might be better clarified and worth of further investigation.

**Major points:**

- As a general observation, most of the figures need to be improved, in terms of quality and resolution. Figure 2 looks very crowded and blurred when zoomed for inspection. Moreover, no information on the event depth can be inferred from this representation. The authors are invited to improve the figure. Also Figure 3 appears blurred when zoomed, with labels on the right panels difficult to read. Please, remove words underlined in red from the left panels, also in Figure 4.
- P4-L25: For the analysis, the authors used the catalog provided by the Osservatorio Vesuviano, whose hypocenters are obtained through absolute location techniques. However, relocated catalogs obtained through relative location techniques or implementing source-specific corrections might feature a higher degree of clustering as compared to absolute locations, simplifying the identification of seismicity patterns, as also observed in the Campi Flegrei area, along with lower location uncertainties (Tramelli et al., 2022; Scotto di Uccio et al., 2024; Giacomuzzi et al., 2025). Moreover, artificial effects introduced by the discretization of the investigated area emerge when zooming into the catalog of the Osservatorio Vesuviano, leading to vertical and horizontal stripes of seismicity, which also include some  $M_d > 2.5$  earthquakes.

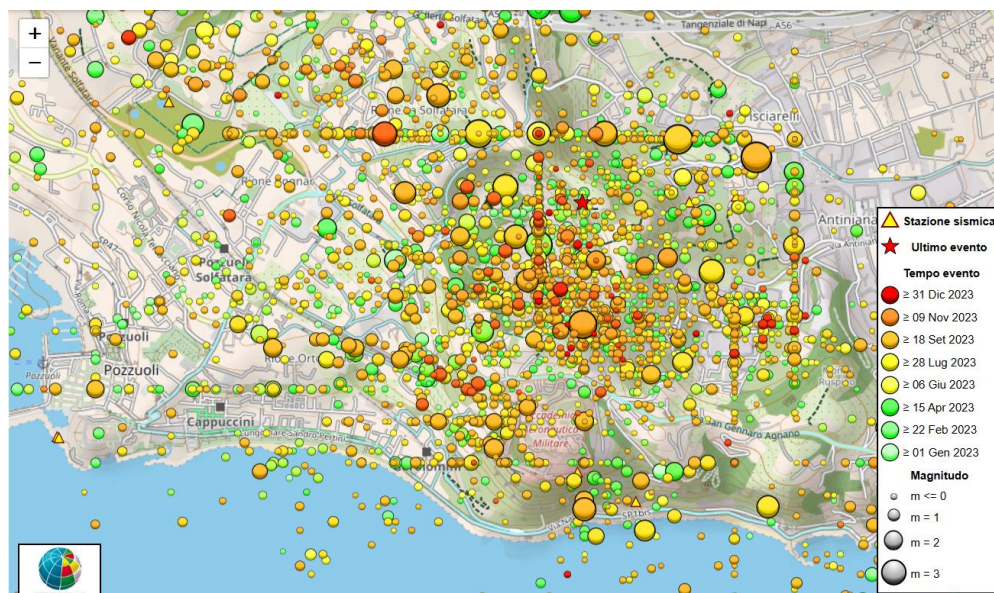


Figure 1) Snapshot extracted from the Osservatorio Vesuviano catalog for the 2023  
(<https://terremoti.ov.ingv.it/gossip/flegrei/2023>)

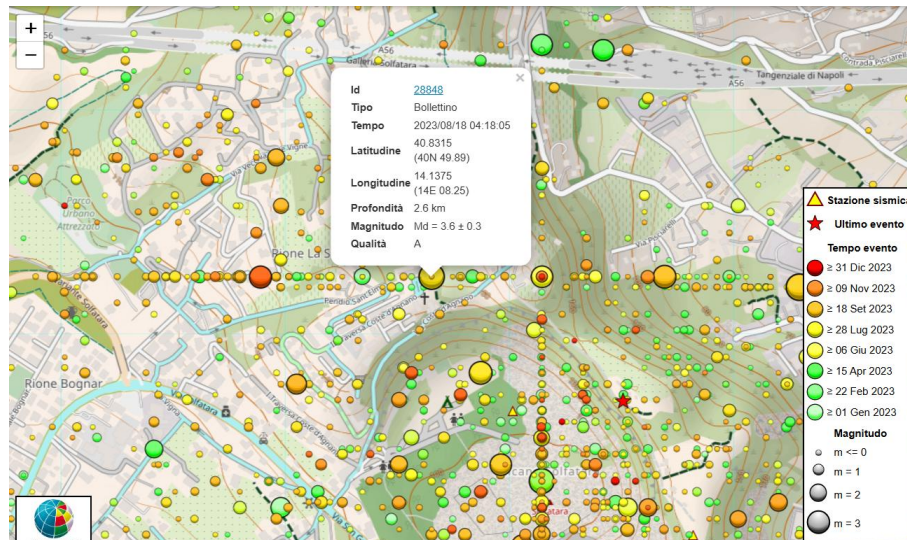


Figure 2) Md 3.6 earthquake located within a horizontal seismicity stripe.

The authors should better support the choice of the starting catalog and discuss the use of a higher-resolution relocated catalog.

- P4-L31: The authors report the average spatial location uncertainties for the hypocenters in the selected Osservatorio Vesuviano catalog. However, the authors should discuss the different resolution in earthquake location for onshore and offshore seismicity, since the latter typically occurs deeper and the density of stations at sea is lower than the analogous onshore. Do the authors believe that the difference in resolution between onshore and offshore events can prevent from identifying seismicity clusters at sea?
- P6-L41: How do the authors interpret the possibility that the same cylinder features different best fit planes in different years? Cylinder 4.4 is characterized by variations in the strike and dip from 2019 to 2021, also with differences of 70° and 45° in strike and dip direction, respectively. What might cause these variations?
- P7-L18: The area of Bagnoli hosted the Md 4.2 earthquake in 2023. How does the best fit plane relate to the orientation of the N-S sub-vertical structure identified in Scotto di Uccio et al., (2024). From the representation of the cylinder map in Figure M1, the area is covered by the cylinders 8\_5 and 7\_6, which are characterized by different values in strike and dip as compared to the mentioned structure.
- P9-L1: The authors suggest clusters 6\_3, 6\_4, 5\_4 and 7\_3 as PIF. Did any major earthquake occur within clusters? Are the estimated values in agreement with focal mechanisms for major events/composite focal mechanisms for earthquakes in the area?
- P9-L27: The authors stated that lower standard deviation values on the strike and dip measurements from 2023 are indicative of the seismicity clustering along the identified structure. Could the observed feature simply result from the increase in the number of earthquakes within the PIF, moving from dozens of earthquakes in 2019 to hundreds of earthquakes? This could lead to more constrained inversion of events within the cylinder.

## Minor points

- P1-L34: The authors could better describe the alerts levels proposed for the Campi Flegrei region.
- P1- L37: The author should change the reported maximum magnitude, given the occurrence of the Md 4.6 earthquake on March 13<sup>th</sup>, 2025.
- P5-L18: How did the authors choose the extension of the cylinders for the inversion?
- P6-L38: Please, check the number of events. Some of them slightly differ from the corresponding in the Supplementary Materials.
- P8-L12: How is the angular distance evaluated? Please, specify.
- P14-L13: The maximum magnitude proposed in Iervolino et al. (2024) is expressed in terms of moment magnitude, as also reported in Scotto di Uccio et al., (2024)

## References

- Giacomuzzi, G., Fonzetti, R., Govoni, A., De Gori, P., & Chiarabba, C. (2025). Causal processes of shallow and deep seismicity at Campi Flegrei caldera. *Communications Earth & Environment*, 6(1), 70.
- Iervolino, I., Cito, P., De Falco, M., Festa, G., Herrmann, M., Lomax, A., ... & Zollo, A. (2024). Seismic risk mitigation at Campi Flegrei in volcanic unrest. *Nature Communications*, 15(1), 1-14.
- Tramelli, A., Giudicepietro, F., Ricciolino, P., & Chiodini, G. (2022). The seismicity of Campi Flegrei in the contest of an evolving long term unrest. *Scientific reports*, 12(1), 2900.
- Scotto di Uccio, F., Lomax, A., Natale, J., Muzellec, T., Festa, G., Nazeri, S., ... & Zollo, A. (2024). Delineation and fine-scale structure of fault zones activated during the 2014–2024 unrest at the Campi Flegrei caldera (Southern Italy) from high-precision earthquake locations. *Geophysical Research Letters*, 51(12), e2023GL107680.

# Birth and growth of a volcanotectonic fault during the current volcanic unrest at Campi Flegrei caldera (Italy)

Authors: <sup>1\*</sup>Giordano G., <sup>1</sup>Alfonsi G., <sup>1\*</sup>Salvini F., <sup>2</sup>Bianco F., <sup>3</sup>Chiarabba C., <sup>2</sup>Di Vito M., <sup>2</sup>Tramelli A.

<sup>1</sup> Dipartimento di Scienze – Scienze Geologiche, Università RomaTre, Largo San Leonardo Murialdo 1, 00146, Rome, Italy

<sup>2</sup> Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Vesuviano, Napoli, Italy

<sup>3</sup> Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143, Rome, Italy

\*Corresponding authors: [guido.giordano@uniroma3.it](mailto:guido.giordano@uniroma3.it); [francesco.salvini@uniroma3.it](mailto:francesco.salvini@uniroma3.it)

## Abstract

The ~~2006 ongoing unrest~~ at the highly populated Campi Flegrei caldera is accompanied by incremental seismic activity, ground uplift and geochemical anomalies which are raising severe public concern. Here we show a ~~progressive clustering of seismicity started in 2023~~ along a ~~preferential N249°±4°, 53°±1° plane near the center of the caldera, concentrating more than 50% of seismic events and most of the released seismic energy. This clustering is evidence for an internal process that drives the transition from diffuse micro-seismicity to the development of an extensional fault in its initial stages. The nucleation (or reactivation) of this fault represents a significant event for volcanic hazard evaluation at Campi Flegrei and indicates that rocks may have overcome elastic deformation resulted, until 2023, in an almost perfect axisymmetric uplift around the caldera center and are experiencing conditions for critical failure since 2023.~~

## Main

Multiparametric monitoring of volcanic unrest at quiescent calderas includes detection of seismicity, ground deformation and geochemical anomalies. The acceleration of these monitored parameters is crucial for predicting the progression of an unrest toward an eruption, as they would indicate the behavior of materials approaching failure (failure forecast method; FFM), hence indicating the conditions at which magma pressure can induce a dyke to propagate through the country rocks (Voight 1988).

Common applications of the FFM to volcanic unrest target the acceleration over time of seismicity and ground deformation (Cornelius and Voight, 1995; Boué et al 2015; Robertson and Kilburn, 2016; Kilburn 2018; Aji et al. 2024). Kilburn (2018) proposed the mutual dependence of ground deformation and volcanotectonic (VT) seismicity as the expression, respectively, of the elastic versus inelastic response of the crust to magma pressurization, where VT earthquakes represent

1 rock fracturing beyond the limit of its elastic deformation. Accelerations of monitored parameters  
2 are commonly evaluated upon variations of ~~usually monitored~~ scalar quantities, e.g. the number  
3 of earthquakes per day and/or the ~~absolute~~ ground uplift at a specific monitoring site (e.g.  
4 Bevilacqua et al. 2024). **This is a reasonable assumption** for seismic activity during volcanic unrests,  
5 particularly in the early stages preceding the final magma ascent. During these stages, seismicity  
6 tends to be distributed within rock volumes occupied by the hydrothermal system, typically at  
7 depths  $\leq 2\text{--}3$  km. It is dominated by scattered swarms of small magnitude VT earthquakes  
8 (commonly  $M \leq 3$ ), associated with diffuse microfracturing (McNutt 1996, 2002; Thompson 2016;  
9 Saccorotti and Lokmer 2021). Seismic swarms differ from seismic sequences in that they do not  
10 follow or precede a mainshock (Benoit and McNutt, 1996). In volcanic environments they are not  
11 associated with extensive fault planes ~~but~~ are commonly attributed to rock microfracturing  
12 resulting from variations in pore pressure, similarly to fluid-induced seismicity (e.g. Fischer and  
13 Hainzl, 2021; Fischer et al. 2023), during episodes of pressurizations of the hydrothermal systems,  
14 possibly in relation to magma migration and degassing (Godano et al. 2023; Nespoli et al. 2023).

15 The Campi Flegrei caldera (Fig. 1) **is arguably the most at risk** on Earth, with nearly 350,000 people  
16 exposed to the threat of immediate evacuation in case of an impending eruption (Rosi et al. 2022).  
17 It has been active since at least 110 ka (Sparice et al. 2024). After long deflation following the last  
18 eruption in 1538 (Di Vito et al. 2016), unrest episodes characterized by ground uplift and seismicity  
19 occurred in the ~~XX~~ century in 1950–51, 1969–72 and 1982–84 (Del Gaudio et al. 2010). The ~~most~~  
20 ~~recent and ongoing~~ period of unrest started in 2005, characterized by progressive increase in  
21 ground uplift, a rising number of earthquakes with growing maximum magnitude and an  
22 escalation of the seismic energy released, as well as geochemical anomalies (e.g. Del Gaudio et al.  
23 2010; Chiodini et al. 2012, 2015, Trasatti et al. 2015; Tramelli et al. 2021; Del Pezzo and Bianco,  
24 2024; Giacomuzzi et al. 2024, 2025; Astort et al. 2024; Caliro et al. 2025). For these reasons, since  
25 2012 the alert level at Campi Flegrei has been raised to yellow (Dipartimento della Protezione  
26 Civile, 2024). During 2023 and 2024 the number of earthquakes felt by the population has  
27 increased, with a maximum duration-magnitude,  $M_d=4$ , recorded on May 20, 2024, the largest  
28 on record since the existence of a **monitoring network** in the area. This earthquake caused limited  
29 damage to buildings but severe public concerns, also because an increasing number of scientific  
30 works are now suggesting the direct involvement of magma at relatively shallow levels (5–8 km  
31 depth) associated with the unrest (Giacomuzzi et al. 2024; Astort et al. 2024; Caliro et al. 2025).  
32 The ground uplift shows an overall symmetric bell-shape and has reached in December 2024 (time  
33 of writing) a total maximum of more than 1.36 m at the center of the caldera since ~~the beginning~~  
34 ~~of this last unrest~~ (INGV-Osservatorio Vesuviano, 2024a).

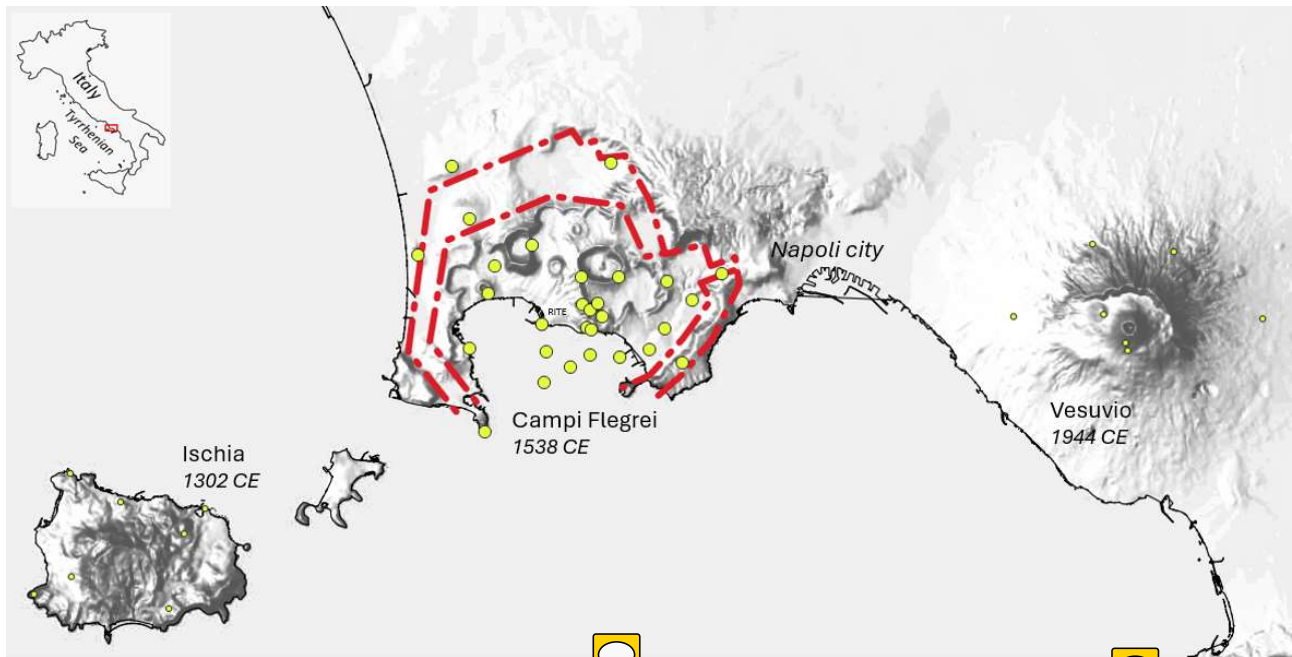


**Fig. 1 – Location of the restless Campi Flegrei caldera and its neighboring volcanoes of Vesuvius and Ischia. The date of the last eruption for each volcano is indicated in italic. Napoli city and its hinterland extend inside the floor of the Campi Flegrei caldera. The INGV-OV seismic network (large yellow dots for the Campi Flegrei and small yellow dots for Ischia and Vesuvius seismic stations) both onshore and offshore allows very precise localization of earthquakes also very small in magnitude. The simplified outlines of the Campi Flegrei nested calderas (red dashed lines) are taken from Vitale and Isaia (2014).**

FFM approaches to the accelerations of seismicity, ground deformation and geochemical anomalies during the current unrest have been applied to Campi Flegrei in a series of recent works (Kilburn et al. 2017, 2023; Bevilacqua et al. 2020, 2024; Tramelli et al. 2021). Bevilacqua et al. (2020) analyzed probabilistically the evolution of the earthquake occurrence and, by applying the FFM, forecasted the reaching of a critical state of the caldera in 2023 at the 50<sup>th</sup> percentile of probability and in 2031 at the 95<sup>th</sup> percentile. Kilburn et al. (2023), based on the variations in the relative rates of earthquake occurrence and ground uplift, suggest that since 2020 the caldera has entered an inelastic regime of deformation, that is when rock brittle failure and permanent deformation begin to prevail over the elastic response to pressurization. Bevilacqua et al. (2024) suggest that the increasing exponential relationship between ground deformation and cumulative number of earthquakes is indicative of progressive mechanical weakening of the stressed caldera rocks.

The FFM approach does not take into account the spatial distribution of the investigated parameters, so it remains uncertain if and where a fault or a series of faults accommodating the inelastic behaviour and the mechanical weakening have nucleated or reactivated. The identification of faults from clustering of hypocenters has been attempted by Scotto di Uccio et al. (2024) by comparison with documented superficial expression of preexisting volcano-tectonic lineaments. However, while showing some possible overlaps, this overlay approach remains qualitative and time-independent, and it does not provide constraints to the FFM. By contrast, the

distribution of the Energy Space Density of Campi Flegrei earthquakes from 2000 to 2023 shows, since 2023, a significant enlargement of the volume of fracturing rocks at ~3km depth approximately at the center of the caldera, that is the same region where the maximum uplift occurs (Del Pezzo and Bianco, 2024; Calò and Tramelli 2025). This enlargement strictly depends on the exponential increase of the number of earthquakes occurred in 2023 and 2024 (Fig. 2), as well as of their relative energy released and, while clearly indicating an increase in inelastic response of the caldera rocks, it does not discriminate between diffuse microfracturing and a possible spatial and temporal clustering along a new and/or reactivated volcano-tectonic fault or fault system.

In this study, we investigate the three-dimensional spatial and temporal clustering of earthquake hypocenters associated with seismic events recorded between 2018 and 2024 by the monitoring network of INGV-Osservatorio Vesuviano (2024b). The objective is to determine whether, when, and where seismicity has transitioned from diffuse microfracturing to localization along a well-defined fault plane. We use an innovative Monte Carlo approach designed to overcome the limitations in spatial clustering associated with diffuse distribution of hypocenters within a relatively small and shallow crustal volume. Our findings indicate that, since 2023, onshore seismicity has evolved from a volumetrically dispersed pattern to a more localized distribution along a planar structure. This clustering persisted on the same planar structure in 2024 with a strike of  $N249^{\circ}\pm4^{\circ}$ , and a dip of  $53^{\circ}\pm1^{\circ}$  located near the center of the caldera. The observed spatial and temporal evolution of seismicity is analyzed in the context of ongoing ground uplift, considering two possible scenarios: (i) the nucleation of a new volcanotectonic fault or (ii) the reactivation and unclamping of a pre-existing fault. In both cases, the implications for volcanic hazard assessment are significant.

## Materials

We utilized the seismic catalog of Campi Flegrei, compiled by the Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Vesuviano (Riccolino et al. 2024). This catalog provides the origin time, location along with its uncertainties, and duration-magnitude of each earthquake. The events were located using manual pickings and a layered velocity model as described by Tramelli et al. (2022). The catalog encompasses seismic events recorded between January 1, 2019, and October 10, 2024, with depths ranging from 0.1 to 5.6 km and magnitudes between -1.6 and 4.4. The average location errors are 0.2 km for both horizontal and vertical positions. We selected earthquakes with a duration magnitude ( $M_d$ )  $\geq 0.5$ , following the completeness magnitude determined by Del Pezzo and Bianco (2024) for the period 2000-2023 (Supplementary materials S1).

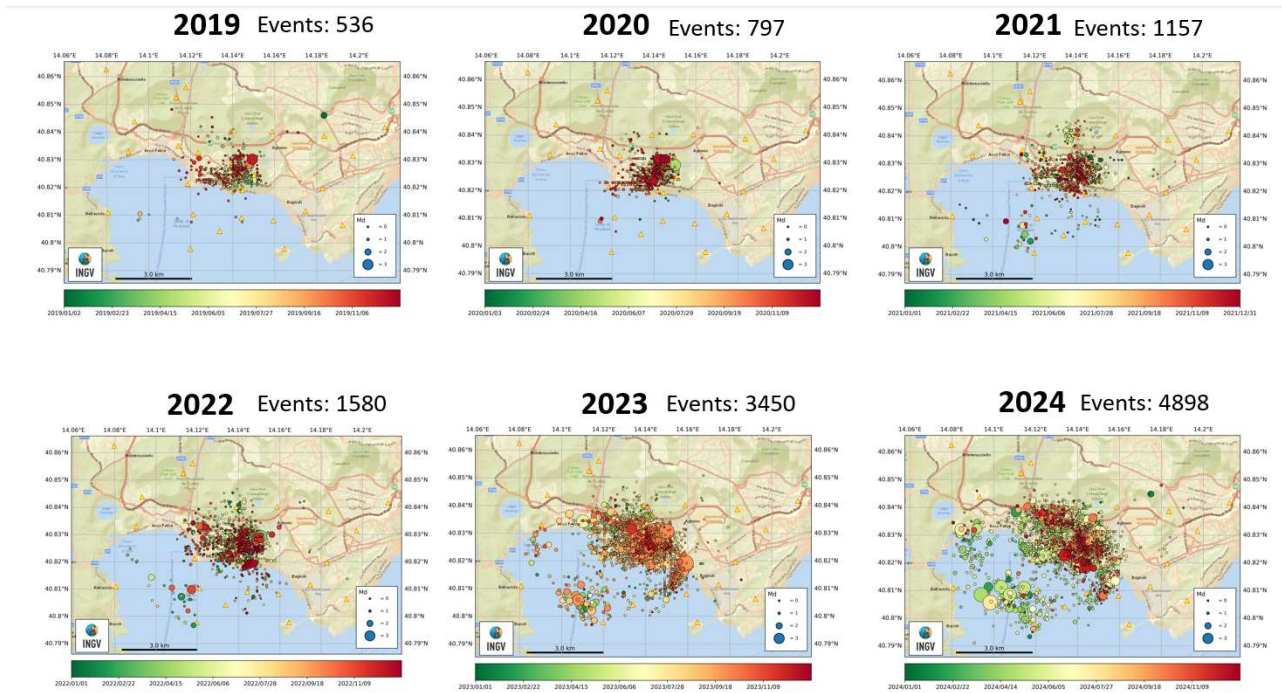


Fig. 2 Areal distribution of epicenters of earthquakes registered by INGV-OV seismic network in 2018-2024 (INGV-Osservatorio Vesuviano, 2024b)

## Approach

The 3D spatial analysis over time performed to find possible planar trends of the seismic event locations at Campi Flegrei, like at any other caldera, presents several challenges. First, most events have magnitudes close to 0 or negative for which the location uncertainty is too high for our application. Our analysis is limited to events with  $M_d \geq 0.5$  for which the average uncertainty on both horizontal and vertical localization is around 200 m (Del Pezzo and Bianco 2024).

Second, the space distribution of data is highly inhomogeneous, with the horizontal distribution of event locations larger (about 6 km x 6 km) than the depth range (mostly concentrated at <3 km with fewer offshore extending down to 5.5 km). This type of spatial distribution introduces an unsolvable bias for any objective trend analysis of the totality of data, that would inevitably result in flattening any possible searched planar trend. To override this bias, in this study we used a multiple inversion approach to analyze data fitting into a hexagonally centered lattice of vertical cylinder cells of a given radius and a grid pace providing the minimal cell overlap to guarantee the analysis of all data. The cylinders have a base-diameter of 1000 m with a grid pace of 866 m (see Methodology; Fig. M1).

Third, the spatial analysis commonly uses the Least Square Method (LSM) to identify the trend that best fits the data, which in our case should represent the potential planar structure to which hypocenters may be associated. However, LSM assumes that all data belong to the same population, enhancing the relevance of data with values falling far from the predicted model, measured by the square of their distance from the predicted distribution. Seismic swarms in calderas may instead be associated with variably overlapping causes (e.g. gas pressure in the hydrothermal system, magma pressure in geometrically complex reservoirs, strain localization



along different pre-existing volcano-tectonic faults and across variable rock-rheology). This limitation has been reduced in this study by using a different factor for the distance as root square, the Least Root Square (LRS) method (see Methodology). This implies the use of a specific Monte Carlo approach (in this study we used a Monte Carlo-Like Convergent Method (MCC, see Methodology) that automatically reduces the influence of distant data (e.g. as outliers), yet without imposing any arbitrary threshold.

Data for each cylinder were processed with MCC, to obtain the best planar solutions within those volumes. To test the influence of the lattice in the trend identifications, the grid analysis was repeated by shifting the lattice by a random value and proved congruent results (Supplementary materials S2). The minimum number of data to define a potential plane was set to eight, which provides the minimum acceptable degree of freedom (5 for this planar approach) in a three-dimensional space to obtain a reliable planar solution.

Where planar solutions from adjacent cells showed close attitudes (i.e. the pole of the identified best-fit planes at angular distances  $<45^\circ$ , i.e. planes falling inside the same quadrant), we verified the effective presence of a unique planar structure extending across the lattice, by performing a new MCC inversion analysis within the merged volume of the related cylinders (Fig. M1; Supplementary materials S3a). To avoid any bias imposed by the potentially elongated geometry of the merged volume, the analysis was also performed on a single larger cylindrical volume centered around the merged cylinders (Fig. M1-2; Supplementary materials S3b). The MCC analysis was then repeated several times (the original set of random values guarantees always slightly different results within the satisfactory resolution) to test the robustness of the solution and its associated error by computing the Mean and the Standard Deviation of the set of results and allowed us to identify the presence of a consistent planar trend.

This multiple analysis procedure was repeated also by adding to earthquake locations their error. This was performed by adding a vertical and horizontal shift to each data chosen randomly within the associated error of the measure. Results of this analysis show only a modest increase in the data scattering along the identified planar trends, confirming the reliability of the solutions (Supplementary materials S3c).

## Results

The results of the MCC inversions have identified best-fit planes associated with the distribution of earthquakes hypocenters which show variations both in space and time. The best-fit planes obtained within each individual cylindrical volume are shown in Fig. 3.

In 2019, 2020, 2021 and 2022, the total number of located events increased from 536, to 797, 1157 and 1580 (Fig. 2). The number of events with  $M_d \geq 0.5$  increased from 118 in 2019, to 176 in 2020, 220 in 2021, and 378 in 2022 (Supplementary material S1). Significant planar trends (i.e. associated with a minimum of 8 events) were identified only in 6 cylinders, in 2019, in 5 cylinders in 2020, in 8 cylinders in 2021, and 10 cylinders in 2022, all located in the area of maximum seismicity below Pozzuoli-Solfatara (Fig. 3 a, b, c, g; Supplementary material S2). These best-fit

planes are associated with a small number of events (with a maximum of 51 in 2022) and show completely scattered orientations (Fig. 3 d,e,f,j), indicating a random distribution of earthquakes in the seismogenic volume.

With the sharp increase in seismicity observed in 2023 and 2024 (Fig. 2), the identified best-fit planes increased in number and spatial distribution, as well as in clustering progressively larger numbers of earthquakes.

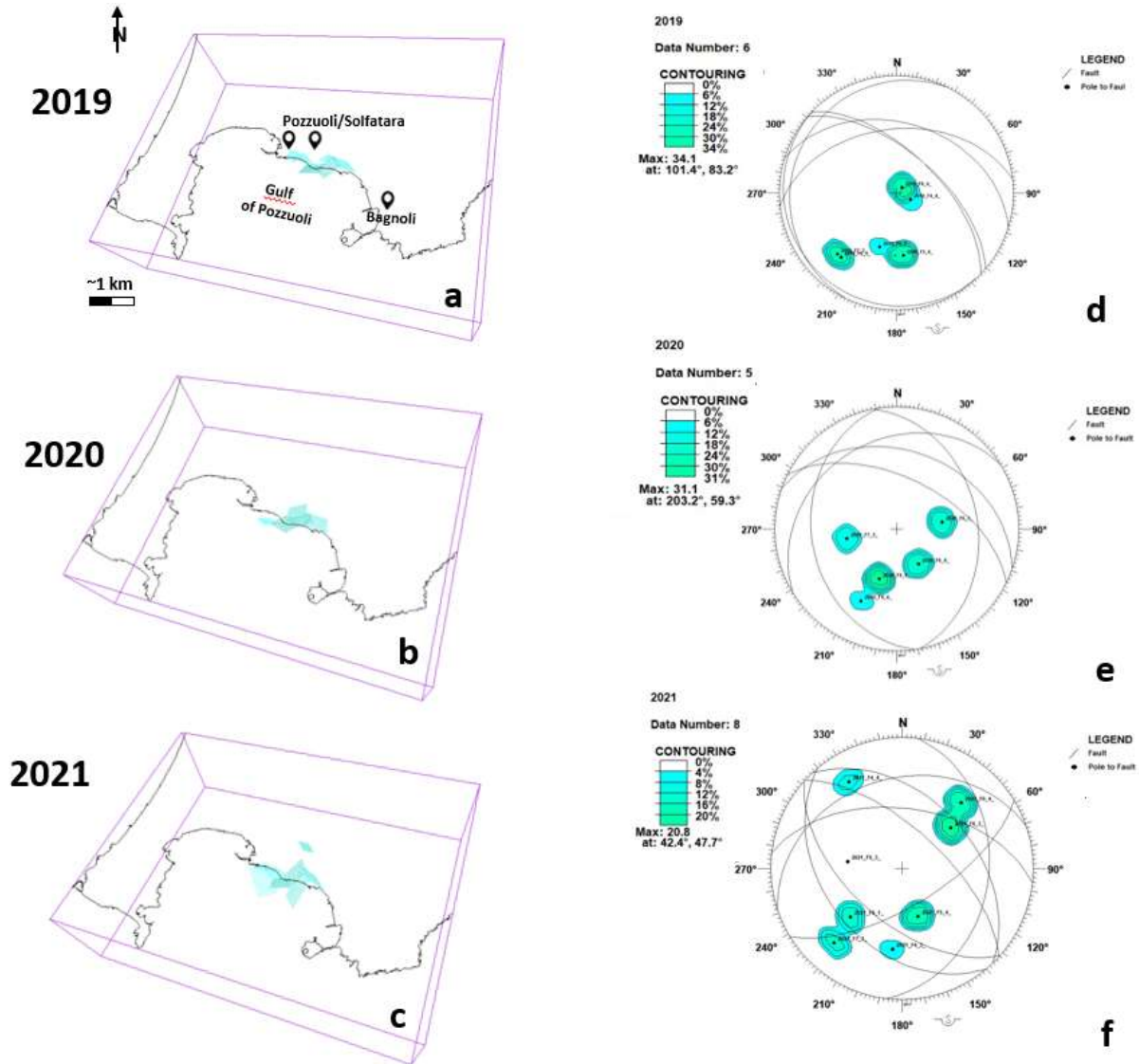


Fig. 3 – Perspective views (a,b,c,g,h,i) and stereonet representation (d,e,f,j,k,l; southern hemisphere projection) of planes and poles of the planar features clustering earthquakes hypocenters in the years 2018-2024. Colours ranges from pale blue to red at increasing the number of earthquakes clustered by each plane. Since 2023, a planar structure well-defined by hypocenter clustering appears in the center of the caldera. See text for explanation

In 2023, a total number of 3448 events occurred, with 1083  $M_d \geq 0.5$  (Fig. 2; Supplementary material S1), which allowed the identification of 26 cylinders with significant best-fit planes (Supplementary material S2). Most of the best-fit planes are in the correspondence of Pozzuoli-Solfatara but also extending in the area of Bagnoli (Fig. 3h), clustering up to 143 events. An

enlargement of the identified best-fit planes off-shore can also be appreciated in the Gulf of Pozzuoli (Fig. 3h). In 2023, the area of most intense seismicity Pozzuoli-Solfatara shows clustering of events around coherent NNW dipping planes (Fig. 3k) in 3 contiguous cylinders, with best-fit planes oriented at an angular distance  $<28.5^\circ$  (Supplementary material S4).

In 2024, the number of earthquakes until October (time of analysis) further increased to 4456 (Fig. 2) with 1341  $M_d \geq 0.5$ . This allowed the identification of 30 cylinders with best-fit planes that occupy a vast portion of the caldera, both around the zone of maximum seismicity Pozzuoli-Solfatara, in the Bagnoli area, and offshore (Fig. 3i). The largest number of earthquakes occur within the same three adjacent cylinders identified for the first time in 2023 (Fig. 3i,l; Supplementary materials S2) and extended to a fourth adjacent cylinder, with close NNW dipping orientations at angular distance  $<36.8^\circ$  (Supplementary materials S4).

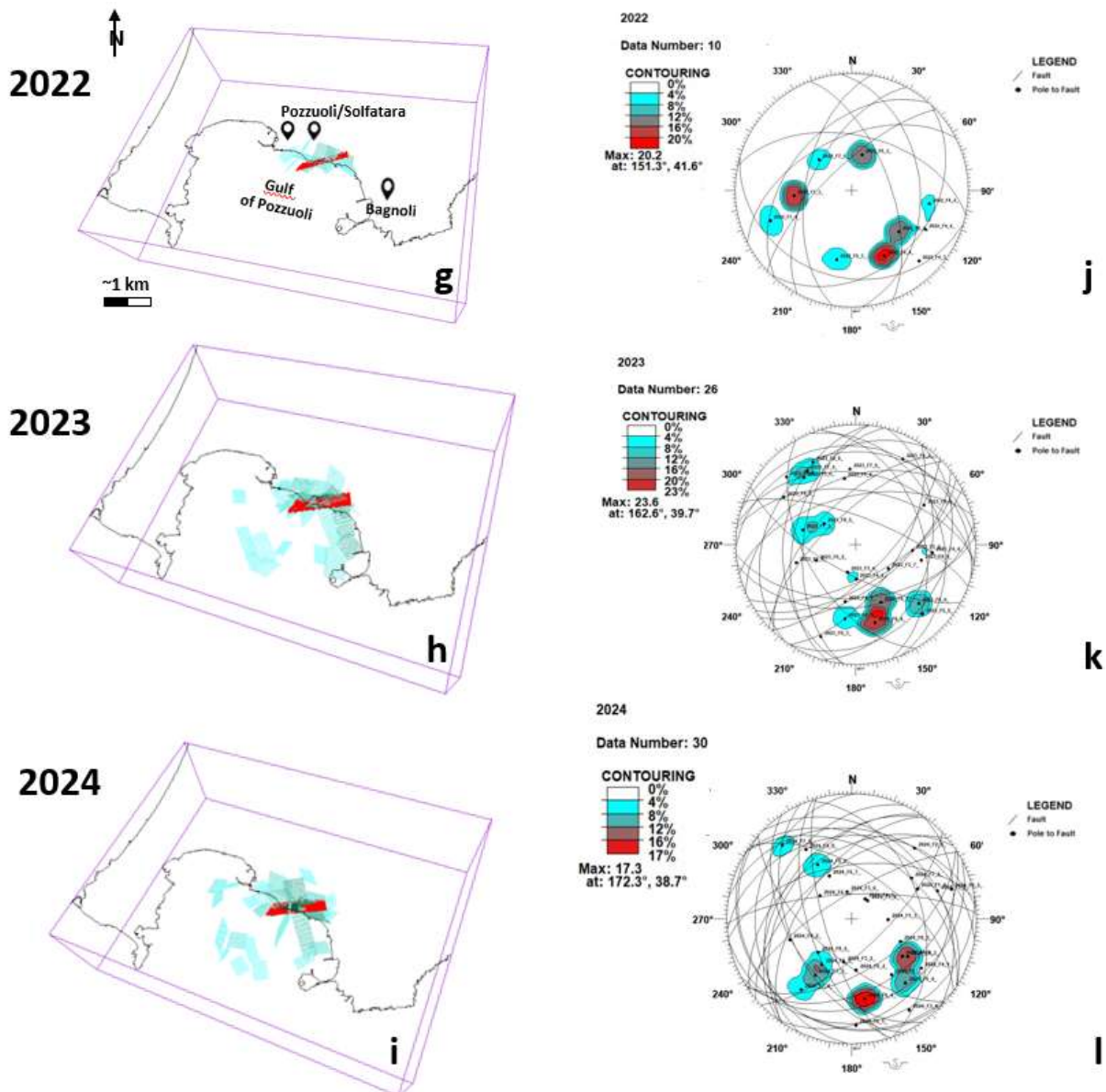


Fig. 3 follows

1 We selected these four cylinders identified as 6\_3, 6\_4, 5\_4 and 7\_3 (Fig. M1) to test the reliability  
2 of the results (Supplementary materials S3a, 4), by running the MCC analysis in the merged  
3 volume of the four adjacent cylinders. The surface area of the four merged cylinders is about 3 km  
4 x 2 km (Fig. M1). To test the influence of the volume geometry, MCC analyses were also  
5 performed within a 3 km diameter cylinder centered on the merged volume, providing very close  
6 results (see Methodology, Fig.M1; Supplementary materials S3b, 4)

7  
8 Results confirm that in 2023 and 2024 the identified planes in the extended merged volume  
9 coincide with those identified within adjacent cylinders and provide orientations of N247°, 53° in  
10 2023 and N244°, 53° in 2024 (Supplementary materials S3a). The total number of events that are  
11 associated with the clustering plane in the first ten months of 2024 is 401 (Fig. 4b,d). Very similar  
12 results are obtained within the 3 km diameter cylinder centered on the merged volume  
13 (Supplementary materials S3b). The persistence of a very similar direction for the best-fit planes in  
14 2023 and 2024 suggests that a change has occurred in the pattern of event location since 2023,  
15 which we will discuss as the nucleation of a potential incipient volcanotectonic fault (PIF) or the  
16 activation of a pre-existing volcanotectonic fault.

17  
18 A robustness-like analysis was performed by repeating 10 times the MCC inversion for all 2023-  
19 2024 events located in the merged volume (hereafter the PIF volume), and by adding a random  
20 error to event locations within the declared measure error for each event location. Results are  
21 presented in Fig. 4a and Supplementary materials S3c1 and show the strong reliability of the found  
22 PIF solution within the merged volume, with a mean value in 2024 of  $N249^{\circ} \pm 4^{\circ}$ ,  $53^{\circ} \pm 1^{\circ}$ . Very  
23 similar results are obtained within the 3 km diameter cylinder centered on the merged volume  
24 (Supplementary materials S3c2). By recalculating the best-fit plane within the PIF merged volume  
25 since 2019 (Supplementary materials S3c1,2), it is possible to confirm that from 2019 to 2021 the  
26 orientation is random, and that in 2022 there is the first clustering around the PIF orientation that  
27 then dominates in 2023 and 2024 (Fig. 4c). Alongside, the standard deviation both on strike and  
28 dip decreases substantially, demonstrating the effect of clustering over time (Fig. 4c). It must be  
29 also noted that the dip angle increases over time, because of the identification of the PIF plane,  
30 progressive prevailing over the distributed volumetric small events which tend to bias toward  
31 subhorizontal or low angle solutions (e.g. 2019, 2020, 2021). By imposing the PIF orientation in  
32 the PIF merged volume to the distribution of events since 2019 it is also possible to appreciate the  
33 increase in the number of events clustered around the PIF (Fig. 4d).

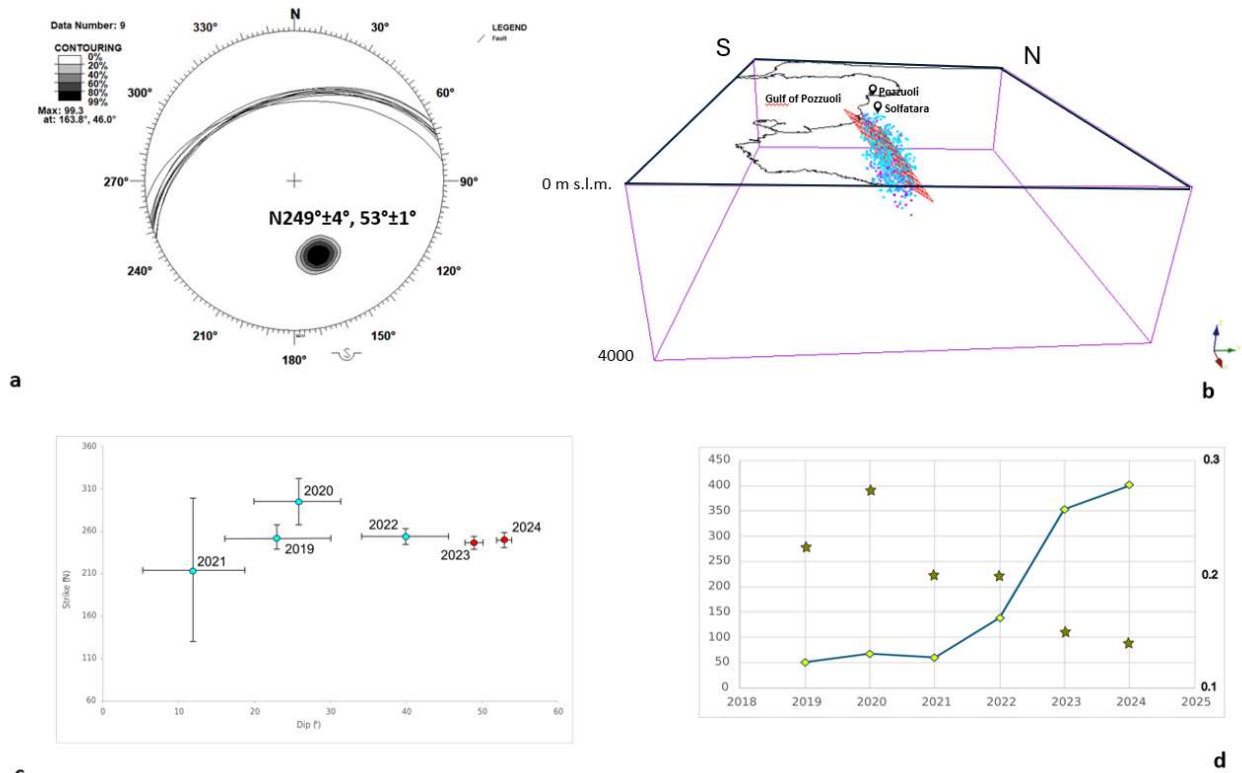


**Fig. 4 Geometry and location of the PIF in the Pozzuoli-Solfatara area of Campi Flegrei Caldera.** a) Contouring (Schmidt stereonet, lower hemisphere) of the of poles to the PIF planes identified in the merged PIF volume (cylinders 6\_3, 6\_4, 5\_4 and 7\_3, see Fig. M1 in Methodology) by a set of 10 repeated MCC analyses with the random error added to earthquake locations, showing the consistency of the MCC processing and the limited influence of the location error. b) 3D perspective of the PIF represented as a red grid; the associated events (i.e. within 300 m from the PIF plane) are dots color coded by their distance. c) Plane features calculated within the PIF volume since 2019, showing a scattering of dip and azimuth until 2023 and 2024; colours of squares indicate the number of events associated with the plane (pale blue <250; red >500); error bars indicate 1 standard deviation. d) Yellow diamonds indicate the progressive increase of number of events associated to the PIF since 2019 until October 2024; yellow stars indicate concomitant reduction in the ratio of the RMS of hypocenters with distance <200m from the plane respect to the RMS distance of all hypocenters from the plane; the reduction of this ratio illustrates that the clustering around the PIF in 2023 and 2024 prevails over dispersion of earthquakes in the progressively larger seismic volume.

## Discussion

Very recent analyses of seismicity and ground deformation during the current ongoing unrest at Campi Flegrei caldera are progressively highlighting the marked and simultaneous changes in uplift velocity and seismicity rate that have occurred over the last few years. Bevilacqua et al. (2024) highlight the parabolic increase in ground uplift and a super-exponential rise of earthquake number and seismic energy released, interpreted as possibly related to a progressive mechanical weakening of the crust. Giudicepietro et al. (2025) showed that since 2021 the style of seismicity has changed with development of burst-like swarms. Del Pezzo and Bianco (2024) show that since 2023 the Energy Space Density of the Campi Flegrei seismicity highlights an enlarged volume of fractured rocks at the depth of around 3 km. At the same depths, Calò and Tramelli (2024) and Giacomuzzi et al. (2025) identify a rock volume characterized by high  $V_p/V_s$  ratios possibly for the

1 presence of pressurized fluids, qualitatively in agreement with electrical resistivity imaging (Isaia et  
2 al. 2021).

3 Within this context it remains unclear whether the system, as described by the FFM approach, is  
4 nearing or has already reached a critical state (e.g. Kilburn et al. 2023). Specifically, it is unclear  
5 whether the mechanical behaviour of the crust is currently already in its final stages of failure or  
6 still progressing toward that point. This is particularly important as very recent studies now  
7 converge in addressing the current unrest at Campi Flegrei to the migration and accumulation of  
8 magma in the plumbing system (Giacomuzzi et al. 2024; Astort et al. 2024; Caliro et al. 2025).

9 The spatial and temporal distributions of earthquakes are powerful indicators to identify if, when  
10 and where the nucleation (or the reactivation) of a volcanotectonic fault has occurred. By  
11 overcoming the main limitations to spatial clustering analysis of VT earthquakes hypocenters, our  
12 innovative approach shows that since 2023 the seismicity shifted from randomly scattered within  
13 the most stressed volume of Campi Flegrei caldera, i.e. at its center, to self-organized around a  
14 main clustering plane with orientation  $N249^{\circ}\pm4^{\circ}$ ,  $53^{\circ}\pm1^{\circ}$  (Fig. 4).

15 The clustering plane crosses the volume of maximum vertical deformation, dipping inland and  
16 almost emerging at surface to the southeast of Pozzuoli with a horizontal extension of 2.8 km and  
17 extending at depth of 3 km (Fig. 5; cf Feature D in Scotto di Uccio et al. 2024). Pozzuoli is the area  
18 of maximum axisymmetric strain (Fig. 5) and can be interpreted as indicating the localization and  
19 vertical orientation of the maximum stress ( $\sigma_1$ ). The attitude of the clustering plane (dip of  $53^{\circ}$ )  
20 and its position respect to maximum uplift resemble that of an Andersonian fault (Anderson 1905;  
21 Fig. 5a), with theoretical internal friction angle of  $16^{\circ}$ , not unrealistic considering the weak rock  
22 rheology of the shallow Campi Flegrei rocks (e.g. Dello Iacono et al. 2009; Meyer et al. 2016).

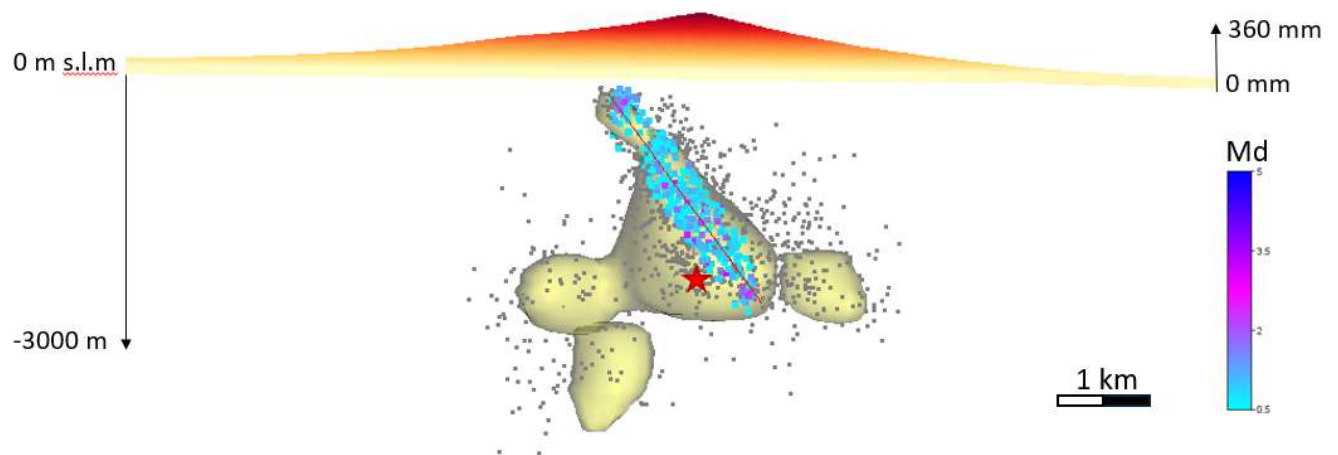
23 Discriminating whether the identified clustering plane may represent the reactivation of a pre-  
24 existing fault, or the nucleation of a new fault is not easy. Field studies on the distribution of faults  
25 and fractures in the Campi Flegrei caldera floor, both onshore (Cosentino et al. 1984; Acocella et  
26 al., 1999; Acocella 2010; Selva et al. 2012; Vitale and Isaia 2014; Isaia et al. 2015, 2021; Iervolino et  
27 al. 2025; Caliro et al. 2025) and offshore (Milia et al. 2000; Natale et al. 2022) show many  
28 structural elements, mostly NE-SW and NW-SE oriented, that are associated with the episodes of   
29 volcanotectonic resurgence and subsidence since 15 ka (Di Vito et al. 1999; Marturano et al. 2018).

30 **However, field evidence does not clearly show the presence of a fault in the position, and with**  
31 **orientation and extension similar to the plane that is currently clustering the seismicity.**

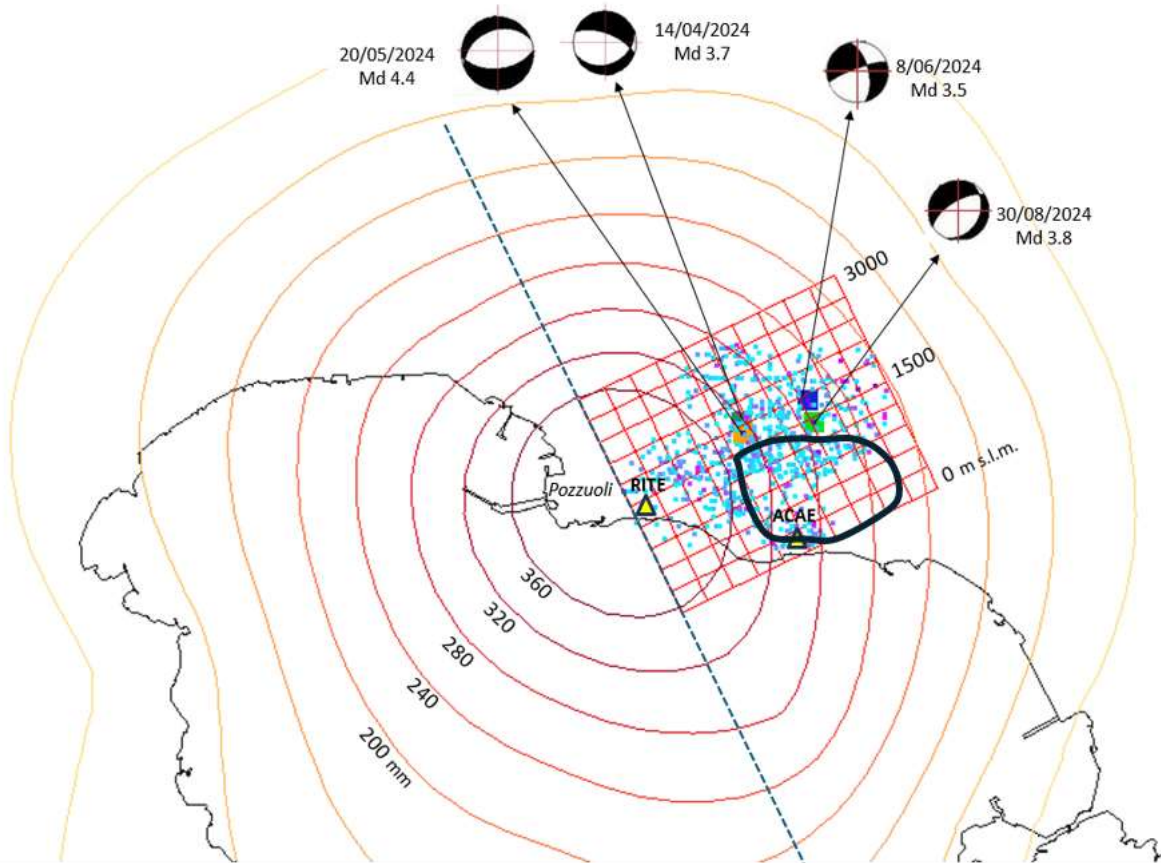
32 In addition, the high density and quality of the INGV seismic monitoring network that allows now to  
33 detect and track the clustering plane during the current unrest, was not available during the  
34 former unrests (1982-84; 1969-72; 1950-52), making it impossible to ascertain whether previous  
35 seismic activity was already clustering on a similar plane (cf. De Siena et al. 2017).

36 Nevertheless, we note that the event distribution along the clustering plane is rather stochastic,  
37 suggesting that this plane is formed by the progressive jointing of micro-dislocation surfaces. By  
38 comparing the geometry of the clustering plane and the Energy Space Distribution (Del Pezzo and  
39 Bianco 2024; Fig. 5a) we note that both localized and scattered seismicity occurs in a volume that  
40 is centered on but is larger than the plane itself. Also, some of the mainshocks do not occur on the

1 clustering plane (Fig. 5a), suggesting that damage and energy dissipation are not confined to the  
2 region where the jointing or micro-fractures is occurring, possibly involving also secondary planes  
3 (e.g. Griffith et al. 2010). We therefore prefer to interpret the change in spatial distribution of  
4 seismicity occurring since 2023 as the birth of a potential incipient fault (PIF). The adjective  
5 “potential” clarifies that we have so far identified a statistical not a physical fault plane. With the  
6 term “incipient” we stress that we are not describing yet a fully developed classic seismic fault, but  
7 rather the initiated and ongoing process of self-organization of the micro-fracturing which is in the  
8 course of defining a fault plane. This is important as the merging of small dislocation planes into a  
9 larger one results in a significant increase in stress along its tips, thus producing their propagation  
10 and eventually the full development of a fault (Griffith et al. 2009), whose dimensions control the  
11 maximum expected magnitude on that plane.



12  
13 a)



b)

Fig. 5 (a) Cross sectional view and (b) planar view (red square net) of the PIF respect to the axisymmetric ground uplift pattern centered at RITE GNSS station (indicated as yellow triangle along with the ACAE station). Uplift isolines are in millimeters and show the uplift measured in 2024 (INGV-Osservatorio Vesuviano, 2024a). The dotted line indicates the trace of the cross section shown in (a). The yellow surface in (a) represents the -3.84 iso-value envelope for the observed Energy Space Density in 2023 (from Del Pezzo and Bianco 2024) and shows the concentration of the seismic energy along the PIF and over the central domal volume. Focal mechanisms in (b) show mainly extensional trends parallel to the PIF strike, which, associated with the PIF dip, suggests downthrow toward the NNW. This is perfectly coherent with the location of the area of geodetic anomaly (thick blue line from Giudicepietro et al. 2025) defined by a deficit in uplift rate.

It is worth specifying that a fault is generally a complex structure that involves a volume (i.e. the fault zone), often with several displacement surfaces that at times may concentrate most of the slip, i.e. the fault core (e.g. Caine et al., 1996)

Two are the end member models for fault generation. The first involves their nucleation from an initial relatively small zone where the acting stress overrides the brittle strength of the rock and then expands along its edges, eased by the stress concentration that generates at its tips (Mandl, 2013). This evolutionary model applies when regional (e.g. external) stresses are acting.

The second considers the initial development of a cloud of small fractures with limited displacement. As their dimensions increase by the increasing stress and, again, fault tip stress concentration, adjacent faults join and, if their sense of movement is compatible, form a larger fault with increasing displacement. Eventually, the joining process ends with the development of

a major fault surface (Turcotte, 1997; Mandl, 2013; Safaeipour et al., 2021). This latter model seems to apply for the development of the observed PIF, where a progressive clustering of seismic events is observed along a preferential orientation, ascribable to a sort of creeping along minor faults (Wesson, 1988). The required coherence among the minor fault population relates to the mechanism for their origin, in the case of the Campi Flegrei unrest, the extensional regime ~~produced by the deformation~~ resulting from the observed uplift (Astort et al. 2024). This may exclude an origin of the PIF as the effect of the increase of a regional (tectonic) stress and the PIF can be considered the effect of the kinematics of the resurgence acting in the Campi Flegrei caldera, allowing us to classify the PIF within the kinematic fault family (that is, faults produced by rock dislocation rather than an asymmetrical regional stress; Turcotte and Schubert, 2002). Consequently, this evolutionary model does not predict a significant increase in the dimensions of the fault plane and of the magnitude of the future seismic events, that for Campi Flegrei are expected to a maximum of  $M_d=5.1$  (Iervolino et al. 2024). On the other hand, the PIF evolution will likely result in an increase of its displacement, thus providing a more and more efficient gravity discharge over the resurgent block, potentially resulting in a progressive acceleration of its uplift. Initial effects of the PIF normal dislocation could well explain the observed geodetic anomaly with a relative decrease in the uplifting rate around the GNSS station ACAE (Fig. 5b), which since 2023 is altering the perfect axisymmetric shape of the uplift (Giudicepietro et al. 2025). The area of geodetic anomaly is coherent with a normal displacement toward the NNW, also in agreement with focal mechanisms (Fig. 5b). The dipping of the PIF towards inland (NNE), that is towards inner, higher elevation areas (with a higher gravity load) represents anyhow a delaying factor to its displacement. Nevertheless, great care must be taken to monitor its development and evolution, given its influence on resurgence patterns and its potential to provide preferential pathways for uprising of hydrothermal and volcanic fluids.

## Acknowledgements

GG and AV acknowledge the grant to the Department of Science, Roma Tre University (MIUR-Italy Dipartimenti di Eccellenza, ARTICOLO 1, COMMI 314–337 LEGGE 232/2016). AT and MDV acknowledge the grant of Departmental Project LOVE\_CF (INGV Pianeta Dinamico) and the Italian DPC, in the frame of INGV-DPC (2022–2025) agreements, although it does not necessarily represent DPC official opinion and policies. We acknowledge E. Del Pezzo for the EDS isosurfaces used in Fig. 5a.

## Authors' contributions

GG and FS conceived the study; GA, FS, GG performed the statistical analyses; FB, AT took care of the seismic dataset; All authors discussed the results and contributed to the writing and commented on the manuscript.

## 1 Data availability

2 The code Montecarlo\_Fault is available upon request to the corresponding authors.

3 The seismic record used in this work is acquired by the INGV-OV seismic monitoring network and  
4 publicly available at <https://terremoti.ov.ingv.it/gossip/>

5

## 6 The authors declare no competing interests

7

## 8 Methods

### 9 Foreword

10 The Least Square Method (LSM) is a largely and successfully used mathematical algorithm to test  
11 and identify linear trends of a set of data (Legendre,1805; Gauss, 1809; Tarantola, 1987) and, with  
12 some iterative computations, can be extended also to non-linear trends (Suzuki & Fraser, 1968;  
13 Salvini, 2023). The Least Square Method is characterized by a fast and simple computation by  
14 minimizing the sum of the squares of the deviations of the data values from a given expected  
15 trend

16 
$$\text{Min } \sum_i (z_i - f(x_i, y_i))^2$$

17 This is easily solved by zeroing the parameter partial first derivatives of this equation.

18 Despite its advantages, two severe boundary conditions limit its wide and indiscriminate use. The  
19 first is that all data must belong to the population following the searched trend shape. This  
20 constraint is difficult to be respected in nature due to the complexity of the real world, where  
21 measures depend on several, often independent, causes, including barely scattered ones. This  
22 results in unreliable or fake solutions.

23 The second limiting condition is intrinsic in the method. Measures are weighed by the square of  
24 their distance along the dependent variable from the searched trend. This provides, when data  
25 belongs to different populations (including randomly scattered ones), a strong bias in the relative  
26 relevance of each datum since measures more distant from the trend will weight in the  
27 computation far more than the data that follow closely the searched trend. This is a strong  
28 limitation, since, in a complex situation (i.e. where measures depend on more than a single  
29 population/trend as in this study) the farer data are those that most likely do not follow the trend  
30 under test, yet accordingly they will weigh (by square of the distance) more than the closer  
31 trend data. A small percentage of measures from a different population is sufficient to invalidate  
32 the results.

33 To override this limit, a common (and dangerously subjective) technique is applied and consists in  
34 the identification and elimination of data more distant from the desired trend as “outliers”.  
35 Generally, this is accomplished by discarding from the inversion process data that shows the  
36 (assumed) larger distance from the initially approximated trend and repeating the inversion by



excluding them. This represents a serious external influence on the data and should be always avoided or used with great care, since it is strongly influenced by the subjective rules applied as well as the relative number of data following the searched trend **with respect to the independent ones.** The outlier identification is even more and more complex as the number of data increases, especially ~~when used~~ strongly scattered data population, i.e., where only a reduced percentage of data follows the expected trend. This latter scenario is what expected in the seismic event location population in the studied Campi Flegrei active region, where the spatial distribution of the events derives from the contemporary action of at the minimum two main causes, the doming related to gas escape and/or rising of a magmatic body, and the potential presence of a fault. The first cause will provide a locally scattered swarms of events. The presence of an active fault or a PIF would provide a concentration of events along the approximated planar fault zone.

### **The Least Root Method (LRM)**

With these premises, a slightly different and objective method was proposed and used in the present study, the Least Root Method. LRM). Similarly to the LSM approach, this method searches to minimize the sum of the square root of the absolute distances between trend and the dependent variable (elevation  $z$ , in our study), thus lowering the weight of the most distant data,

The equation to be minimized is then

$$\text{Min } \sum_i |(z_i - f(x_i, y_i))|^{1/2}$$

Unfortunately, this equation cannot be easily minimized in analytical formulation in most cases, and the distances must have always a positive value, as automatically results in the case of using their square as in the LSM. This prevents the use of the elegant and fast, analytical solution provided by that method and must be substituted by an iterative Monte Carlo Convergent (MCC) type search for the minimum sum by comparing different sets of parameters. This computation is simpler, yet it requires long, iterative computations (easily done, thanks to the computational speed of present-day computers). As in the Monte Carlo method, this result is achieved, by an iterative “trial and error” approach testing a huge set of different and independent parameter values, **and the hint resides in the large amount of available and independent parameter sets.**

It is worthwhile noticing that the used LRM implementation can be extended to any value of the power of the distances. Its decrease would produce a progressive lowering of the weight of data ~~farer~~ from the trend, with the risk of providing excessive emphasis of random alignment of data along a factious trend (as in the case of rounded coordinates along given  $x$  or  $y$  coordinates).

The MCC implementation is characterized by the search of the possible parameters within a variable range of values for each parameter. These ranges are then focused (and reduced) on each cycle around the best parameter set found by the application providing an AI approach to the process. These ranges reduce progressively at any cycle of attempts to improve the parameter sets closer to the expected satisfactory result and thus improve the probability of a reliable final match.

### **Application of LRM to search of a planar trend within a biased dataset**

In this study, the MCC method was used with the LRM approach by a set to 60 cycles of 200,000 attempts and a parameter range reduction fraction  $r = 0.1$  at each new cycle. This change in the parameter range at each cycle provides a new independent set of random parameter values within the 16-digit precision of the computation. Computation time for each MCC inversion is strongly dependent on the computer performance used and directly proportional to the number of data. Our application was able to perform the required 12,000,000 iterations with 1500 measures in about 1 hour. The final range decrease of the parameter ranges, after the 60 cycles, was eventually reduced to  $(1-0.1)^{60} = 0.002$  times the initial ranges, thus providing a very high resolution in the best parameter final values.

In the implementation of the MCC used in this study we used a set of random number generators with over  $1.6 \times 10^7$  numbers. This set was then used to generate random parameter values within the given parameter range at that cycle with a resolution of the extremes of 16 digits (i.e. over  $10^{16}$  possible combinations). In this way, this procedure provides for each cycle a new set of values different from all the previous ones. The theoretical number of independent random values in this study therefore exceeds  $10^{16}$  independent random values. The test on the used procedure showed no value repetitions within  $3 \times 10^{10}$  random number generated, thus fully satisfying the used number of parameters set. Furthermore, at regular intervals (i.e. every 43051 attempts in our application) the range parameters boundaries were randomly modified by 0.0001%, to prevent any useless and dangerous repetition.

This easily overrides the required number of random values required for an MCC processing (see below), that is equal to:

$$\text{No.cycles} * \text{No.attempts} * \text{No.independent parameters} = 60 * 200,000 * 3 = 48,000,000$$

This scenario closely resembles the distribution of the locations of seismic events during this last Campi Flegrei crisis, where data are consistently distributed along an annular shape around the area, yet with a very strong asymmetry and most of the events locating more and more in the western coast of the Pozzuoli area within the last years.

The MCC implementation of the LRM method has been applied to identify the presence of active potentially incipient faults (PIF) by searching planar trends within the highly scattered locations of seismic events.

In this analysis, we consider that each measured event belongs to either the planar distribution of a PIF or to scattered data (the doming?)

$$Z_i = Z_{ri} | Z_i$$

Where  $Z_r(x,y)$  distribution represents data scattered along the resurgent dome structure, and

$$Z(x,y) = a(x + Dx) + b(y + Dy) + c$$

represent events scattered along a planar surface trend, where the unknown parameters are  $a, b, c, Dx, Dy, x, y$  are the UTM coordinate of the event location (converted from the original



1 Geographic coordinates),  $z$  the hypocenter elevation, and  $Z$  is the expected depth of the plane at  
2 position  $x, y$

3 The application of the method for our purpose is therefore to provide the best parameter values  
4 to minimize the equation of the sum of the root of the distance from the event computed depth  
5 and the expected depth at the given point.

6 
$$\text{Min } \sum_i | [(z_i - a(x_i + Dx) - b(y_i - Dy) - c)] |^{1/2}$$



7 where  $a, b, c$ , represent the analytical parameters of the searched plane in a space centered at  $Dx$

8  $Dy$ . These last two parameters were fixed in the analysis and centered in the mean  $x$  and  $y$   
9 measured values:

10 
$$Dx = (\sum_i x_i)/N$$

11 
$$Dy = (\sum_i y_i)/N$$

12 Where  $x_i, y_i$  are the horizontal coordinates of the  $i$  event and  $N$  is the number of total events

13 At each attempt, a set of parameters is generated as:

14 
$$P_j = \text{Prange}_j * \text{rnd} + \text{Pmin}_j \quad \text{where } \text{Prange}_j = \text{Pmax}_j - \text{Pmin}_j$$

15 Where  $\text{rnd}$  is the (next) generated random value and  $\text{Pmax}_j, \text{Pmin}_j$  are the range limits of the  $j$   
16 parameter at the given cycle.

17 The initial parameter ranges were:

18 
$$a \quad \text{Pmin}_1 = -100 \quad \text{Pmax}_1 = 100$$

19 
$$b \quad \text{Pmin}_2 = -100. \quad \text{Pmax}_2 = 100$$

20 
$$c \quad \text{Pmin}_3 = -100,000,00. \quad \text{Pmax}_3 = 100,000,000$$

21 At the completion of each cycle, the interval range was narrowed and recomputed around the  
22 best inversion results obtained in the previous cycle.

23 
$$\text{Pint}_i = .5 * \text{Prange}_i * (1 - r) \quad \text{where } r \text{ in the range reduction fraction (0.1 in this}$$
  
24 study)

25 
$$\text{Pmin}_i = \text{Pbest}_i - \text{Pint}_i \quad \text{where } \text{Pbest}_i \text{ is the best approximation since obtained}$$

26 
$$\text{Pmax}_i = \text{Pbest}_i + \text{Pint}_i$$

27 At the completion of the last 60 cycle, the final parameter search ranges in this study were:

28 
$$\text{Prange}_1 = 0.04$$

29 
$$\text{Prange}_2 = 0.04$$

30 
$$\text{Prange}_3 = 4,000$$

31

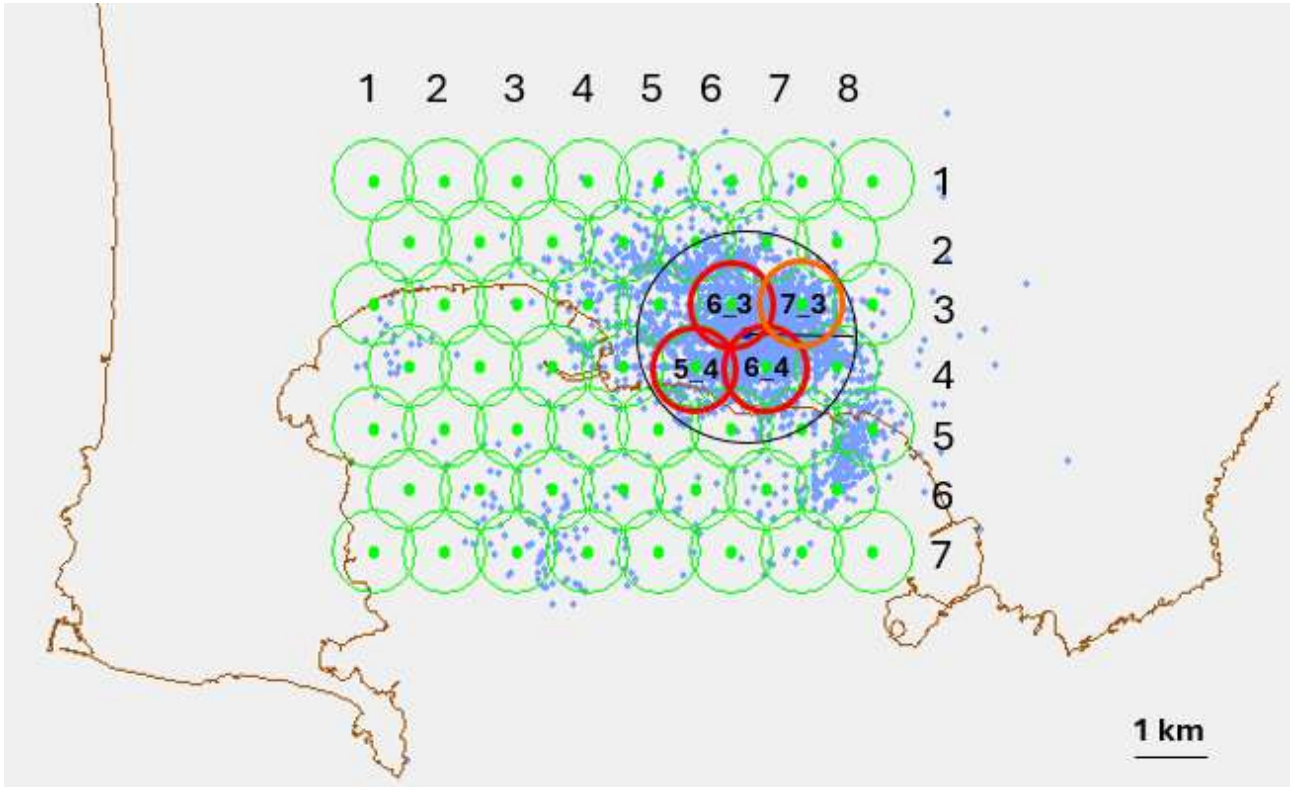


Fig.M1 Lattice of analyses used in this study to homogenize the data distribution (plane view). Red points identify the lattice cells; Red circle indicates cylindric areas; blues dots represent the earthquake locations. The base of the three cylinders (6\_3, 5\_4 and 6\_4) with close orientations of planes identified in 2023 and 2024 (indicated) are highlighted in red, to which adjacent cylinder 7\_3 was added (in orange) to define the merged volume for further MCC analysis in 2023 and 2024. The same was also performed on the cylinder with base circle in blue (see text for explanation).

## Reference list

1. Acocella, V., Salvini, F., Funiciello, R., & Faccenna, C. (1999). The role of transfer structures on volcanic activity at Campi Flegrei (Southern Italy). *Journal of Volcanology and Geothermal Research*, 91(2-4), 123-139.
2. Acocella, V. (2010). Evaluating fracture patterns within a resurgent caldera: Campi Flegrei, Italy. *Bulletin of Volcanology*, 72, 623-638.
3. Aji, A. B., Taisne, B., & Chardot, L. (2024). Forecasting the onset of volcanic eruptions using the increase in seismicity during magma ascent. *Journal of Volcanology and Geothermal Research*, 449, 108053.
4. Anderson, E. M. (1905). The dynamics of faulting. Transactions of the Edinburgh Geological Society, 8(3), 387-402.
5. Astort, A., Trasatti, E., Caricchi, L., Polcari, M., De Martino, P., Acocella, V., & Di Vito, M. A. (2024). Tracking the 2007–2023 magma-driven unrest at Campi Flegrei caldera (Italy). *Communications Earth & Environment*, 5(1), 506.
6. Benoit JP, McNutt SR (1996) Global volcanic earthquake swarm database and preliminary analysis of volcanic earthquake swarm duration. *Annali Di Geofisica* 39(2):221–229
7. Bevilacqua, A., De Martino, P., Giudicepietro, F., Ricciolino, P., Patra, A., Pitman, E. B., ... & Neri, A. (2022). Data analysis of the unsteadily accelerating GPS and seismic records at Campi Flegrei caldera from 2000 to 2020. *Scientific reports*, 12(1), 19175.
8. Bevilacqua, A., Neri, A., De Martino, P., Giudicepietro, F., Macedonio, G., & Ricciolino, P. (2024). Accelerating upper crustal deformation and seismicity of Campi Flegrei caldera (Italy), during the 2000–2023 unrest. *Communications Earth & Environment*, 5(1), 1-14.
9. Boué, A., Lesage, P., Cortés, G., Valette, B., and Reyes-Dávila, G. (2015). Real-time eruption forecasting using the material Failure Forecast Method with a Bayesian approach. *J. Geophys. Res.* 120, 2143–2161. doi: 10.1002/2014JB011637
10. Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault zone architecture and permeability structure. *Geology* 24, 1025±1028.
11. Caliro, S., Chiodini, G., Avino, R., Carandente, A., Cuoco, E., Di Vito, M. A., ... & Aiuppa, A. (2025). Escalation of caldera unrest indicated by increasing emission of isotopically light sulfur. *Nature Geoscience*, 1-8.
12. Calò, M., & Tramelli, A. (2025). Evidences of the structures controlling the unrest in Campi Flegrei, Italy; Joint interpretation of ambient noise and local earthquake tomography. *Journal of Volcanology and Geothermal Research*, 108236.
13. Chiodini, G., Vandemeulebrouck, J., Caliro, S., D'Auria, L., De Martino, P., Mangiacapra, A., & Petrillo, Z. (2015). Evidence of thermal-driven processes triggering the 2005–2014 unrest at Campi Flegrei caldera. *Earth and Planetary Science Letters*, 414, 58-67.
14. Chiodini, G., Caliro, S., De Martino, P., Avino, R., & Gherardi, F. (2012). Early signals of new volcanic unrest at Campi Flegrei caldera? Insights from geochemical data and physical simulations. *Geology*, 40(10), 943-946.

- 1 15. Cornelius, R. R., and Voight, B. (1995). Graphical and PC-software analysis of volcano  
2 eruption precursors according to the Materials Failure Forecast Method (FFM). *J. Volcanol.*  
3 *Geotherm. Res.* 64, 295–320. doi: 10.1016/0377-0273(94) 00078-U
- 4 16. Cosentino, D., De Rita, D., Funicello, R., Parotto, M., Salvini, F., & Vittori, E. (1984). Fracture  
5 system in Phlegraean Fields (naples, southern Italy). *Bulletin volcanologique*, 47, 247-257.
- 6 17. Danesi, S., Pino, N. A., Carlino, S., & Kilburn, C. R. (2024). Evolution in unrest processes at  
7 Campi Flegrei caldera as inferred from local seismicity. *Earth and Planetary Science*  
8 *Letters*, 626, 118530.
- 9 18. Dello Iacono, D., Zollo, A., Vassallo, M., Vanorio, T., & Judenherc, S. (2009). Seismic images  
10 and rock properties of the very shallow structure of Campi Flegrei caldera (southern  
11 Italy). *Bulletin of Volcanology*, 71, 275-284.
- 12 19. Del Gaudio C., Aquino I., Ricciardi G.P., Ricco C. and Scandone R.; 2010: *Unrest episodes at*  
13 *Campi Flegrei: a reconstruction of vertical ground movements during 1905-2009*; 2010: *J.*  
14 *Volcanol. Geotherm. Res.*, 195, 48- 56, doi: 10.1016/j.jvolgeores.2010.05.014.
- 15 20. Del Pezzo, E., & Bianco, F. (2024). Space and time distribution of seismic source energy at  
16 Campi Flegrei, Italy through the last unrest phase (1.1. 2000–31.12. 2023). *Physics of the*  
17 *Earth and Planetary Interiors*, 356, 107258.
- 18 21. De Siena, Luca, Giovanni Chiodini, Giuseppe Vilardo, Edoardo Del Pezzo, Mario Castellano,  
19 Simona Colombelli, Nicola Tisato, and Guido Ventura. "Source and dynamics of a volcanic  
20 caldera unrest: Campi Flegrei, 1983–84." *Scientific reports* 7, no. 1 (2017): 8099.
- 21 22. Dipartimento della Protezione Civile – Repubblica Italiana (2024). Campi Flegrei.  
22 [https://rischi.protezionecivile.gov.it/static/a7cc4318239612826caab525eb8d182b/202303](https://rischi.protezionecivile.gov.it/static/a7cc4318239612826caab525eb8d182b/20230304-vdc-report-c-flegrei-giallo-cgr.pdf)  
23 [04-vdc-report-c-flegrei-giallo-cgr.pdf](https://rischi.protezionecivile.gov.it/static/a7cc4318239612826caab525eb8d182b/20230304-vdc-report-c-flegrei-giallo-cgr.pdf); last access; 11 November, 2024
- 24 23. Di Vito, M. A., Isaia, R., Orsi, G., Southon, J. D., De Vita, S., D'Antonio, M., ... & Piochi, M.  
25 (1999). Volcanism and deformation since 12,000 years at the Campi Flegrei caldera  
26 (Italy). *Journal of Volcanology and Geothermal Research*, 91(2-4), 221-246.
- 27 24. Di Vito, M. A., Acocella, V., Aiello, G., Barra, D., Battaglia, M., Carandente, A., ... & Terrasi,  
28 F. (2016). Magma transfer at Campi Flegrei caldera (Italy) before the 1538 AD  
29 eruption. *Scientific reports*, 6(1), 32245.
- 30 25. Fischer, T., & Hainzl, S. (2021). The growth of earthquake clusters. *Frontiers in Earth*  
31 *Science*, 9, 638336.
- 32 26. Fischer, T., Hainzl, S., & Vlček, J. (2023). Fast migration episodes within earthquake  
33 swarms. *Geophysical Journal International*, 235(1), 312-325.
- 34 27. Giacomuzzi, G., Chiarabba, C., Bianco, F., De Gori, P., & Agostinetti, N. P. (2024). Tracking  
35 transient changes in the plumbing system at Campi Flegrei Caldera. *Earth and Planetary*  
36 *Science Letters*, 637, 118744.
- 37 28. Giacomuzzi, G., Fonzetti, R., Govoni, A., De Gori, P., & Chiarabba, C. (2025). Causal  
38 processes of shallow and deep seismicity at Campi Flegrei caldera. *Communications Earth*  
39 *& Environment*, 6(1), 70.
- 40 29. Giudicepietro, F., Avino, R., Bellucci Sessa, E., Bevilacqua, A., Bonano, M., Caliro, S., ... &  
41 Chiodini, G. (2025). Burst-like swarms in the Campi Flegrei caldera accelerating unrest from  
42 2021 to 2024. *Nature Communications*, 16(1), 1548.

30. Godano, C., Tramelli, A., Mora, M., Taylor, W., & Petrillo, G. (2023). An analytic expression for the volcanic seismic swarms occurrence rate. A case study of some volcanoes in the world. *Earth and Space Science*, 10(2), e2022EA002534.
31. Griffith, W. A., Rosakis, A., Pollard, D. D., & Ko, C. W. (2009). Dynamic rupture experiments elucidate tensile crack development during propagating earthquake ruptures. *Geology*, 37(9), 795-798.
32. Griffith, W. A., Nielsen, S., Di Toro, G., & Smith, S. A. (2010). Rough faults, distributed weakening, and off-fault deformation. *Journal of Geophysical Research: Solid Earth*, 115(B8).
33. Iervolino, I., Cito, P., De Falco, M., Festa, G., Herrmann, M., Lomax, A., ... & Zollo, A. (2024). Seismic risk mitigation at Campi Flegrei in volcanic unrest. *Nature Communications*, 15(1), 1-14.
34. INGV-Osservatorio Vesuviano (2024a) Bollettino di Sorveglianza Mensile Campi Flegrei Ottobre 2024. <https://www.ov.ingv.it/index.php/monitoraggio-e-infrastrutture/bollettini-tutti/mensili-dei-vulcani-della-campania/flegrei/anno-2024-3>; last access 11, November, 2024
35. INGV-Osservatorio Vesuviano (2024b) Localizzazioni sismiche Campi Flegrei. <https://terremoti.ov.ingv.it/gossip/flegrei/> last access 11, November, 2024
36. Isaia, R., Vitale, S., Di Giuseppe, M. G., Iannuzzi, E., D'Assisi Tramparulo, F., & Troiano, A. (2015). Stratigraphy, structure, and volcano-tectonic evolution of Solfatara maar-diatreme (Campi Flegrei, Italy). *Bulletin*, 127(9-10), 1485-1504.
37. Isaia, R., Di Giuseppe, M. G., Natale, J., Tramparulo, F. D. A., Troiano, A., & Vitale, S. (2021). Volcano-tectonic setting of the Pisciarelli fumarole field, Campi Flegrei caldera, southern Italy: Insights into fluid circulation patterns and hazard scenarios. *Tectonics*, 40(5), e2020TC006227.
38. Kilburn, C. R. (2018). Forecasting volcanic eruptions: Beyond the failure forecast method. *Frontiers in Earth Science*, 6, 369380.
39. Kilburn, C. R., De Natale, G., & Carlino, S. (2017). Progressive approach to eruption at Campi Flegrei caldera in southern Italy. *Nature Communications*, 8(1), 1-8.
40. Kilburn, C. R., Carlino, S., Danesi, S., & Pino, N. A. (2023). Potential for rupture before eruption at Campi Flegrei caldera, Southern Italy. *Communications Earth & Environment*, 4(1), 190.
41. Mandl, G. (2013). *Faulting in brittle rocks: an introduction to the mechanics of tectonic faults*. Springer Science & Business Media,, 444pp ISBN-10: 354066436X.
42. Marturano, A., Isaia, R., Aiello, G., & Barra, D. (2018). Complex dome growth at Campi Flegrei caldera (Italy) in the last 15 ka. *Journal of Geophysical Research: Solid Earth*, 123(9), 8180-8197.
43. Mayer, K., Scheu, B., Montanaro, C., Yilmaz, T. I., Isaia, R., Aßbichler, D., & Dingwell, D. B. (2016). Hydrothermal alteration of surficial rocks at Solfatara (Campi Flegrei): Petrophysical properties and implications for phreatic eruption processes. *Journal of Volcanology and Geothermal Research*, 320, 128-143.

44. McNutt, S.R. (1996). Seismic Monitoring and Eruption Forecasting of Volcanoes: A Review of the State-of-the-Art and Case Histories. In: Monitoring and Mitigation of Volcano Hazards. Springer, Berlin, Heidelberg. [https://doi.org/10.1007/978-3-642-80087-0\\_3](https://doi.org/10.1007/978-3-642-80087-0_3)
45. McNutt, S. R. (2002). Volcano seismology and monitoring for eruptions. *International Geophysics*, 81, 383-cp1.
46. Milia, A., Torrente, M. M., & Giordano, F. (2000). Active deformation and volcanism offshore Campi Flegrei, Italy: new data from high-resolution seismic reflection profiles. *Marine Geology*, 171(1-4), 61-73.
47. Natale, J., Camanni, G., Ferranti, L., Isaia, R., Sacchi, M., Spiess, V., ... & Vitale, S. (2022). Fault systems in the offshore sector of the Campi Flegrei caldera (southern Italy): Implications for nested caldera structure, resurgent dome, and volcano-tectonic evolution. *Journal of Structural Geology*, 163, 104723.
48. Nespoli, M., Tramelli, A., Belardinelli, M. E., & Bonafede, M. (2023). The effects of hot and pressurized fluid flow across a brittle layer on the recent seismicity and deformation in the Campi Flegrei caldera (Italy). *Journal of Volcanology and Geothermal Research*, 443, 107930.
49. Ricciolino, P., Lo Bascio, D., & Esposito, R. (2024). GOSSIP—Database sismologico Pubblico INGV-Osservatorio Vesuviano. Istituto Nazionale di Geofisica e Vulcanologia (INGV).
50. Robertson, R. M., & Kilburn, C. R. (2016). Deformation regime and long-term precursors to eruption at large calderas: Rabaul, Papua New Guinea. *Earth and Planetary Science Letters*, 438, 86-94.
51. Rosi, M., Acocella, V., Cioni, R., Bianco, F., Costa, A., De Martino, P., ... & Inguaggiato, S. (2022). Defining the pre-eruptive states of active volcanoes for improving eruption forecasting. *Frontiers in Earth Science*, 10, 795700.
52. Saccorotti, G., & Lokmer, I. (2021). A review of seismic methods for monitoring and understanding active volcanoes. *Forecasting and planning for volcanic hazards, risks, and disasters*, 25-73.
53. Safaeipour, H., Forouzanfar, M., Casavola, A. (2021). A survey and classification of incipient fault diagnosis approaches. *Journal of Process Control*, 97, 1-16.
54. Scarpati, C., Perrotta, A., Lepore, S., & Calvert, A. (2013). Eruptive history of Neapolitan volcanoes: constraints from <sup>40</sup>Ar–<sup>39</sup>Ar dating. *Geological Magazine*, 150(3), 412-425.
55. Scotto di Uccio, F., Lomax, A., Natale, J., Muzellec, T., Festa, G., Nazeri, S., ... & Zollo, A. (2024). Delineation and fine-scale structure of fault zones activated during the 2014–2024 unrest at the Campi Flegrei caldera (Southern Italy) from high-precision earthquake locations. *Geophysical Research Letters*, 51(12), e2023GL107680.
56. Selva, J., Orsi, G., Di Vito, M. A., Marzocchi, W., & Sandri, L. (2012). Probability hazard map for future vent opening at the Campi Flegrei caldera, Italy. *Bulletin of volcanology*, 74, 497-510.
57. Thompson, G. (2015). Seismic monitoring of volcanoes. *Encyclopedia of earthquake engineering*, 10, 1-25.

- 1 58. Tramelli, A., Godano, C., Ricciolino, P., Giudicepietro, F., Caliro, S., Orazi, M., ... & Chiodini,  
2 G. (2021). Statistics of seismicity to investigate the Campi Flegrei caldera unrest. *Scientific*  
3 *reports*, 11(1), 7211.
- 4 59. Trasatti, E., Polcari, M., Bonafede, M., & Stramondo, S. (2015). Geodetic constraints to the  
5 source mechanism of the 2011–2013 unrest at Campi Flegrei (Italy) caldera. *Geophysical*  
6 *Research Letters*, 42(10), 3847-3854.
- 7 60. Turcotte D.L. (1997). Fractals and Chaos in Geology and Geophysics. 2nd Edition. 383pp  
8 Cambridge University Press. ISBN-10: 0521567335.
- 9 61. Turcotte, D. L., & Schubert, G. (2002). *Geodynamics*. Cambridge University Press.
- 10 62. Vitale, S., & Isaia, R. (2014). Fractures and faults in volcanic rocks (Campi Flegrei, southern  
11 Italy): insight into volcano-tectonic processes. *International Journal of Earth Sciences*, 103,  
12 801-819.
- 13 63. Voight, B. (1988). A method for prediction of volcanic eruptions. *Nature* 332, 125–130. doi:  
14 10.1038/332125a0
- 15 64. Wesson, R. L. (1988). Dynamics of fault creep. *Journal of Geophysical Research: Solid*  
16 *Earth*, 93(B8), 8929-8951.

# **Birth and growth of a volcanotectonic fault during the current volcanic unrest at Campi Flegrei caldera (Italy)**

Authors: <sup>1\*</sup>Giordano G., <sup>1</sup>Alfonsi G., <sup>1\*</sup>Salvini F., <sup>2</sup>Bianco F., <sup>3</sup>Chiarabba C., <sup>2</sup>Di Vito M., <sup>2</sup>Tramelli A.

<sup>1</sup> Dipartimento di Scienze – Scienze Geologiche, Università RomaTre, Largo San Leonardo Murialdo 1, 00146, Rome, Italy

<sup>2</sup> Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Vesuviano, Napoli, Italy

<sup>3</sup> Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143, Rome, Italy

\*Corresponding authors: [guido.giordano@uniroma3.it](mailto:guido.giordano@uniroma3.it); [francesco.salvini@uniroma3.it](mailto:francesco.salvini@uniroma3.it)

## **Abstract**

**The ongoing volcanic unrest at the highly populated Campi Flegrei caldera is accompanied by incremental seismic activity, ground uplift and geochemical anomalies that are raising severe public concern. Here we show with a novel statistically-based method that since 2023 seismicity has progressively clustered along a preferential  $N249^{\circ}\pm4^{\circ}$ ,  $53^{\circ}\pm1^{\circ}$  plane near the center of the caldera, concentrating more than 50% of seismic events and most of the released seismic energy. This clustering is evidence for the transition from diffuse micro-seismicity to the development of an extensional volcanotectonic fault in its initial stages. The nucleation (or reactivation) of this fault suggests that caldera rocks are experiencing conditions for critical failure and may have overcome elastic deformation that resulted, until 2023, in an almost perfect axisymmetric uplift, thus representing a significant change for volcanic and related hazards evaluation at Campi Flegrei.**

## **Main**

The 12 km x 15 km wide Campi Flegrei caldera (Fig. 1) arguably presents the highest volcanic risk on Earth, with nearly 500,000 people exposed to the threat of immediate evacuation in case of an impending eruption (Rosi et al. 2022; <https://www.regione.campania.it/it/printable/rischio-vulcanico-campi-flegrei>). It has been active since at least 110 ka (Sparice et al. 2024). The VEI 7, Magnitude 7.8 Campanian Ignimbrite eruption, occurred at 40 ka, represents the largest caldera-forming event (Silleni et al. 2020). After a long period of deflation following the historical last eruption in 1538 (Di Vito et al. 2016), unrest episodes characterized by ground uplift and seismicity occurred in the 20<sup>th</sup> century in 1950-51, 1969-72 and 1982-84 (Del Gaudio et al. 2010). The most recent and ongoing period of unrest started in 2005, and it is characterized by progressive increase in ground uplift, a rising number of earthquakes with growing maximum magnitude and an escalation of the seismic energy released, as well as geochemical anomalies (e.g. Del Gaudio et al.

2010; Chiodini et al. 2012, 2015, Trasatti et al. 2015; Tramelli et al. 2021; Del Pezzo and Bianco, 2024; Giacomuzzi et al. 2024, 2025; Astort et al. 2024; Caliro et al. 2025; Giudicepietro et al. 2025; Vanorio et al. 2025). For these reasons, since 2012, the alert level at Campi Flegrei has been raised to yellow, the second level of four, denoting conditions of mild unrest above background levels (Dipartimento della Protezione Civile, 2024). During 2023 and 2024, and through 2025, the number of earthquakes felt by the population has progressively increased, with a maximum duration-magnitude,  $M_d=4.6$ , recorded on March 13, 2025, the largest on record since the existence of a seismic monitoring network installed at Campi Flegrei in 1970. These earthquakes caused limited damage to buildings, but created severe public concern, not least because an increasing number of scientific works are now suggesting the direct involvement of magma at relatively shallow levels (5-8 km depth) associated with the unrest (Giacomuzzi et al. 2024; Astort et al. 2024; Caliro et al. 2025). The ground uplift shows an overall symmetric bell-shape and has reached in May 2025 a total maximum of more than 1.46 m at the center of the caldera since the beginning of this last unrest in 2005 (INGV-Osservatorio Vesuviano, 2024a).

The Failure Forecast Method (FFM) has been proposed as an assessment of the likelihood of the progression of an unrest episode toward a volcanic eruption. The FFM relies on acceleration of monitored scalar parameters, such as seismicity, ground deformation and geochemical anomalies, to indicate the potential 'critical' conditions at which magma pressure can induce a dyke to propagate through the country rocks (Voight 1988). (Cornelius and Voight, 1995; Boué et al 2015; Robertson and Kilburn, 2016; Kilburn 2018; Aji et al. 2024). FFM approaches have been applied to understand the current unrest at Campi Flegrei in a series of recent works (Kilburn et al. 2017, 2023; Bevilacqua et al. 2020, 2024; Tramelli et al. 2021). Bevilacqua et al. (2020) analyzed probabilistically the evolution of the earthquake occurrence and, by applying the FFM, forecasted the reaching of a critical state of the caldera in 2023 at the 50<sup>th</sup> percentile of probability and in 2031 at the 95<sup>th</sup> percentile. Kilburn et al. (2023), based on the variations in the relative rates of earthquake occurrence and ground uplift, suggest that since 2020 the caldera has entered an inelastic regime of deformation, that is when rock brittle failure and permanent deformation begin to prevail over the elastic response to pressurization. Bevilacqua et al. (2024) suggest that the increasing exponential relationship between ground deformation and cumulative number of earthquakes is indicative of progressive mechanical weakening of the stressed caldera rocks.

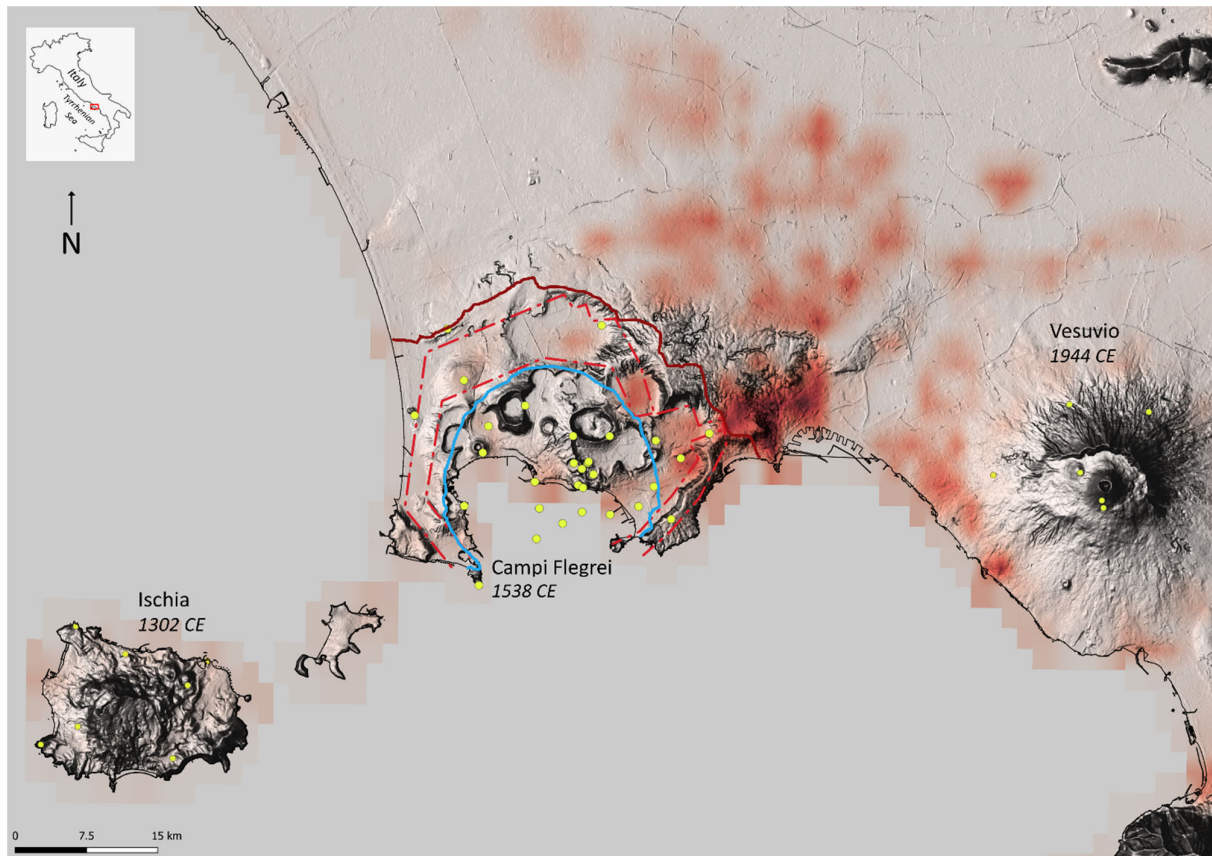


Fig. 1 – Location of the restless Campi Flegrei caldera and its neighboring active volcanoes of Vesuvius and Ischia. The date of the last eruption for each volcano is indicated in italic. The hillshade of the terrain is overlain by the NASA population density (the intensity of the red indicates up to 30,000 persons/km<sup>2</sup>; [https://neo.gsfc.nasa.gov/view.php?datasetId=SEDAC\\_POP](https://neo.gsfc.nasa.gov/view.php?datasetId=SEDAC_POP)) to highlight the high risk of the area. The INGV-OV seismic network (large yellow dots for the Campi Flegrei and small yellow dots for Ischia and Vesuvius seismic stations) both onshore and offshore allows very precise localization of earthquakes also very small in magnitude ( $M_{d_{min}} = -1.6$ ; see text). The simplified outlines of the Campi Flegrei nested calderas (red dashed lines) are taken from Vitale and Isaia (2014). To better highlight the risk at Campi Flegrei caldera, the figure shows: the area of current highest seismic risk (the inner blue line) as the area with minimum uplift of 10 cm since 2005 and that encloses all epicenters of earthquakes  $M_d > 2$  (<https://www.protezionecivile.gov.it/it/normativa/decreto-legge-n-140-del-12-ottobre-2023-misure-urgenti-di-prevenzione-del-rischio-sismico-connesso-al-fenomeno-bradisismico-nellarea-dei-campi-flegrei/>); the red zone (the outer solid dark red line), i.e. the area identified by the current Emergency Plan to be fully evacuated in case of an impending eruption (<https://mappe.protezionecivile.gov.it/it/mappe-e-dashboards-rischi/piano-nazionale-campi-flegrei/>).

FFM approaches do not consider the spatial distribution of the investigated parameters, however, and so they lack crucial information on where pre-failure strain is localising and thus on where magma eruption or large earthquakes may occur. At Campi Flegrei, for instance, it remains uncertain if and where a fault - or a series of faults - accommodating the inelastic behaviour and the mechanical weakening have nucleated or reactivated. The identification of faults from clustering of hypocenters has been attempted by Scotto di Uccio et al. (2024) by comparison with documented superficial expression of preexisting volcano-tectonic lineaments. However, while showing some possible overlaps, this overlay approach remains qualitative, requires an expert

evaluation and it is time-independent, hence it does not provide constraints to the FFM. By contrast, the distribution of the Energy Space Density of Campi Flegrei earthquakes from 2000 to 2023 shows, since 2023, a significant enlargement of the volume of fracturing rocks at ~3km depth approximately at the center of the caldera, that is the same region where the maximum uplift occurs (Del Pezzo and Bianco, 2024; Calò and Tramelli 2025). This enlargement strictly depends both on the exponential increase of the number of earthquakes that occurred in 2023 and 2024 (Fig. 2), and on their relative energy released. While clearly indicating an increase in the inelastic response of the caldera rocks, an enlargement of the volume of fracturing rocks does not discriminate between diffuse rock microfracturing and spatio-temporal clustering along a new and/or reactivated volcano-tectonic fault or fault system.

In this study, we investigate the four-dimensional (spatial and temporal) clustering of earthquake hypocenters between 2018 and 2024 (time of manuscript preparation) by the monitoring network of INGV-Osservatorio Vesuviano (2024b) around Campi Flegrei. The objective is to augment FFM approaches by determining whether, when, and where seismicity has transitioned from diffuse microfracturing to localization along a well-defined fault plane. We use an innovative Monte Carlo approach designed to overcome the limitations in spatial clustering associated with diffuse distribution of hypocenters within a relatively small and shallow crustal volume. Our findings indicate that, since 2023, onshore seismicity has evolved from a volumetrically dispersed pattern to a more localized distribution along a planar structure. This clustering persisted on the same planar structure in 2024 with a strike of  $N249^{\circ}\pm4^{\circ}$ , and a dip of  $53^{\circ}\pm1^{\circ}$  (i.e. toward the NW), located near the center of the caldera. The observed spatial and temporal evolution of seismicity is analyzed in the context of ongoing ground uplift, considering two possible scenarios: (i) the nucleation of a new volcanotectonic fault or (ii) the reactivation and unclamping of a pre-existing fault. In both cases, the implications for volcanic and related hazards assessment are significant.

## Materials

We utilized the seismic catalog of Campi Flegrei, compiled by the Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Vesuviano (Ricciolino et al. 2024). This official and publicly accessible catalog (<https://terremoti.ov.ingv.it/gossip/flegrei/>) provides the origin time, location along with its uncertainties, and duration-magnitude of each earthquake. The events were located by using manual pickings and a layered velocity model as described by Tramelli et al. (2022). The catalog encompasses seismic events recorded between January 1, 2019, and October 10, 2024 (time of manuscript preparation), with depths ranging from 0.1 to 5.6 km and duration magnitudes (Md) between -1.6 and 4.4. The average location errors are 0.2 km for both horizontal and vertical positions. As location of micro-earthquakes is affected by large uncertainties, we selected earthquakes with  $M_d \geq 0.5$ , following the completeness magnitude determined by Del Pezzo and Bianco (2024) for the period 2000-2023 (Supplementary materials S1). The well-distributed geometry of the seismic monitoring network, which also includes four offshore stations (Fig. 1), ensures a comparable level of earthquake location accuracy across the various sectors of the caldera, at least for seismic events with  $M_d \geq 0.5$ .

We chose to use the catalog provided by the Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Vesuviano because it is an institutional product, continuously updated and validated by the official monitoring authority of the area. Its certified and standardized nature ensures the consistency, transparency, and reproducibility of our analysis over time, which we consider essential for the scope of our work. We acknowledge that relocated catalogs (e.g. Tramelli et al. 2022; Scotto di Uccio et al. 2024, Giacomuzzi et al. 2025), obtained through relative location techniques such as double-difference methods or source-specific corrections, can offer improved clustering and lower location uncertainties, which can facilitate the identification of seismicity patterns. However, such catalogs are often not available continuously or systematically over the entire time window of interest and may introduce a bias toward artificially increased clustering due to the nature of the relocation algorithm itself.

The goal of our study is to offer a statistical, unsupervised approach to identify temporal clustering of earthquakes, highlighting the potential activation of main fault structures. Several authors have previously mapped multiple fractures and faults in the area using both seismic and geological data; an overview of these structures is summarized in Iervolino et al. (2024). In that same work, the authors define the upper bound of reference magnitude scenarios as the simultaneous activation of multiple faults. In a similar spirit, our method aims not just to detect individual small-scale faults, but their possible merging or interaction over time, and for this reason we preferred to use a catalog that does not implicitly cluster events through a double-difference approach.

To ensure the reliability of the seismic locations used in the analysis, we applied a completeness magnitude threshold of 0.5, which allowed us to select events for which 95% of the catalog has a location quality of B or better. This quality code incorporates several factors, including the root mean square (RMS) residuals, horizontal and vertical errors, number of phase picks, and azimuthal gap.

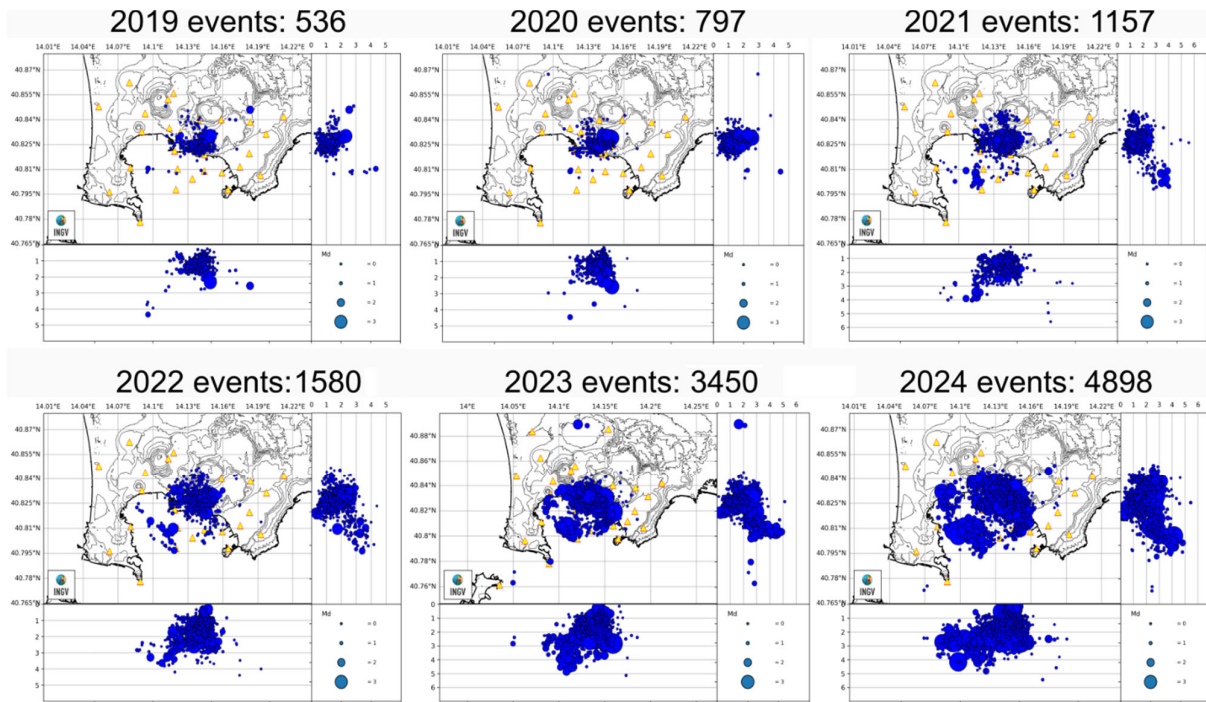


Fig. 2 Areal distribution of epicenters of earthquakes registered by the INGV-OV seismic network in 2018-2024 (INGV-Osservatorio Vesuviano, 2024b). Each panel shows also the projection of hypocenters across N-S and E-W cross sections.

## Approach

Seismicity at Campi Flegrei is mostly concentrated onshore in the center of the caldera, but over time it has also progressively extended offshore, where it is less frequent and deeper, defining an overall annular seismic volume, likely along ring-fractures (Fig. 2; e.g. Scotto di Uccio et al. 2024). We focused our analysis on the most seismic and at-risk onshore area, where the number of earthquakes ensures a statistically significant analysis, to assess whether earthquake hypocenters may show evidence of clustering over time and space. The 3D spatial analysis over time presents several challenges.

First, most events have magnitudes close to 0 or negative for which the location uncertainty is too high for our application. Our analysis is limited to events with  $M_d \geq 0.5$ , for which the average uncertainty on both horizontal and vertical localization is around 200 m (Del Pezzo and Bianco 2024).

Second, the spatial distribution of hypocenters is highly inhomogeneous, with the horizontal distribution of event locations larger (about 6 km x 6 km) than the depth range (mostly concentrated at <3 km with fewer offshore extending down to 5.5 km). This type of spatial distribution introduces an unsolvable bias for any objective trend analysis of the totality of data, that would inevitably result in flattening any possible searched planar trend. To override this bias, in this study we used a multiple inversion approach to analyze data falling into a hexagonally centered lattice of vertical cylinder cells of a given radius and a grid spacing providing the minimal cell overlap to guarantee the analysis of all data. The cylinders have a base-diameter of 1000 m

with a grid spacing of 866 m. These dimensions optimize the need to have a vertically extended computational domain (the ratio of vertical:horizontal extents is  $\sim 5:1$  for each cylinder) enclosing at the same time a statistically significant number of events (see Methodology; Fig. M1).

Third, spatial analysis commonly uses the Least Square Method (LSM) to identify the trend that best fits the data, which in our case should represent the potential planar structure to which hypocenters may be associated. However, LSM assumes that all data belong to the same population, enhancing the relevance of data with values falling far from the predicted model, measured by the square of their distance from the predicted distribution. Seismic swarms in calderas may instead be associated with variably overlapping causes (e.g. gas pressure in the hydrothermal system, magma pressure in geometrically complex reservoirs, strain localization along different pre-existing volcano-tectonic faults and across variable rock-rheology). This limitation has been reduced in this study by using a different factor for the distance (cf. Tarantola 2005) as its root square, the Least Root Square (LRS) method to automatically reduce the influence of distant data (e.g. as outliers), yet without imposing any arbitrary threshold. This method proves to be much more efficient in identifying clustering within dispersed datasets respect to LSM approach (see Methodology for explanation, Fig. M2, where the performance of various exponents  $L$  [3, 2, 1, 0.5, 0.333] has been tested on the 2023 data and confirm the best performance for the used exponent  $L=0.5$  to weigh the data distance from proposed planes). This implies the use of a specific Monte Carlo approach (in this study we used a Monte Carlo-Like Convergent Method (MCC, see Methodology, Schmidt and Salvini, 2024) . Data for each cylinder were processed with MCC, to obtain the best planar solutions within those volumes. To test the reliability of the solutions we have performed a random data sampling analysis for the diffusive years, confirming, as expected, that the variance is independent of the number of samples as the total number is statistically significant (see Supplementary material 2a). To test the influence of the lattice position in the trend identifications, the grid analysis was repeated by shifting the lattice by a random value and proved congruent results (Supplementary materials S2b). The minimum number of data to define a potential plane was set to eight, which provides the minimum acceptable degree of freedom (5 for this planar approach) in a three-dimensional space to obtain a reliable planar solution.

If identified planes of adjacent cells show close attitudes (i.e. planes have similar strike and dip, defined as planes falling inside the same quadrant, i.e. with the poles to planes at angular distances  $<45^\circ$ ), we verified the effective presence of a unique planar structure extending across the lattice, by performing a new MCC inversion analysis within the merged volume of the related cylinders (Fig. M1; Supplementary materials S3a). To avoid any bias imposed by the potentially elongated geometry of the merged volume, the analysis was also performed on a single larger cylindrical volume centered around the merged cylinders (Fig. M1; Supplementary materials S3b). The MCC analysis was then repeated several times (the original set of random values guarantees always slightly different results within the satisfactory resolution) to test the robustness of the solution and its associated error by computing the Mean and the Standard Deviation of the set of results allowed us to identify the presence of a consistent planar trend.

This multiple analysis procedure was repeated also by adding to earthquake locations their error. This was performed by adding a vertical and horizontal shift to each data chosen randomly within

the associated error of the measure. Results of this analysis show only a modest increase in the data scattering along the identified planar trends, confirming the reliability of the solutions (Supplementary materials S3c).

## Results

The results of the MCC inversions of the distribution of earthquakes hypocenters have identified best-fit planes which vary both in space and time. The best-fit planes obtained within each individual cylindrical volume are shown in Fig. 3.

In 2019, 2020, 2021 and 2022, the total number of located events increased from 536, to 797, 1157 and 1580 (Fig. 2). The number of events with  $M_d \geq 0.5$  increased from 119 in 2019, to 193 in 2020, 264 in 2021, and 443 in 2022 (Supplementary material S1). Significant planar trends (i.e. associated with a minimum of 8 events) were identified only in 6 cylinders, in 2019, in 5 cylinders in 2020, in 8 cylinders in 2021, and 10 cylinders in 2022, all located in the area of maximum seismicity below Pozzuoli-Solfatara (Fig. 3 a; Supplementary material S2b). These best-fit planes are associated with a small number of events (with a maximum of 51 in 2022) and show completely scattered orientations (Fig. 3b), indicating a random distribution of earthquakes in the seismogenic volume and a poor reliability of the best-fit planes.

With the sharp increase in seismicity observed in 2023 and 2024 (Fig. 2), the identified best-fit planes increased in number and spatial distribution, as well as in clustering progressively larger numbers of earthquakes.

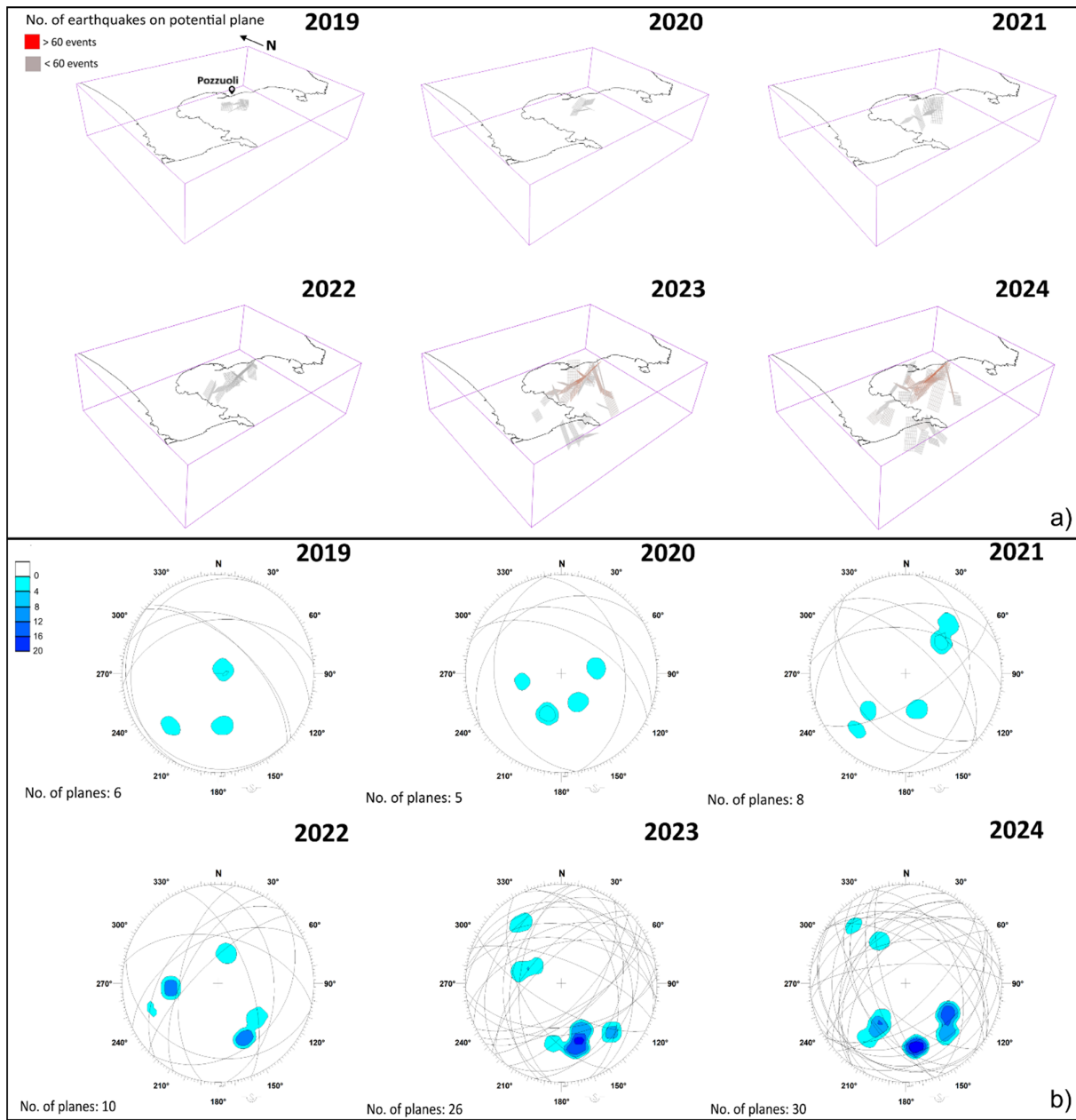


*Fig. 3 – Perspective views (a) and stereonet representation (b; southern hemisphere projection) of planes and poles of the planar features clustering earthquakes hypocenters in the years 2018-2024. Since 2023, a planar structure well-defined by hypocenter clustering appears in the center of the caldera. See text for explanation.*

In 2023, a total number of 3448 events occurred, with 1181  $M_d \geq 0.5$  (Fig. 2; Supplementary material S1), which allowed the identification of 26 cylinders with significant best-fit planes (Supplementary material S2b). Most of the best-fit planes are in the correspondence of Pozzuoli-Solfatara but also extending in the area of Bagnoli (Fig. 3a). These planes cluster up to 143 events (i.e. located within 300 m from the plane). An enlargement of the identified best-fit planes offshore can also be appreciated in the Gulf of Pozzuoli (Fig. 3a). In 2023, the area of most intense seismicity Pozzuoli-Solfatara shows clustering of events around coherent NNW dipping planes (Fig. 3b) in 3 contiguous cylinders, with best-fit planes oriented at a dihedral angular distance  $< 28.5^\circ$  (Supplementary material S4).

In 2024, the number of earthquakes until October (time of analysis) further increased to 4456 (Fig. 2) with 1528  $M_d \geq 0.5$ . This allowed the identification of 30 cylinders with best-fit planes that occupy a vast portion of the caldera, both around the zone of maximum seismicity Pozzuoli-Solfatara, in the Bagnoli area, and offshore (Fig. 3a). The largest number of earthquakes occur within the same three adjacent cylinders identified for the first time in 2023 (Fig. 3b, Supplementary materials S2b) and extended to a fourth adjacent cylinder, with close NNW dipping orientations at dihedral angular distance  $< 36.8^\circ$  (Supplementary materials S4).

We selected these four cylinders identified as 6\_3, 6\_4, 5\_4 and 7\_3 (Fig. M1) to test the reliability of the results (Supplementary materials S3a, 4), by running the MCC analysis in the merged volume of the four adjacent cylinders. The surface area of the four merged cylinders is about 3 km x 2 km (Fig. M1). To test the influence of the volume geometry, MCC analyses were also performed within a 3 km diameter cylinder centered on the merged volume, providing very close results (see Methodology, Fig. M1; Supplementary materials S3b, S4)

Results confirm that in 2023 and 2024 the identified planes in the extended merged volume coincide with those identified within adjacent cylinders and provide orientations of  $N247^\circ, 53^\circ$  in 2023 and  $N244^\circ, 53^\circ$  in 2024 (Supplementary materials S3a). The total number of events that are associated with the clustering plane in the first ten months of 2024 is 401 (Fig. 4c). Very similar results are obtained within the 3 km diameter cylinder centered on the merged volume (Supplementary materials S3b). The persistence of a very similar direction for the best-fit planes in 2023 and 2024 suggests that a change has occurred in the pattern of event location since 2023, which we will discuss as the nucleation of a potential incipient volcanotectonic fault (PIF) or the activation of a pre-existing volcanotectonic fault.

A robustness-like analysis was performed by repeating 10 times the MCC inversion for all 2023-2024 events located in the merged volume (hereafter the PIF volume), and by adding a random error to event locations within the declared measure error for each event location. Results are presented in Fig. 4a and Supplementary materials S3c1 and show the strong reliability of the found PIF solution within the merged volume, with a mean value in 2024 of  $N249^\circ \pm 4^\circ, 53^\circ \pm 1^\circ$ . Very similar results are obtained within the 3 km diameter cylinder centered on the merged volume (Supplementary materials S3c2). By recalculating the best-fit plane within the PIF merged volume since 2019 (Supplementary materials S3c1,2), it is possible to confirm that from 2019 to 2021 the orientation is random, and that in 2022 there is the first mild clustering around the PIF orientation that then dominates in 2023 and 2024 (Fig. 4b). Alongside, the standard deviation both on strike and dip decreases substantially, demonstrating the effect of clustering over time (Fig. 4b). It must be also noted that the dip angle increases over time, because of the identification of the PIF plane, progressive prevailing over the distributed volumetric small events which tend to bias toward subhorizontal or low angle solutions (e.g. 2019, 2020, 2021). By imposing the PIF orientation in the PIF merged volume to the distribution of events since 2019 it is also possible to appreciate both the increase in the number of events clustered around the PIF and the progressive decrease

1 of the root mean power (RMP, that represents the mean residual value, computed with the used  
2 exponent  $L = 0.5$ ) associated with earthquakes at distances  $< 200$  m from the PIF (Fig. 4c).

3  
4 While the analysis presented in this paper stops in 2024, i.e. the time of submission of the  
5 manuscript, we have also analyzed, during revision, the seismicity that occurred in the first months  
6 of 2025. This analysis confirms a further increase in number of events and total energy released,  
7 and it also confirms the persistence of the same clustering plane identified in 2023 and 2024.

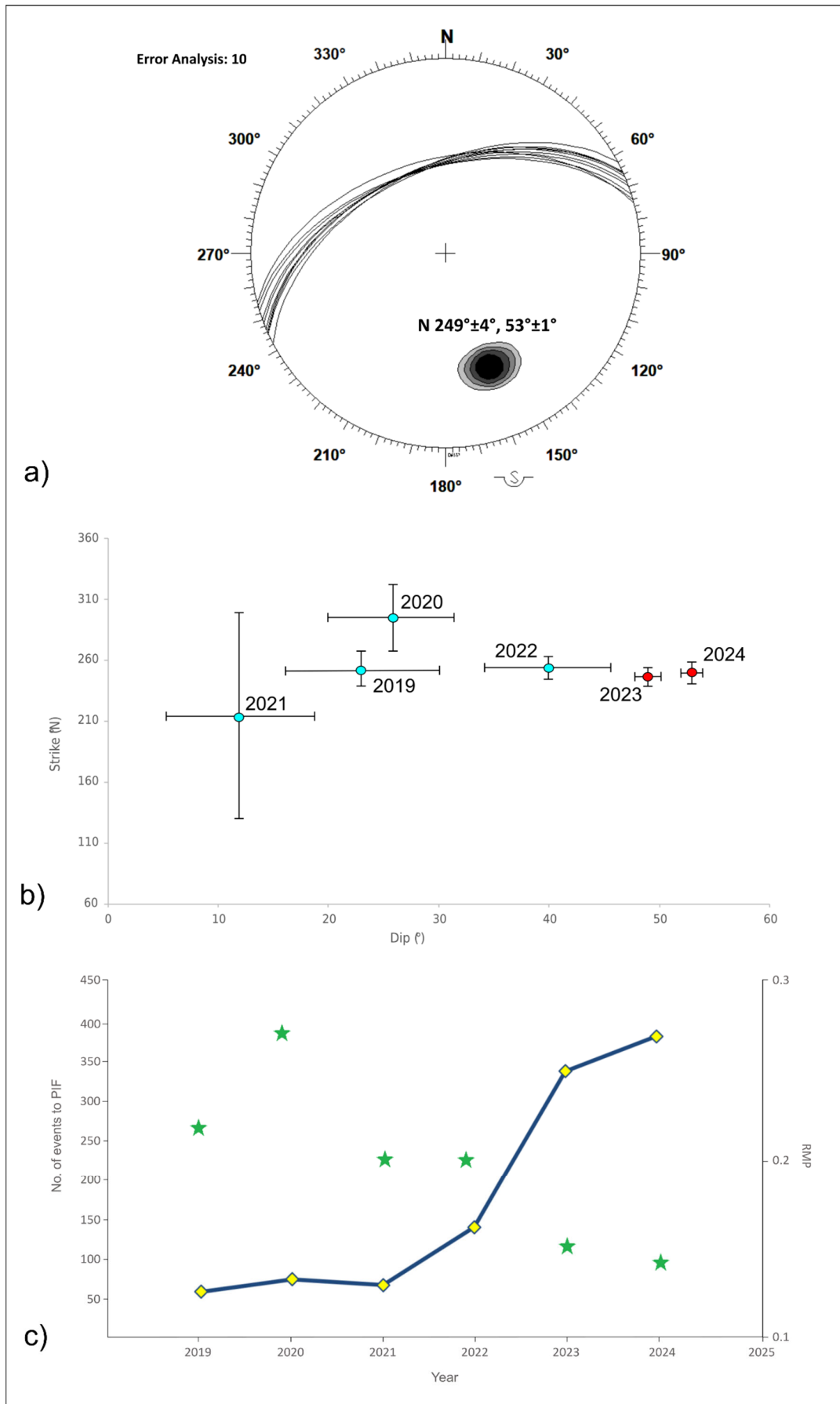


Fig. 4 a) Contouring (Schmidt stereonet, lower hemisphere) of the poles to the PIF planes identified in the merged PIF volume (cylinders 6\_3, 6\_4, 5\_4 and 7\_3, see Fig. M1 in Methodology) by a set of 10 repeated MCC analyses with the random error added to earthquake locations, showing the consistency of the MCC processing and the limited influence of the location error. b) Plane features calculated within the PIF volume since 2019, showing a scattering of dip and azimuth until 2023 and 2024; colours of squares indicate the number of events associated with the plane (pale blue <250; red >500); error bars indicate 1 standard deviation. c) Yellow diamonds indicate the progressive increase of number of events associated with the PIF since 2019 until October 2024; green stars indicate concomitant reduction in the ratio of the root mean power RMP ( $L = 0.5$ ) of hypocenters with distance <200m from the plane respect to the RMP distance of all hypocenters from the plane; the reduction of this ratio illustrates that the clustering around the PIF in 2023 and 2024 prevails over dispersion of earthquakes in the progressively larger seismic volume.

## Discussion

Seismicity and deformation are well documented indicators of the evolution of caldera unrest and of the localization of intra-caldera fracture systems (e.g. Mori and McKee, 1987; Gudmundsson et al. 2016; Hill et al. 2020; Bell et al. 2021). Very recent analyses of seismicity and ground deformation during the current ongoing unrest at Campi Flegrei caldera are progressively highlighting the marked and simultaneous changes in uplift velocity and seismicity rate that have occurred over the last few years. Bevilacqua et al. (2024) highlight the parabolic increase in ground uplift and a super-exponential rise of earthquake number and seismic energy released, interpreted as possibly related to a progressive mechanical weakening of the crust. Giudicepietro et al. (2025) showed that since 2021 the style of seismicity has changed with development of burst-like swarms. Del Pezzo and Bianco (2024) show that since 2023 the Energy Space Density of the Campi Flegrei seismicity highlights an enlarged volume of fractured rocks at a depth of around 3 km. At the same depths, Calò and Tramelli (2024) and Giacomuzzi et al. (2025) identify a rock volume characterized by high  $V_p/V_s$  ratios possibly for the presence of pressurized fluids, qualitatively in agreement with electrical resistivity imaging (Isaia et al. 2021). Collectively, recent studies on geophysical and geochemical data now converge in ascribing the current unrest at Campi Flegrei to the migration and accumulation of magma in the plumbing system (8-5 km depth) which, also by releasing volcanic fluids, pressurizes the shallow hydrothermal system (< 4 km) (Giacomuzzi et al. 2024; Astort et al. 2024; Caliro et al. 2025).

While the exact mechanisms behind the observed deformational patterns at Campi Flegrei caldera are still open to some discussion (e.g. De Siena et al. 2024), it remains unclear whether the system, as described by the FFM approach, is nearing or has already reached a critical state (e.g. Kilburn et al. 2023). Specifically, it is unclear whether the mechanical behaviour of the rock mass surrounding the sub-caldera plumbing system is currently already in its final stages of failure or still progressing toward that point. This is particularly important as it is therefore essential to move from classic analysis of scalar quantities, such as the variations of the number of earthquakes and uplift over time, to a four-dimensional (spatial and temporal) analysis such as in this study.

Our novel methodology allows one to move beyond a classic FFM approach and to define if and where the deforming caldera is showing evidence of a transition from diffuse microfracturing, typical of the early stages of an unrest, to clustering and linkage of microfractures along a defined

plane that may act as an individual fault or a fault system. In particular, by overcoming the main limitations to spatial clustering analysis of VT earthquakes hypocenters, our innovative unsupervised approach shows that since 2023 the seismicity shifted from randomly scattered within the most stressed volume of Campi Flegrei caldera, i.e. at its center, to self-organized around a main clustering plane with orientation  $N249^{\circ}\pm4^{\circ}$ ,  $53^{\circ}\pm1^{\circ}$  (Fig. 4). This transition may have significant implications for the hazard assessment in terms of the maximum expected earthquake magnitude (e.g. Iervolino et al. 2024) and the location(s) of preferred pathways for the uprise of both hydrothermal fluids and magma.

The clustering plane projects radially from volume of maximum vertical deformation under Pozzuoli (Fig. 5). With a horizontal extent of 2.8 km and a vertical extent of 2.5 km, the plane dips to the northwest and almost emerges at the Earth's surface to the southeast of Pozzuoli (Fig. 5; cf. Feature D in Scotto di Uccio et al. 2024). Assuming Andersonian faulting conditions (Anderson 1905; Fig. 5a), the attitude of the clustering plane (dip of  $53^{\circ}$ ) and its position respect to maximum uplift can be interpreted as indicating a vertical orientation of the maximum stress ( $\sigma_1$ ) and a theoretical rock mass internal friction angle of  $16^{\circ}$ . The latter value is not unrealistic considering the weak rock rheology of the shallow Campi Flegrei rocks (e.g. Dello Iacono et al. 2009; Meyer et al. 2016).

Discriminating whether the identified clustering plane may represent the reactivation of a pre-existing fault, or the nucleation of a new fault is not easy. Field studies on the distribution of faults and fractures in the Campi Flegrei caldera floor, both onshore (Cosentino et al. 1984; Acocella et al., 1999; Acocella 2010; Selva et al. 2012; Vitale and Isaia 2014; Isaia et al. 2015, 2021; Sbrana et al. 2022; Iervolino et al. 2024; Caliro et al. 2025) and offshore (Milia et al. 2000; Natale et al. 2022) show many structural elements, mostly NE-SW and NW-SE oriented, that are associated with the episodes of volcanotectonic resurgence and subsidence since 15 ka (Di Vito et al. 1999; Marturano et al. 2018). However, field evidence does not clearly show the presence of a fault in the position, and with orientation and extension similar to the plane that is currently clustering the seismicity. In addition, the high density and quality of the INGV seismic monitoring network that now allows us to detect and track the clustering plane during the current unrest was not available during the former unrest episodes (1982-84; 1969-72; 1950-52), which makes it impossible to ascertain whether previous seismic activity was already clustering on a similar plane (cf. De Siena et al. 2017).

Nevertheless, we note that the event distribution along the clustering plane is rather stochastic, which suggests that this plane is formed by the progressive linkage of micro-dislocation surfaces. By comparing the geometry of the clustering plane and the Energy Space Distribution (Del Pezzo and Bianco 2024; Fig. 5a), we note that both localized and scattered seismicity occur in a volume that is centered on, but is larger than, the plane itself. Also, the observation that some of the mainshocks do not occur on the clustering plane (Fig. 5a) can be interpreted to mean that damage and energy dissipation are not confined to the region where the linkage of micro-fractures is occurring, but are possibly also related to secondary failure planes (e.g. Griffith et al. 2010). The progressive definition of a clustering plane is substantiated by the location of the majority of

1 earthquakes, including several of the largest magnitude ones. Consequently, this plane localises  
2 the largest energy released (Fig. 5a), but also other structures can be activated.

3 We therefore prefer to interpret the change in spatial distribution of seismicity occurring since  
4 2023 as the birth of a potential incipient fault (PIF). The adjective “potential” clarifies that we have  
5 so far identified a fault plane by statistical methods rather than by more physics-based methods  
6 such as seismic reflection or geodetic modelling. With the term “incipient” we stress that we are  
7 not describing yet a fully developed classic seismic fault, but rather the initiated and ongoing  
8 process of self-organization of the micro-fracturing which is in the course of defining a fault plane.  
9 This is important as the merging of small dislocation planes into a larger one results in a significant  
10 increase in stress along its tips, thus producing their propagation and eventually the full  
11 development of a fault (Griffith et al. 2009), whose dimensions control the maximum expected  
12 magnitude on that plane (cf. Iervolino et al. 2024).

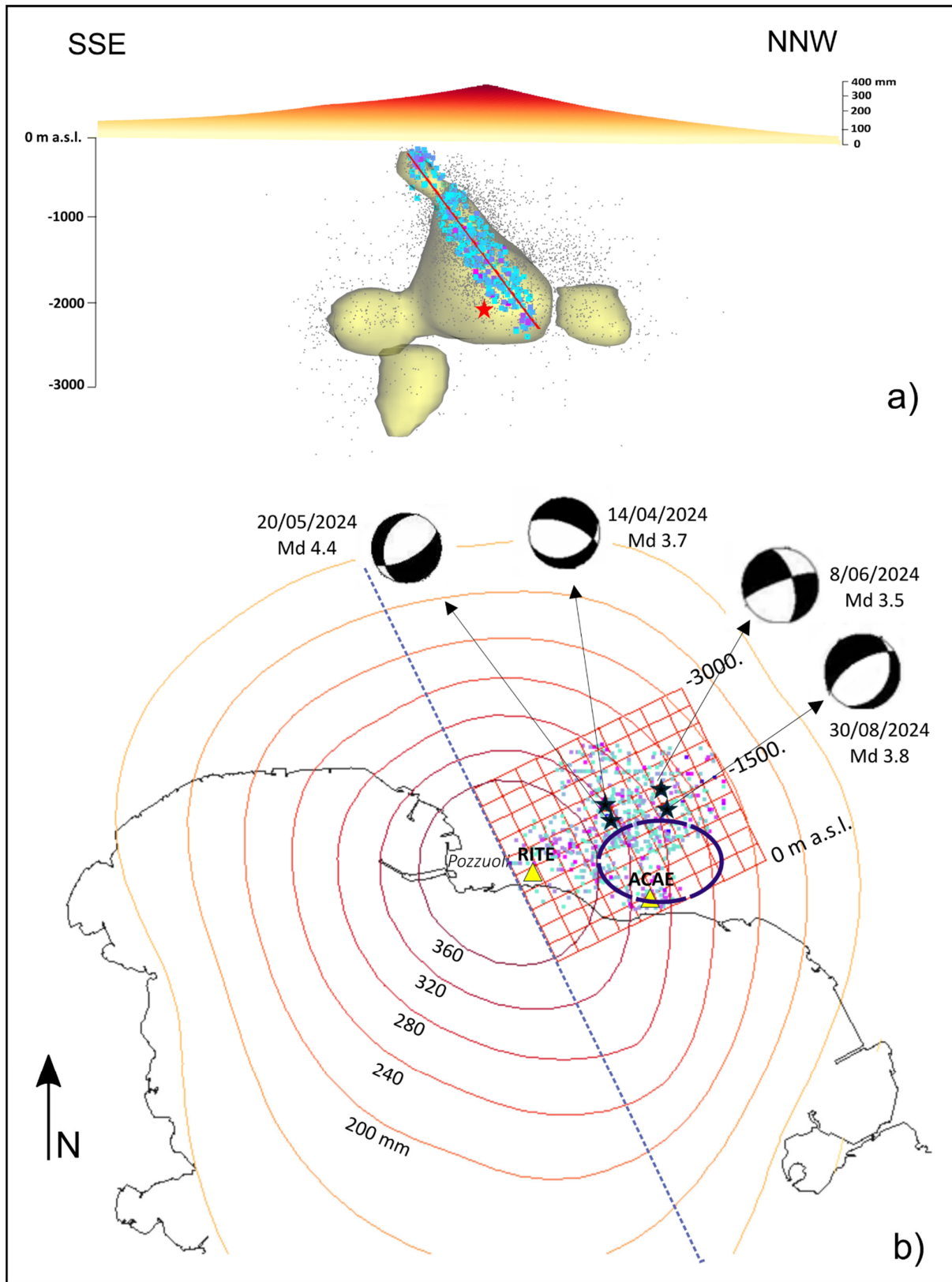


Fig. 5 (a) Cross sectional view and (b) planar view (red square net) of the PIF respect to the axisymmetric ground uplift pattern centered at RITE GNSS station (indicated as yellow triangle along with the ACAE GNSS station). Hypocenters

associated with the PIF in (a) are colour coded for duration magnitude from  $M_d=0.5$  (light blue) to  $>3.5$  (dark blue). All other hypocenters are grey in the background. Uplift isolines in (b) are in millimeters and show the uplift measured in 2024 (INGV-Osservatorio Vesuviano, 2024a). The dotted line in (b) indicates the trace of the cross section shown in (a). The yellow surface in (a) represents the  $-3.84$  iso-value envelope for the observed Energy Space Density in 2023 (from Del Pezzo and Bianco 2024) and shows the concentration of the seismic energy along the PIF and over the central domal volume. Focal mechanisms in (b) show mainly extensional trends parallel to the PIF strike, which, associated with the PIF dip, suggests downthrow toward the NNW. This is perfectly coherent with the location of the area of geodetic anomaly (thick blue line from Giudicepietro et al. 2025) defined by a deficit in uplift rate.

It is worth specifying that a fault is generally a complex structure that involves a volume (i.e. the fault zone), often with several displacement surfaces that at times may concentrate most of the slip, i.e. the fault core (e.g. Caine et al., 1996)

There are two end member models for fault generation. The first involves their nucleation from an initial relatively small zone where the acting stress overrides the brittle strength of the rock and then expands along its edges, eased by the stress concentration that generates at its tips (Mandl, 2013). This evolutionary model applies when regional (e.g. external) stresses are acting. The second considers the initial development of a cloud of small fractures with limited displacement. As their dimensions increase by increasing stress and, again, fault tip stress concentration, adjacent faults join and, if their sense of movement is compatible, form a larger fault with increasing displacement. Eventually, the linkage process ends with the development of a major fault surface (Turcotte, 1997; Mandl, 2013; Safaeipour et al., 2021).

This latter model seems to apply for the development of the observed PIF, where a progressive clustering of seismic events is observed along a preferential orientation, ascribable to a sort of creeping along minor faults (Wesson, 1988). The required coherence among the minor fault population relates to the mechanism for their origin, in the case of the Campi Flegrei unrest, the extensional regime produced by the deformation resulting from the observed uplift (Astort et al. 2024). This may exclude an origin of the PIF as the effect of the increase of a regional (tectonic) stress and the PIF can be considered the effect of the kinematics of the resurgence acting in the Campi Flegrei caldera, allowing us to classify the PIF within the kinematic fault family (that is, faults produced by rock dislocation rather than an asymmetrical regional stress; Turcotte and Schubert, 2002). Consequently, this evolutionary model does not predict a significant increase in the dimensions of the fault plane and of the magnitude of the future seismic events, that for Campi Flegrei are expected to a maximum of  $M_d=5.1$  (Iervolino et al. 2024). On the other hand, the PIF evolution will likely result in an increase of its displacement, thus providing a more and more efficient gravity discharge over the resurgent block, potentially resulting in a progressive acceleration of its uplift. This is because in a stress field characterized by a vertical  $\sigma_1$ , the presence of a normal fault slip allows to reduce the hangingwall thickness (i.e. the load on the fault).

Initial effects of the PIF normal dislocation could well explain the observed geodetic anomaly with a relative decrease in the uplifting rate around the GNSS station ACAE (Fig. 5b), which since 2023 is altering the perfect axisymmetric shape of the uplift (Giudicepietro et al. 2025), as well as other

time-dependent deformation features that have been highlighted to occur in correspondence of the PIF (e.g. De Siena et al. 2024, Tizzani et al. 2024). The area of geodetic anomaly is coherent with a normal displacement toward the NNW, also in agreement with focal mechanisms (Fig. 5b). The dipping of the PIF towards inland (NNE), that is towards inner, higher elevation areas (with a higher gravity load) represents anyhow a delaying factor to its displacement. Nevertheless, great care must be taken to monitor its development and evolution, given its influence on resurgence patterns and its potential to provide preferential pathways for uprising hydrothermal and volcanic fluids. We finally remark that the proposed unsupervised analysis of the spatio-temporal evolution of seismicity during volcanic unrests has a general validity and can be applied to any active volcanic system.

### **Acknowledgements**

GG and AV acknowledge the grant to the Department of Science, Roma Tre University (MIUR-Italy Dipartimenti di Eccellenza, ARTICOLO 1, COMMI 314–337 LEGGE 232/2016). AT and MDV acknowledge the grant of Departmental Project LOVE\_CF (INGV Pianeta Dinamico) and the Italian DPC, in the frame of INGV-DPC (2022–2025) agreements, although it does not necessarily represent DPC official opinion and policies. We acknowledge E. Del Pezzo for the EDS isosurfaces used in Fig. 5a. We thank E. Holohan, L. De Siena and an anonymous reviewer for their thoughtful and constructive reviews.

### **Authors' contributions**

GG and FS conceived the study; GA, FS, GG performed the statistical analyses; FB, AT took care of the seismic dataset; All authors discussed the results and contributed to the writing and commented on the manuscript.

### **Data availability**

The code Montecarlo\_Fault is available upon request to the corresponding authors.

The seismic record used in this work is acquired by the INGV-OV seismic monitoring network and publicly available at <https://terremoti.ov.ingv.it/gossip/>

### **The authors declare no competing interests**

### **Methods**

### **Foreword**

The Least Square Method (LSM) is a largely and successfully used mathematical algorithm to test and identify linear trends of a set of data (Tarantola, 2005) and, with some iterative computations, can be extended also to non-linear trends (Fraser & Suzuki, 1969). The Least Square Method is characterized by a fast and simple computation by minimizing the sum of the squares of the deviations of the data values from a given expected trend

$$\text{Min } \sum_i (z_i - f(x_i, y_i))^2$$

This is easily solved by zeroing the parameter partial first derivatives of this equation.

Despite its advantages, two severe boundary conditions limit the wide and indiscriminate use of the LSM. The first is the assumption that all data must belong to the population following the searched trend shape. This constraint is difficult to be fully respected in nature due to the complexity of the real world, where the scattering of measured data may not simply depend on the diffusion of a single process but by several, often independent and overlapping causes, including casual ones. The application of the LSM to such complex data populations may result in unreliable or fake solutions.

The second limiting condition is intrinsic in the method. Measures in the LSM approach are weighed by the square of their distance along the dependent variable from the searched trend. This provides, when data belongs to different populations (including randomly scattered ones), a strong bias in the relative relevance of each datum, since measures more distant from the trend will weigh in the computation far more than the data that follow closely the searched trend. This is a strong limitation, since, in a complex situation (i.e. where measures depend on more than a single population/trend as in this study) the farthestmost data are those that most likely do not follow the trend under test, yet accordingly they will weigh (by the square of the distance) more than the closer trend data. Therefore, a small percentage of data belonging to a different population is sufficient to invalidate the results.

To override this limit, a common (and dangerously subjective) technique is often applied and consists in the identification and elimination of data more distant from the desired trend, classified as “outliers”. Generally, this is accomplished by discarding from the inversion process data that show the (assumed) larger distance from the initially approximated trend and repeating the inversion by excluding them. This represents a serious external influence on the data and should be always avoided or used with great care, since it is strongly influenced by the subjective rules applied, as well as the relative number of data following the searched trend with respect to those that belong to different populations. The outlier identification is even more and more complex as the number of data increases, especially when used strongly scattered data population, i.e., where only a reduced percentage of data follows the expected trend. This latter scenario is expected in the seismic event location population such that in the studied Campi Flegrei active region, where the spatial distribution of the events derives from the contemporary action of at the minimum two main causes, the doming related to gas escape and/or rising of a magmatic body, and the potential presence of a fault or more faults acting contemporaneously. The first cause will provide a locally scattered swarms of events. The activation of an active fault or a PIF would provide a concentration of events along the approximated planar fault zone. This

scenario closely resembles the distribution of the locations of seismic events during this last Campi Flegrei crisis, where data are consistently distributed along an annular shape around the area, yet with a very strong asymmetry and most of the events locating more and more in the western coast of the Pozzuoli area within the last years.

### **The Least Root Method (LRM)**

With these premises, a slightly different and objective method is proposed deriving from Tarantola (2005) and used in the present study: the Least Root Method (LRM). Similarly to the LSM approach, this method searches to minimize the sum of the square root of the absolute distances between trend and the dependent variable (elevation  $z$ , in our study), thus lowering the weight of the most distant data.

The equation to be minimized is then

$$\text{Min } \sum_i |(z_i - f(x_i, y_i))|^L$$

, where  $L = 0.5$  is the used exponent in LRM method.

Unfortunately, this equation cannot be easily minimized in analytical formulation in most cases, and the distances must have always a positive value, as automatically results in the case of using their square as in the LSM. This prevents the use of the elegant and fast, analytical solution provided by that method and must be substituted by an iterative Monte Carlo Convergent (MCC) type search for the minimum sum by comparing different sets of parameters. This computation is simpler, yet it requires long, iterative computations (easily done, thanks to the computational speed of present-day computers). As in the Monte Carlo method, this result is achieved, by an iterative “trial and error” approach testing a huge set of different and independent parameter values, where the advantage resides in the large amount of available and independent parameter sets.

A quantitative representation of the mean residual value is provided by the computation of the root mean power (RMP) value as

$$\text{RMP} = [(\sum_i |(z_i - f(x_i, y_i))|^L) / n]^{1/L} \text{ where } n \text{ is the number of data.}$$

It is immediately seen that for  $L = 2$ , RMP corresponds to the classical RMS value. In the applied LMR method, the exponent is  $L = 0.5$ , thus exchanging the square and square root exponents.

It is worthwhile noticing that the used LRM implementation can be extended to any value of the power of the distances. Its decrease would produce a progressive lowering of the weight of data that are farther from the main trend, with the risk of providing excessive emphasis of random alignment of data along a fictitious trend (as in the case of rounded coordinates along given  $x$  or  $y$  coordinates).

In order to test the reliability of the application of LRM respect to other possible minimization solutions, we tested the use of different values of the power  $L$  of the distances (i.e exponents 3, 2 that is the LSM, 1, 0.5 that is the adopted LRM, and 0.333) on a sample of our dataset, i.e. the earthquake hypocenters recorded in 2023 in the PIF area. Results are shown in Fig. M2 and confirm the best reliability of the  $L=0.5$  approach, with a high number of associated events and reduced (LRM) distance average value.

The MCC implementation was proposed in Tarantola (2005) and Schmidt and Salvini (2024) and is characterized by the search of the possible parameters within a variable range of values for each parameter. A cycle of attempts of random values of parameters, within the given range, is used to compute a plane and then compared by LRM with the data. These ranges are then focused (and reduced) on a successive cycle of attempts around the best parameter set found by the application in the previous cycles, thus providing an unsupervised machine learning approach to the process. These ranges reduce progressively by a given fraction at any cycle of attempts to improve the number of parameter sets closer to the expected satisfactory result and thus improve the probability of a reliable final match. Fig. M3 shows a qualitative example of the range reduction of the 3 parameters compared to the progressive parameter best values during the range reduction process in the progressive cycles.

#### **Application of LRM to search of a planar trend within a biased dataset**

In this study, the MCC method was used with the LRM approach by a set to 60 cycles of 200,000 attempts and a parameter range reduction fraction  $r=0.1$  at each new cycle. This change in the parameter range at each cycle provides a new independent set of random parameter values within the 16-digit precision of the computation. The code is developed in Compiled VB6 (Microsoft) and computation time for each MCC inversion is strongly dependent on the computer performance used and directly proportional to the number of data. Our application was able to perform the required 12,000,000 iterations with 1500 measures in about 1 hour. The final range decrease of the parameter ranges, after the 60 cycles, was eventually reduced to  $(1-0.1)^{60} = 0.001797010$  times the initial ranges, thus providing a very high resolution in the best parameter final values (Fig. M3).

In the implementation of the MCC used in this study we used a set of random number generators with over  $1.6 \times 10^7$  numbers. This set was then then used to generate random parameter values within the given parameter range at that cycle with a resolution of the extremes of 16 digits (i.e. over  $10^{16}$  possible combinations). In this way, this procedure provides for each cycle a new set of values different from all the previous ones. The theoretical number of independent random values in this study therefore exceeds  $10^{16}$  independent random values. The test on the used procedure showed no value repetitions within  $3 \times 10^{10}$  random number generated, thus fully satisfying the used number of parameters set. Furthermore, at regular intervals (i.e. every 43051 attempts in our application) the range parameters boundaries were randomly modified by 0.0001%, to prevent any useless and dangerous repetition.

This easily overrides the required number of random values required for an MCC processing (see below), that is equal to:

$$\text{No.cycles} * \text{No.attempts} * \text{No.independent parameters} = 60 * 200,000 * 3 = 48,000,000$$

The MCC implementation of the LRM method has been applied to identify the presence of active potentially incipient faults (PIF) by searching for planar trends within the highly scattered locations of seismic events.

In this analysis, we consider that each measured event belongs to either the planar distribution of a PIF or to scattered data (the doming?)

$$D_i(x, y, z) = R_i | F_i$$

where R is the scattered population and F is the searched planar feature represented as

$$z(x, y) = a(x + \Delta x) + b(y + \Delta y) + c$$

and represents events clustering along a planar surface trend.

z is the hypocenter depth (converted as negative value, i.e. elevation). The unknown parameters are a, b, c which represent the analytical parameters of the searched plane in a space centered at  $\Delta x$  and  $\Delta y$ .

x, y are the UTM coordinate of the event location (converted from the original Geographic coordinates), and z is the expected depth of the plane at position x, y.

The application of the method for our purpose is therefore to provide the best parameter values to minimize the equation of the sum of the root of the distance from the event computed depth and the expected depth at the given point.

$$\text{Min } \sum_i | [(z_i - a(x_i + \Delta x) - b(y_i - \Delta y) - c)] |^L$$

$\Delta x$  and  $\Delta y$  parameters were fixed in the analysis and centered in the mean x and y measured values:

$$\Delta x = (\sum_i x_i) / N$$

$$\Delta y = (\sum_i y_i) / N$$

where  $x_i$ ,  $y_i$  are the horizontal coordinates of the i event and N is the number of total events; L = 0.5.

At each attempt, a set of parameters  $P_j$  (i.e. the parameters a, b, c) is generated as:

$$P_j = \text{Prange}_j * \text{rnd} + \text{Pmin}_j$$

where  $\text{Prange}_j = (\text{Pmax}_j - \text{Pmin}_j)$  and represents the width of the searched interval, and rnd is the (next) generated random value.  $\text{Pmax}_j$ ,  $\text{Pmin}_j$  are the range limits of the j parameter at the given cycle.

The initial parameter ranges are:

- 1           a        $P_{min_1} = -100$             $P_{max_1} = 100$   
 2           b        $P_{min_2} = -100$             $P_{max_2} = 100$   
 3           c        $P_{min_3} = -1,000,000$  m  $P_{max_3} = 1,000,000$  m

4   At the completion of each cycle  $i$  of attempts, the interval ranges  $Prange_j$  are narrowed and  
 5   recomputed around the best inversion results obtained in the previous cycle, according to:

6            $Prange_{j,i+1} = Prange_{j,i} * (1 - r)$  where  $r$  in the range reduction fraction (0.1 in this study)

7            $P_{min_{i,j}} = P_{best_j} - (0.5 * Prange_{j,i+1})$  where  $P_{best_j}$  is the best approximation throughout the  
 8   cycles.

9   At the completion of the last 60th cycle, the final parameter search ranges in this study were:

10    $Prange_1 = 0.359$

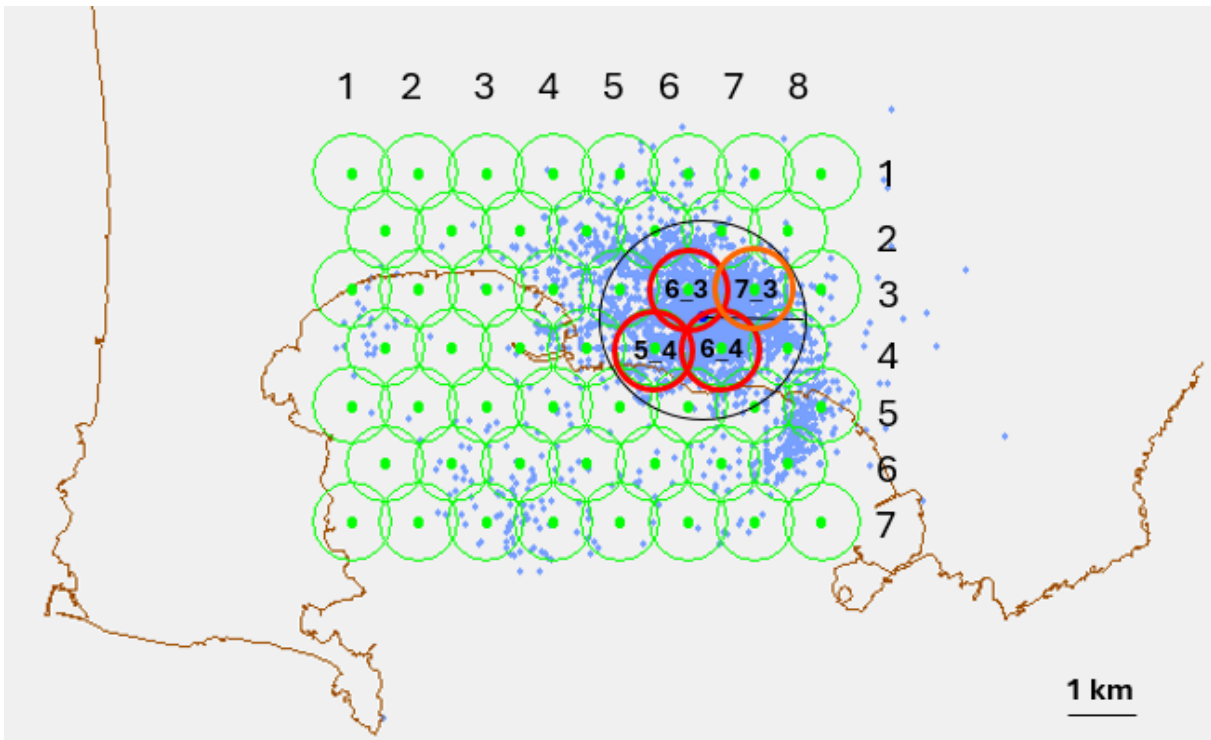
11    $Prange_2 = 0.359$

12    $Prange_3 = 3594$

13

14

15



16

17       *Fig.M1 - Lattice of analyses used in this study to homogenize the data distribution (plane*  
 18       *view). Red points identify the lattice cells; Red circle indicates cylindric areas; blues dots represent*  
 19       *the earthquake locations. The base of the three cylinders (6\_3, 5\_4 and 6\_4) with close*

orientations of planes identified in 2023 and 2024 (indicated) are highlighted in red, to which adjacent cylinder 7\_3 was added (in orange) to define the merged volume for further MCC analysis in 2023 and 2024. The same was also performed on the cylinder with base circle in blue (see text for explanation).

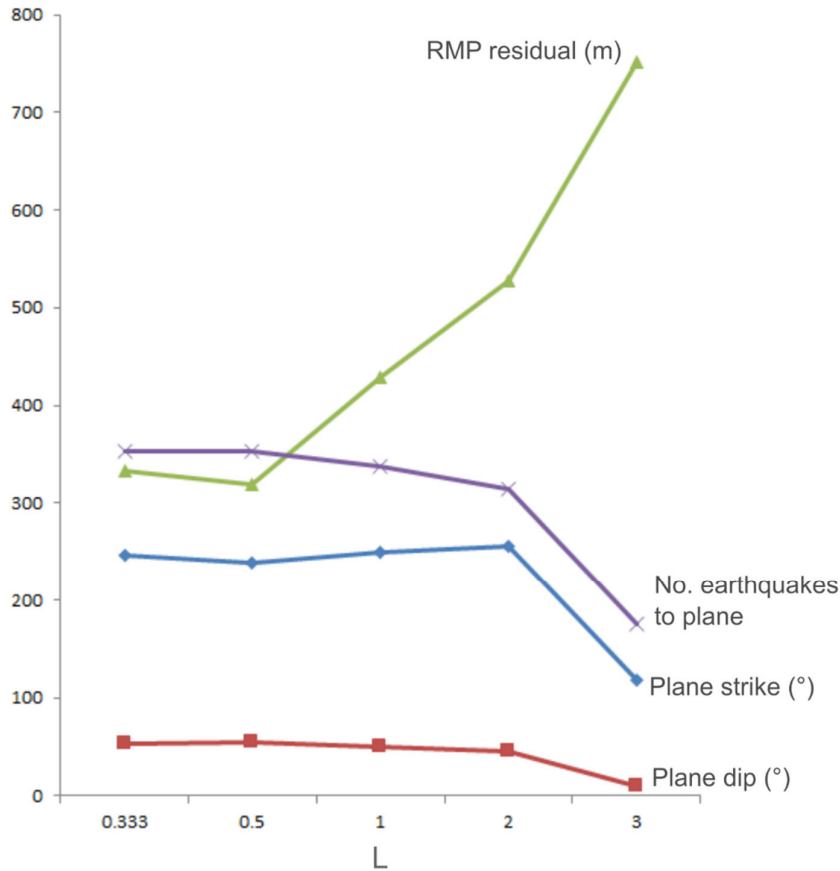


Fig. M2 – Comparison among results of MCC analyses with different exponents  $L$  related to the 2023 events selected within the PIF area. MCC was applied for exponents 3 ( $L_3$ ), 2 ( $L_2$ , LMR), 1 ( $L_1$ ), 0.5 (LRM), and 0.333. Graphs show the values of strike (blue diamonds) and dip (red squares) of the plane solution, the RMP (root mean power) residuals (green triangles) and number of earthquakes associated with the plane (blue crosses). The total of the analyzed earthquakes is 576. Note the concomitant increase of number of events and reduction of their distance from the plane (RMP) by reducing the exponent that testify the presence of “outliers”, that are the earthquakes not associated with the plane solution. The maximum of events close to the plane is achieved for exponents  $L$  equal or lower than 0.5, where over 55% of the events fall close to the PIF plane and correspond to the LRM used in this work. At exponent  $L = 0.5$  there is also the minimum of the RMP residuals. It is important to note that the presence of scattered data strongly influences, as expected by the uneven distribution of data in the 3 dimensions, the dip and azimuth of the best fit plane. There is a small difference between results from  $L$  exponents 0.5 and 0.333.

Yet, the smaller the exponent  $L$ , the larger the influence produced by artifact, as the rounding of the event coordinates. Accordingly, the exponent  $L=0.5$  was considered the best compromise to process the data.

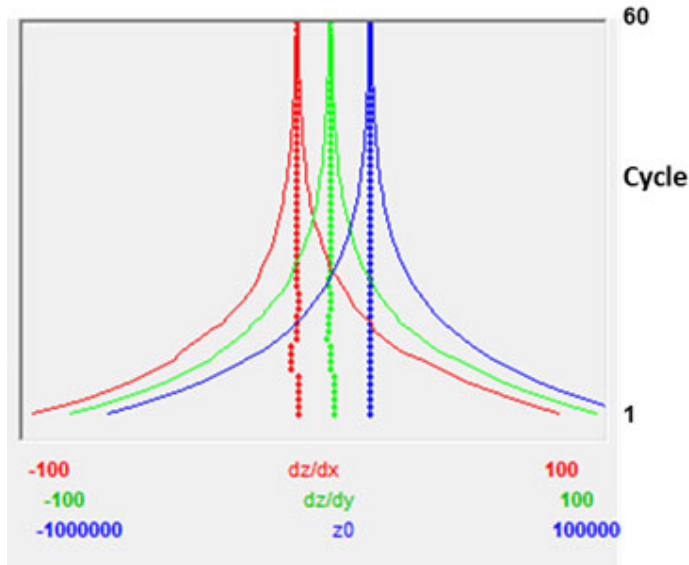


Fig.M3 – Quantitative Graph generated by MCC of the 2023 earthquakes in the PIF area to show the progressive reduction of parameter search range through cycles. Colors refer to the plane parameters: red is  $dz/dx$ ; green is  $dz/dy$ ; blue is  $z_0$ , i.e. the intersection of plane to  $z$ -axis. Numbers indicate the range scale along the  $x$ -axis. The  $y$ -axis is the Cycle number (1-60). Continuous lines show the range migration limit values. Squares indicate the best value found at each cycle.

## Reference list

1. Acocella, V., Salvini, F., Funicello, R., & Faccenna, C. (1999). The role of transfer structures on volcanic activity at Campi Flegrei (Southern Italy). *Journal of Volcanology and Geothermal Research*, 91(2-4), 123-139.
2. Acocella, V. (2010). Evaluating fracture patterns within a resurgent caldera: Campi Flegrei, Italy. *Bulletin of Volcanology*, 72, 623-638.
3. Aji, A. B., Taisne, B., & Chardot, L. (2024). Forecasting the onset of volcanic eruptions using the increase in seismicity during magma ascent. *Journal of Volcanology and Geothermal Research*, 449, 108053.
4. Anderson, E. M. (1905). The dynamics of faulting. Transactions of the Edinburgh Geological Society, 8(3), 387-402.
5. Astort, A., Trasatti, E., Caricchi, L., Polcari, M., De Martino, P., Acocella, V., & Di Vito, M. A. (2024). Tracking the 2007–2023 magma-driven unrest at Campi Flegrei caldera (Italy). *Communications Earth & Environment*, 5(1), 506.
6. Bell, A. F., La Femina, P. C., Ruiz, M., Amelung, F., Bagnardi, M., Bean, C. J., ... & Stock, M. J. (2021). Caldera resurgence during the 2018 eruption of Sierra Negra volcano, Galápagos Islands. *Nature Communications*, 12(1), 1397.
7. Benoit JP, McNutt SR (1996) Global volcanic earthquake swarm database and preliminary analysis of volcanic earthquake swarm duration. *Annali Di Geofisica* 39(2):221–229
8. Bevilacqua, A., De Martino, P., Giudicepietro, F., Ricciolino, P., Patra, A., Pitman, E. B., ... & Neri, A. (2022). Data analysis of the unsteadily accelerating GPS and seismic records at Campi Flegrei caldera from 2000 to 2020. *Scientific reports*, 12(1), 19175.
9. Bevilacqua, A., Neri, A., De Martino, P., Giudicepietro, F., Macedonio, G., & Ricciolino, P. (2024). Accelerating upper crustal deformation and seismicity of Campi Flegrei caldera (Italy), during the 2000–2023 unrest. *Communications Earth & Environment*, 5(1), 1-14.
10. Boué, A., Lesage, P., Cortés, G., Valette, B., and Reyes-Dávila, G. (2015). Real-time eruption forecasting using the material Failure Forecast Method with a Bayesian approach. *J. Geophys. Res.* 120, 2143–2161. doi: 10.1002/2014JB011637
11. Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault zone architecture and permeability structure. *Geology* 24, 1025±1028. Caliro, S., Chiodini, G., Avino, R., Carandente, A., Cuoco, E., Di Vito, M. A., ... & Aiuppa, A. (2025). Escalation of caldera unrest indicated by increasing emission of isotopically light sulfur. *Nature Geoscience*, 1-8.
12. Calò, M., & Tramelli, A. (2025). Evidences of the structures controlling the unrest in Campi Flegrei, Italy; Joint interpretation of ambient noise and local earthquake tomography. *Journal of Volcanology and Geothermal Research*, 108236.
13. Childs, C., Manzocchi, T., Walsh, J. J., Bonson, C. G., Nicol, A., & Schöpfer, M. P. (2009). A geometric model of fault zone and fault rock thickness variations. *Journal of Structural Geology*, 31(2), 117-127.
- 14.

- 1 15. Chiodini, G., Vandemeulebrouck, J., Caliro, S., D'Auria, L., De Martino, P., Mangiacapra, A.,  
2 & Petrillo, Z. (2015). Evidence of thermal-driven processes triggering the 2005–2014 unrest  
3 at Campi Flegrei caldera. *Earth and Planetary Science Letters*, 414, 58-67.
- 4 16. Chiodini, G., Caliro, S., De Martino, P., Avino, R., & Gherardi, F. (2012). Early signals of new  
5 volcanic unrest at Campi Flegrei caldera? Insights from geochemical data and physical  
6 simulations. *Geology*, 40(10), 943-946.
- 7 17. Cornelius, R. R., and Voight, B. (1995). Graphical and PC-software analysis of volcano  
8 eruption precursors according to the Materials Failure Forecast Method (FFM). *J. Volcanol.*  
9 *Geotherm. Res.* 64, 295–320. doi: 10.1016/0377-0273(94) 00078-U
- 10 18. Cosentino, D., De Rita, D., Funicello, R., Parotto, M., Salvini, F., & Vittori, E. (1984). Fracture  
11 system in Phlegraean Fields (naples, southern Italy). *Bulletin volcanologique*, 47, 247-257.
- 12 19. Danesi, S., Pino, N. A., Carlino, S., & Kilburn, C. R. (2024). Evolution in unrest processes at  
13 Campi Flegrei caldera as inferred from local seismicity. *Earth and Planetary Science*  
14 *Letters*, 626, 118530.
- 15 20. Dello Iacono, D., Zollo, A., Vassallo, M., Vanorio, T., & Judenherc, S. (2009). Seismic images  
16 and rock properties of the very shallow structure of Campi Flegrei caldera (southern  
17 Italy). *Bulletin of Volcanology*, 71, 275-284.
- 18 21. Del Gaudio C., Aquino I., Ricciardi G.P., Ricco C. and Scandone R.; 2010: *Unrest episodes at*  
19 *Campi Flegrei: a reconstruction of vertical ground movements during 1905-2009*; 2010: J.  
20 *Volcanol. Geotherm. Res.*, 195, 48- 56, doi: 10.1016/j.jvolgeores.2010.05.014.
- 21 22. Del Pezzo, E., & Bianco, F. (2024). Space and time distribution of seismic source energy at  
22 Campi Flegrei, Italy through the last unrest phase (1.1. 2000–31.12. 2023). *Physics of the*  
23 *Earth and Planetary Interiors*, 356, 107258.
- 24 23. De Siena, L., Amoruso, A., Petrosino, S., & Crescentini, L. (2024). Geophysical responses to  
25 an environmentally-boosted volcanic unrest. *Geophysical Research Letters*, 51,  
26 e2023GL104895. <https://doi.org/10.1029/2023GL104895>
- 27 24. De Siena, Luca, Giovanni Chiodini, Giuseppe Vilardo, Edoardo Del Pezzo, Mario Castellano,  
28 Simona Colombelli, Nicola Tisato, and Guido Ventura. "Source and dynamics of a volcanic  
29 caldera unrest: Campi Flegrei, 1983–84." *Scientific reports* 7, no. 1 (2017): 8099.
- 30 25. Dipartimento della Protezione Civile – Repubblica Italiana (2024). Campi Flegrei.  
31 [https://rischi.protezionecivile.gov.it/static/a7cc4318239612826caab525eb8d182b/202303](https://rischi.protezionecivile.gov.it/static/a7cc4318239612826caab525eb8d182b/20230304-vdc-report-c-flegrei-giallo-cgr.pdf)  
32 [04-vdc-report-c-flegrei-giallo-cgr.pdf](https://rischi.protezionecivile.gov.it/static/a7cc4318239612826caab525eb8d182b/20230304-vdc-report-c-flegrei-giallo-cgr.pdf); last access; 11 November, 2024
- 33 26. Di Vito, M. A., Isaia, R., Orsi, G., Southon, J. D., De Vita, S., D'Antonio, M., ... & Piochi, M.  
34 (1999). Volcanism and deformation since 12,000 years at the Campi Flegrei caldera  
35 (Italy). *Journal of Volcanology and Geothermal Research*, 91(2-4), 221-246.
- 36 27. Di Vito, M. A., Acocella, V., Aiello, G., Barra, D., Battaglia, M., Carandente, A., ... & Terrasi,  
37 F. (2016). Magma transfer at Campi Flegrei caldera (Italy) before the 1538 AD  
38 eruption. *Scientific reports*, 6(1), 32245.
- 39 28. Fischer, T., & Hainzl, S. (2021). The growth of earthquake clusters. *Frontiers in Earth*  
40 *Science*, 9, 638336.
- 41 29. Fischer, T., Hainzl, S., & Vlček, J. (2023). Fast migration episodes within earthquake  
42 swarms. *Geophysical Journal International*, 235(1), 312-325.

30. Giacomuzzi, G., Chiarabba, C., Bianco, F., De Gori, P., & Agostinetti, N. P. (2024). Tracking transient changes in the plumbing system at Campi Flegrei Caldera. *Earth and Planetary Science Letters*, 637, 118744.
31. Giacomuzzi, G., Fonzetti, R., Govoni, A., De Gori, P., & Chiarabba, C. (2025). Causal processes of shallow and deep seismicity at Campi Flegrei caldera. *Communications Earth & Environment*, 6(1), 70.
32. Giudicepietro, F., Avino, R., Bellucci Sessa, E., Bevilacqua, A., Bonano, M., Caliro, S., ... & Chiodini, G. (2025). Burst-like swarms in the Campi Flegrei caldera accelerating unrest from 2021 to 2024. *Nature Communications*, 16(1), 1548.
33. Godano, C., Tramelli, A., Mora, M., Taylor, W., & Petrillo, G. (2023). An analytic expression for the volcanic seismic swarms occurrence rate. A case study of some volcanoes in the world. *Earth and Space Science*, 10(2), e2022EA002534.
34. Griffith, W. A., Rosakis, A., Pollard, D. D., & Ko, C. W. (2009). Dynamic rupture experiments elucidate tensile crack development during propagating earthquake ruptures. *Geology*, 37(9), 795-798.
35. Griffith, W. A., Nielsen, S., Di Toro, G., & Smith, S. A. (2010). Rough faults, distributed weakening, and off-fault deformation. *Journal of Geophysical Research: Solid Earth*, 115(B8).
36. Gudmundsson, M. T., Jónsdóttir, K., Hooper, A., Holohan, E. P., Halldórsson, S. A., Ófeigsson, B. G., ... & Aiuppa, A. (2016). Gradual caldera collapse at Bárðarbunga volcano, Iceland, regulated by lateral magma outflow. *Science*, 353(6296), aaf8988.
37. Hill, D. P., Montgomery-Brown, E. K., Shelly, D. R., Flinders, A. F., & Prejean, S. (2020). Post-1978 tumescence at Long Valley caldera, California: a geophysical perspective. *Journal of Volcanology and Geothermal Research*, 400, 106900.
38. Iervolino, I., Cito, P., De Falco, M., Festa, G., Herrmann, M., Lomax, A., ... & Zollo, A. (2024). Seismic risk mitigation at Campi Flegrei in volcanic unrest. *Nature Communications*, 15(1), 1-14.
39. INGV-Osservatorio Vesiviano (2024a) Bollettino di Sorveglianza Mensile Campi Flegrei Ottobre 2024. <https://www.ov.ingv.it/index.php/monitoraggio-e-infrastrutture/bollettini-tutti/mensili-dei-vulcani-della-campania/flegrei/anno-2024-3>; last access 11, November, 2024
40. INGV-Osservatorio Vesiviano (2024b) Localizzazioni sismiche Campi Flegrei. <https://terremoti.ov.ingv.it/gossip/flegrei/> last access 11, November, 2024
41. Isaia, R., Vitale, S., Di Giuseppe, M. G., Iannuzzi, E., D'Assisi Tramparulo, F., & Troiano, A. (2015). Stratigraphy, structure, and volcano-tectonic evolution of Solfatara maar-diatreme (Campi Flegrei, Italy). *Bulletin*, 127(9-10), 1485-1504.
42. Isaia, R., Di Giuseppe, M. G., Natale, J., Tramparulo, F. D. A., Troiano, A., & Vitale, S. (2021). Volcano-tectonic setting of the Pisciarelli fumarole field, Campi Flegrei caldera, southern Italy: Insights into fluid circulation patterns and hazard scenarios. *Tectonics*, 40(5), e2020TC006227.
43. Kilburn, C. R. (2018). Forecasting volcanic eruptions: Beyond the failure forecast method. *Frontiers in Earth Science*, 6, 369380.

- 1 44. Kilburn, C. R., De Natale, G., & Carlino, S. (2017). Progressive approach to eruption at  
2 Campi Flegrei caldera in southern Italy. *Nature Communications*, 8(1), 1-8.
- 3 45. Kilburn, C. R., Carlino, S., Danesi, S., & Pino, N. A. (2023). Potential for rupture before  
4 eruption at Campi Flegrei caldera, Southern Italy. *Communications Earth &*  
5 *Environment*, 4(1), 190.
- 6 46. Mandl, G. (2013). *Faulting in brittle rocks: an introduction to the mechanics of tectonic*  
7 *faults*. Springer Science & Business Media,, 444pp ISBN-10: 354066436X.
- 8 47. Marturano, A., Isaia, R., Aiello, G., & Barra, D. (2018). Complex dome growth at Campi  
9 Flegrei caldera (Italy) in the last 15 ka. *Journal of Geophysical Research: Solid Earth*, 123(9),  
10 8180-8197.
- 11 48. Mayer, K., Scheu, B., Montanaro, C., Yilmaz, T. I., Isaia, R., Aßbichler, D., & Dingwell, D. B.  
12 (2016). Hydrothermal alteration of surficial rocks at Solfatara (Campi Flegrei): Petrophysical  
13 properties and implications for phreatic eruption processes. *Journal of Volcanology and*  
14 *Geothermal Research*, 320, 128-143.
- 15 49. McNutt, S.R. (1996). Seismic Monitoring and Eruption Forecasting of Volcanoes: A Review  
16 of the State-of-the-Art and Case Histories. In: Monitoring and Mitigation of Volcano  
17 Hazards. Springer, Berlin, Heidelberg. [https://doi.org/10.1007/978-3-642-80087-0\\_3](https://doi.org/10.1007/978-3-642-80087-0_3)
- 18 50. McNutt, S. R. (2002). Volcano seismology and monitoring for eruptions. *International*  
19 *Geophysics*, 81, 383-cp1.
- 20 51. Milia, A., Torrente, M. M., & Giordano, F. (2000). Active deformation and volcanism  
21 offshore Campi Flegrei, Italy: new data from high-resolution seismic reflection  
22 profiles. *Marine Geology*, 171(1-4), 61-73.
- 23 52. Mori, J., & McKee, C. (1987). Outward-dipping ring-fault structure at Rabaul caldera as  
24 shown by earthquake locations. *Science*, 235(4785), 193-195.
- 25 53. Natale, J., Camanni, G., Ferranti, L., Isaia, R., Sacchi, M., Spiess, V., ... & Vitale, S. (2022).  
26 Fault systems in the offshore sector of the Campi Flegrei caldera (southern Italy):  
27 Implications for nested caldera structure, resurgent dome, and volcano-tectonic  
28 evolution. *Journal of Structural Geology*, 163, 104723.
- 29 54. Nespoli, M., Tramelli, A., Belardinelli, M. E., & Bonafede, M. (2023). The effects of hot and  
30 pressurized fluid flow across a brittle layer on the recent seismicity and deformation in the  
31 Campi Flegrei caldera (Italy). *Journal of Volcanology and Geothermal Research*, 443,  
32 107930.
- 33 55. Ricciolino, P., Lo Bascio, D., & Esposito, R. (2024). GOSSIP—Database sismologico Pubblico  
34 INGV-Osservatorio Vesuviano. Istituto Nazionale di Geofisica e Vulcanologia (INGV).
- 35 56. Robertson, R. M., & Kilburn, C. R. (2016). Deformation regime and long-term precursors to  
36 eruption at large calderas: Rabaul, Papua New Guinea. *Earth and Planetary Science*  
37 *Letters*, 438, 86-94.
- 38 57. Rosi, M., Acocella, V., Cioni, R., Bianco, F., Costa, A., De Martino, P., ... & Inguaggiato, S.  
39 (2022). Defining the pre-eruptive states of active volcanoes for improving eruption  
40 forecasting. *Frontiers in Earth Science*, 10, 795700.

58. Saccorotti, G., & Lokmer, I. (2021). A review of seismic methods for monitoring and understanding active volcanoes. *Forecasting and planning for volcanic hazards, risks, and disasters*, 25-73.
59. Safaeipour, H., Forouzanfar, M., Casavola, A. (2021). A survey and classification of incipient fault diagnosis approaches. *Journal of Process Control*, 97, 1-16.
60. Sbrana A., Marianelli P. & Pasquini G. (2021) The Phlegrean Fields volcanological evolution, *Journal of Maps*, 17:2, 557-570, DOI: 10.1080/17445647.2021.1982033
61. Scarpati, C., Perrotta, A., Lepore, S., & Calvert, A. (2013). Eruptive history of Neapolitan volcanoes: constraints from  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  dating. *Geological Magazine*, 150(3), 412-425.
62. Schmidt, G., & Salvini, F. (2024). Thickness of Pluto's Ice Shell from elastic deformation of the Sputnik Planitia forebulge: Response to infill load or vestige of impact event?. *Earth and Planetary Science Letters*, 646, 118974.
63. Scotto di Uccio, F., Lomax, A., Natale, J., Muzellec, T., Festa, G., Nazeri, S., ... & Zollo, A. (2024). Delineation and fine-scale structure of fault zones activated during the 2014–2024 unrest at the Campi Flegrei caldera (Southern Italy) from high-precision earthquake locations. *Geophysical Research Letters*, 51(12), e2023GL107680.
64. Selva, J., Orsi, G., Di Vito, M. A., Marzocchi, W., & Sandri, L. (2012). Probability hazard map for future vent opening at the Campi Flegrei caldera, Italy. *Bulletin of volcanology*, 74, 497-510.
65. Silleni, A., Giordano, G., Isaia, R., & Ort, M. H. (2020). The magnitude of the 39.8 ka Campanian Ignimbrite eruption, Italy: Method, uncertainties and errors. *Frontiers in Earth Science*, 8, 543399.
66. Fraser, R. D. B., & Suzuki, E. (1969). 21 The Use of Least Squares in Data Analysis. *Physical principles and techniques of protein chemistry*, 301.
67. Tarantola, A (2005). Inverse Problem Theory and Methods for Model Parameter Estimation. SIAM. ISBN 978-0-89871-572-9. <https://doi.org/10.1137/1.9780898717921>
68. Thompson, G. (2015). Seismic monitoring of volcanoes. *Encyclopedia of earthquake engineering*, 10, 1-25.
69. Tizzani, P., Fernández, J., Vitale, A., Escayo, J., Barone, A., Castaldo, R., ... & Camacho, A. G. (2024). 4D imaging of the volcano feeding system beneath the urban area of the Campi Flegrei caldera. *Remote Sensing of Environment*, 315, 114480.
70. Tramelli, A., Godano, C., Ricciolino, P., Giudicepietro, F., Caliro, S., Orazi, M., ... & Chiodini, G. (2021). Statistics of seismicity to investigate the Campi Flegrei caldera unrest. *Scientific reports*, 11(1), 7211.
71. Trasatti, E., Polcari, M., Bonafede, M., & Stramondo, S. (2015). Geodetic constraints to the source mechanism of the 2011–2013 unrest at Campi Flegrei (Italy) caldera. *Geophysical Research Letters*, 42(10), 3847-3854.
72. Turcotte D.L. (1997). *Fractals and Chaos in Geology and Geophysics*. 2nd Edition. 383pp Cambridge University Press. ISBN-10: 0521567335.
73. Turcotte, D. L., & Schubert, G. (2002). *Geodynamics*. Cambridge University Press.
74. Vanorio, T., Geremia, D., De Landro, G., & Guo, T. (2025). The recurrence of geophysical manifestations at the Campi Flegrei caldera. *Science Advances*, 11(18), eadt2067.

- 1 75. Vitale, S., & Isaia, R. (2014). Fractures and faults in volcanic rocks (Campi Flegrei, southern  
2 Italy): insight into volcano-tectonic processes. *International Journal of Earth Sciences*, 103,  
3 801-819.
- 4 76. Voight, B. (1988). A method for prediction of volcanic eruptions. *Nature* 332, 125–130. doi:  
5 10.1038/332125a0
- 6 77. Wesson, R. L. (1988). Dynamics of fault creep. *Journal of Geophysical Research: Solid*  
7 *Earth*, 93(B8), 8929-8951.
- 8

Dear Editor,

it is a pleasure to resubmit our manuscript after careful revision which takes into account all comments raised by the reviewers.

We are really grateful for the great effort of the three reviewers whose comments are constructive and allowed to improve the clarity of the paper and hopefully its potential impact.

We thank all of them for acknowledging the novelty and the relevance of our study.

Our replies are listed below written in blue below each comment.

The track-change version of the resubmitted manuscript incorporates all reviewers' comments at the relevant lines with the replies to facilitate your assessment of the changes made in accordance with the comments.

We hope that this review fully answers all reviewers' comments and that you may assess its completeness with no need for a further round of reviews.

Best regards

Guido Giordano on behalf of co-authors

#### REVIEWER COMMENTS:

**Reviewer #1 (Remarks to the Author):** [See attachment]. [See also track-change version of the manuscript for exact location for each comment and related text modification]

Dear Editor,

I hereby report my comments for the submitted version of the manuscript. The manuscript is well written overall and focuses on the identification of a novel activated structure within the Campi Flegrei area, which is undergoing a continuous ground uplift with a relatively high seismicity rate in the last years. The authors identified this structure through a refined spatio-temporal analysis, revealing the clustering of the seismicity along the mentioned structure since 2023. Despite within the manuscript the discussions support the proposed interpretation, I have identified some points which might be better clarified and worth of further investigation.

#### **Major points:**

- As a general observation, most of the figures need to be improved, in terms of quality and resolution. Figure 2 looks very crowded and blurred when zoomed for inspection. Moreover, no information on the event depth can be inferred from this representation. The authors are invited to improve the figure. Also Figure 3 appears blurred when zoomed, with labels on the right panels difficult to read. Please, remove words underlined in red from the left panels, also in Figure 4.

OK we agree with Rev1 and all figures have been improved following the suggestions of the reviewers, increasing their quality and clarity

- P4-L25: For the analysis, the authors used the catalog provided by the Osservatorio Vesuviano, whose hypocenters are obtained through absolute location techniques. However, relocated catalogs obtained through relative location techniques or implementing source-specific corrections might feature a higher degree of clustering as compared to absolute locations, simplifying the identification of seismicity patterns, as also observed in the Campi Flegrei area, along with lower location uncertainties (Tramelli et al., 2022; Scotto di Uccio et al., 2024; Giacomuzzi et al., 2025). Moreover, artificial effects introduced by the discretization of the investigated area emerge when zooming into the catalog of the Osservatorio Vesuviano, leading to vertical and horizontal stripes of seismicity, which also include some  $M_d > 2.5$  earthquakes. -The authors should better support the choice of the starting catalog and discuss the use of a higher-resolution relocated catalog.

We thank the reviewer for the insightful comment. We fully clarify our choice in the Materials section where we take the opportunity to discuss and compare our approach to the ones used by Scotto di Uccio et al and other authors, which differ substantially in scope respect to ours. In addition, the artificial effects introduced by the discretization of the investigated area noted by Rev1, affect mostly the localizations of earthquakes with  $M_d < 0.5$ , not used in our analysis. In any case, statistically they are insignificant as their presence does not affect in any way the results, as it can be seen by the orientation of the planar solution found in this work, in facts strenghtening the method.

The added sentences are at p. 5, lines 10-32:

“We chose to use the catalog provided by the Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Vesuviano because it is an institutional product, continuously updated and validated by the official monitoring authority of the area. Its certified and standardized nature ensures the consistency, transparency, and reproducibility of our analysis over time, which we consider essential for the scope of our work. We acknowledge that relocated catalogs (e.g. Tramelli et al. 2022; Scotto di Uccio et al. 2024, Giacomuzzi et al. 2025), obtained through relative location techniques such as double-difference methods or source-specific corrections, can offer improved clustering and lower location uncertainties, which can facilitate the identification of seismicity patterns. However, such catalogs are often not available continuously or systematically over the entire time window of interest and may introduce a bias toward artificially increased clustering due to the nature of the relocation algorithm itself.

The goal of our study is to offer a statistical, unsupervised approach to identify potential temporal clustering of earthquakes aligning along a main fault structure. Several authors have previously mapped multiple fractures and faults in the area using both seismic and geological data; an overview of these structures is summarized in Iervolino et al. (2024). In that same work, the authors define the upper bound of reference magnitude scenarios as the simultaneous activation of multiple faults. In a similar spirit, our method aims not just to detect individual small-scale faults, but their possible merging or interaction over time, and for this reason we preferred to use a catalog that does not implicitly cluster events through a double-difference approach.

To ensure the reliability of the seismic locations used in the analysis, we applied a completeness magnitude threshold of 0.5, which allowed us to select events for which 95% of the catalog has a location quality of B or better. This quality code incorporates several factors, including RMS residuals, horizontal and vertical errors, number of phase picks, and azimuthal gap.”

- P4-L31: The authors report the average spatial location uncertainties for the hypocenters in the selected Osservatorio Vesuviano catalog. However, the authors should discuss the different resolution in earthquake location for onshore and offshore seismicity, since the latter typically occurs deeper and the density of stations at sea is lower than the analogous onshore. Do the

authors believe that the difference in resolution between onshore and offshore events can prevent from identifying seismicity clusters at sea?

We have added a sentence at p. 5 lines 7-9, to clarify that the geometric configuration of the network and the implementation with 4 stations in the offshore allow excellent locations throughout the entire caldera of comparable levels of accuracy

- P6-L41: How do the authors interpret the possibility that the same cylinder features different best fit planes in different years? Cylinder 4.4 is characterized by variations in the strike and dip from 2019 to 2021, also with differences of 70° and 45° in strike and dip direction, respectively. What might cause these variations?

This comment centers the very reason of our study, the interpretation of the causes of which is the focus of our method and discussion. It must be noted that the MCC always finds a solution. The issue is to define how to assess its reliability. For a small number of scattered events non statistically significant the reliability of the solution is poor. If that is the case, the MCC method will show no convergence over time and space. Therefore the lack of a consistent solution in years 2019-2021 and the little number of events associated with the solutions are the evidence that the solution is not reliable. By contrast what happens in 2023 and confirmed in 2024 shows that the statistical solutions are reliable and correspond to a physical process.

- P7-L18: The area of Bagnoli hosted the Md 4.2 earthquake in 2023. How does the best fit plane relate to the orientation of the N-S sub-vertical structure identified in Scotto di Uccio et al., (2024). From the representation of the cylinder map in Figure M1, the area is covered by the cylinders 8\_5 and 7\_6, which are characterized by different values in strike and dip as compared to the mentioned structure.

We have already fully discussed the comparison between our approach and the relative relocalization performed by Scotto di Uccio et al and other authors, in the reply to the previous comment of Rev1 P4-L25

We here reiterate that essentially the main differences are two:

1. Our method aims at identifying space and time variations of earthquakes distribution, and in this is completely different from other approaches in the literature which only aim at spatial clustering
2. our approach is fully unsupervised, quantitative and statistically defined and does not require an expert evaluation to identify clusters; by contrast other approaches require expert evaluation and rely on the qualitative comparison of clusters with highly uncertain surface expression of faults with no evidence of their 3D expression

- P9-L1: The authors suggest clusters 6\_3, 6\_4, 5\_4 and 7\_3 as PIF. Did any major earthquake occur within clusters? Are the estimated values in agreement with focal mechanisms for major events/composite focal mechanisms for earthquakes in the area?

The spatial relationship between the PIF and the location and MF of the larger earthquakes is later fully discussed in the discussion section at p. 14 lines 30-40. Similarly the relationship with focal mechanisms was already described in the text and also in Fig. 5b

- P9-L27: The authors stated that lower standard deviation values on the strike and dip measurements from 2023 are indicative of the seismicity clustering along the identified structure. Could the observed feature simply result from the increase in the number of

earthquakes within the PIF, moving from dozens of earthquakes in 2019 to hundreds of earthquakes? This could lead to more constrained inversion of events within the cylinder.

The variance is a feature of a population. Therefore its estimation by random sampling within the population should not vary with their number for statistically significant sampling. If by contrast there is a change, this means that the population is not the same or the sampling is not sufficient. In our case, as the number of events increases and therefore the statistical significance of the solution, the change over time of the standard deviation calls for a change in the population (i.e. the appearance of a population of earthquakes associated with a plane in contrast with diffuse microfracturing).

#### **Minor points**

- P1-L34: The authors could better describe the alerts levels proposed for the Campi Flegrei region.

OK done

- P1- L37: The author should change the reported maximum magnitude, given the occurrence of the Md 4.6 earthquake on March 13<sup>th</sup>, 2025.

OK done

- P5-L18: How did the authors choose the extension of the cylinders for the inversion?

These dimensions optimize the need to have a vertically extended computational domain (the ratio of vertical:horizontal extents is ~5:1 for each cylinder) enclosing at the same time a statistically significant number of events

We have clarified the choice of these dimensions in the text (p. 7, lines 1-2) and in the methodology

- P6-L38: Please, check the number of events. Some of them slightly differ from the corresponding in the Supplementary Materials.

We have corrected text and supplementary material S1

2019= 136

2020= 193

2021= 264

2022= 443

2023= 1181

2024= 1528

- P8-L12: How is the angular distance evaluated? Please, specify.

Dihedral angular distance. This is a standard geometrical definition. It is the complement to the angle between the poles (plane normals) to the planes. Probably there is no need to further specify this point in the text

- P14-L13: The maximum magnitude proposed in Iervolino et al. (2024) is expressed in terms of moment magnitude, as also reported in Scotto di Uccio et al., (2024)

yes

**Reviewer #2 (Remarks to the Author): [See attachment]. [All comments and corrections in Rev2 attachment have been done. See also track-change version of the manuscript for exact location for each comment and related text modification]**

The manuscript reports a statistical and geometric analysis of recent (2019-2024) seismicity during 'unrest' and active uplift of Campi Flegrei caldera volcano in Italy. The analysis involves the use of the least square root of distance method (LRM) to test the fit (clustering) of earthquake hypocentre locations to potential fault plane orientations. This method, as well as its pros and cons, are well explained. Overall the analysis seems carefully done and robust.

This study nicely augments several recent geophysical or geodetic studies on the ongoing unrest at Campi Flegrei. In several respects it resembles in its topic and aims the recent paper by Scott di Uccio et al. (2024, Geophys. Res. Lett.), which used the same or very similar datasets and presented some similar general conclusions. The present manuscript differs from that work, however, in (i) its more intricate methodology for identification of potential failure planes, (ii) the more up-to-date time span considered and (iii) its principal finding of a localization since 2023 of seismicity on a ENE-WSW striking and NNW-dipping structure.

Overall the study's results are well presented and its main findings are well supported by the data as presented. I think it represents an important contribution to our understanding of the ongoing evolution of this highly-hazardous and high-risk volcanic system.

There are nonetheless a few issues that could/should be addressed before publication:

(1) The manuscript introduction focusses heavily on the Failure Forecast Model (FFM) and its application to Campi Flegrei and elsewhere. There is only a very brief mention of the FFM in the Discussion section, however, where it is stated that the implications for the FFM from the data and analysis presented are inconclusive. This 'lack of delivery' from the introduction to the conclusions makes the manuscript seem a bit unbalanced. Probably the manuscript's Introduction section should be reorientated a bit more toward imaging/delineation of seismogenic structures and the emergence of potential magma conduits, rather than application of the FFM.

We agree that the FFM approach should be more balanced between intro and discussion. However the FFM is a key issue as currently it is only approached with the time evolution of scalar quantities (number of earthquakes and total uplift rates) whereas here we propose to introduce the spatio-temporal tracking of seismicity to verify if conditions of critical failure (i.e. the transition from diffuse micro-fracturing to the nucleation or reactivation of a fault structure by the linkage of microfractures) are actually achieved. We

have therefore reinforced and better clarified the discussion section at p. 13 lines 31-42 and p. 14 lines 1-2 of the revised ms.

(2) The overall annular (elliptical) distribution of hypocenters at Campi Flegrei, as seen in Figure 2, is not mentioned at all the text ('elephant in the room'). That the overall distribution is non-planar, yet the author's approach considers only planar failure surfaces initially seems a bit incongruous. At a minimum there should be a rationale provided for why the apparent overall localization (emergence) of a ring fracture system is ignored and why instead the study reduces to consideration of smaller-scale planar features.

We agree with REV2 that mentioning the overall seismicity pattern is important so we have added a sentence to clarify this point at the beginning of the Approach section at p. 6 lines 8-10, where we also clarify why selecting the area of maximum seismicity is correct to ensure statistically significant results (p. 7 lines 7-9).

It must be noted that our analysis focuses on spatio-temporal evolution of seismicity, which is shown to affect only the central part of the caldera. Our analysis is unsupervised, so while the annular shape is qualitatively evident, and we agree with Rev2 that must be noted, the seismicity in volumes different from the central area does not show statistically significant evolution that can be appreciated with our method.

(3) The plan view images in Figure 2 are good to show the development of seismicity in 2D, but it would be best to show also the distribution in cross-section to give a sense of the distribution in 3D. I suggest showing a map of the events colour coded for depth and perhaps scaled for magnitude. Beside this map one would ideally plot two cross-sections, one NE-SW and one NW-SE. These images could be appended to the existing Figure 2 as a third row of plots, or perhaps included as an additional figure. Either way such a visualization would be extremely helpful for the reader.

Ok Fig. 2 had been modified as suggested

(4) Following from (1+2), links to other studies of intra-caldera seismicity at other resurgent caldera systems, specifically studies of hypocentre location and related analysis would be useful for context on the originality and wider significance of this study. In particular, a brief comparisons to the cases of unrest at Rabaul caldera, New Britain (e.g. Mori and McKee, 1987, Science, and other works) and Sierra Negra caldera, Galapagos (e.g. Bell et al 2021, Nature Comms, and other works), and Long Valley caldera, California (Hill et al 2020, J. Volcanol. Getherm Res.) and other works) would be useful. Currently the perspective of the manuscript is very focused on Campi Flegrei (naturally so), whereas a general reader may appreciate a wider context to the approach and results presented. Reducing the focus on the FFM in the introduction might facilitate this.

We agree with Rev2 that a comparison with other caldera seismicity case studies would be useful, but there are no similar attempts to ours in the literature. We added a sentence later in the discussion section to highlight the potential for generalization of this study, but a direct comparison with other examples is not possible unless highly speculative. We added a sentence at the beginning of the Discussion section with the proposed references to broaden the perspective. As stated in reply to comment 1 we maintain the emphasis on the FFM

(5) A clearer articulation of the implications for volcanic hazards could be made. Again analogies to other geophysically well-monitored volcanic systems would be useful to illustrate to the reader what one might expect to happen in the future with continued uplift and magma accumulation. For example, the phenomenon of shear fracturing (normal and strike-slip) with magnitudes of M3-M4 preceding or accompanying dyke intrusion that feeds and eruption has been well documented at recent eruptions at Kilauea (in 2018) and Bardarbunga (in 2014) volcanoes, among others.

We have added a long sentence at p.13 lines 31-42 and p. 14 lines 1-2 to fully clarify the implication for hazard of our study, and also to make the discussion better linked with the introduction and the FFM approach as suggested by Rev2

(6) Finally, and linked to points (3+4) above, it might be worth considering for the volcanic hazard that the seismogenic intra-caldera structures at depth may not correspond cleanly with the eventual locations of magma eruption at the surface. At both Rabaul and Sierre Negra, for instance, the vents were located at some horizontal distance (up to several km) outside the seismically-active ring structure.

I attach a marked up pdf of the manuscript with a few further, if more minor, scientific comments (pink) and editorial suggestions (yellow), which I hope the authors might find helpful to improve the manuscript before its final publication.

Yes we found them very useful and we made all the proposed amendments as it can be seen by comparing what proposed by Rev2 in the marked up pdf and the track-change version of the manuscript

Reviewer #3 (Remarks to the Author):

Review of Birth and growth of a volcanotectonic fault during the current volcanic unrest at Campi Flegrei caldera (Italy) by Giordano et al., submitted to CE&E.

Overview:

Giordano et al. present novel models of seismic clustering through time, interpreted as direct evidence of fault nucleation from 2023. These models have significant implications for the development of the current unrest at the Campi Flegrei caldera. The model is based on a novel clustering analysis using a different norm, named Least Root Squares, which necessitates a specific Monte Carlo approach to converge on the optimal solution. The primary aim of this approach is to avoid discarding data distant from the trend; under the new norm, such data has a lesser impact on the final computation. The result is the definition of a  $N249^{\circ}\pm4^{\circ}$ ,  $53^{\circ}\pm1^{\circ}$  fault plane representing a feature in the seismic-deformation response of the caldera that indicates critical failure. The location of the extended fault under the point of maximum ground uplift suggests a first condition for rise of deep materials.

The conclusions are original and of interest to the community. The manuscript is concise and well written. The definition of the PIF brings forward a novel feature that can spark debate on the nature of the current unrest. The technique is novel but requires more details and tests to support the conclusions. The interpretation needs a more thorough assessment, especially of recent results published regarding the caldera unrest. Presentation needs revision.

#### Technique

The technique employed addresses the shortcomings of the least squares approach (LSQ) by modifying the norm to a square root relative to the distance between the data and the proposed model. This approach provides a more effective means of including outliers without having to discard them qualitatively, as it does not make any assumptions about Gaussianity, and the tails of the data probability distribution are better accounted for. It requires an additional computational burden, as Monte-Carlo-like solutions are necessary to resolve the problem. I have the following comments:

1. Before approaching a square-root norm solution, the standard procedure is to attempt a total variation norm (norm L1). The square-root norm allows for increased consideration of outliers, as it differs from the exponential distribution underlying the L1 solution, which is not a standard in fitting applications (at least as far as I know). The material section lacks references that demonstrate, through theoretical and synthetic studies, the validity of the approach, which would help the expert reader assess the technique.

We agree that it is important to give some background and reference here. We have therefore added the critical reference to theoretical work summarized by Tarantola (2005) which is the key and worldwide recognised reference for this type of statistical approach. In addition, following Rev3 suggestions and to allow the reader to fully appreciate the value of our innovative approach, we have added a sentence in the text (p. 7 lines 10-17) and a section to the Methodology (p. 19 lines 23-28) and the related figure M2 where it is possible to appreciate that the performance of the exponent 0.5 respect to exponents 3, 2, 1, and 0.333.

2. More generally, the Materials should provide an assessment of the technique, including the Monte Carlo Convergent (MCC) type search. If references are available, they will help evaluate the validity of the method in known scenarios, enhancing our understanding of the challenges this same method could face in a volcano. If they are not, such technical work should be tested within this study or through technical papers that precede the present work.

As stated above the theoretical approach including the MCC is in Tarantola (2005). We have also added the reference to the recent paper by Schmidt and Salvini 2024 which tested the MCC. We thank Rev3 for suggesting to add such references, that are essential to the reader to appreciate the theoretical and technical approaches.

3. The developed code is currently unavailable, but it is crucial for evaluating the validity of the approach employed. It should be made fully available through open-access repositories with sample datasets, allowing reviewers and the wider community to test it. The study currently lacks the open-access features essential for publication in CE&E, despite the details provided in the materials.

As already stated in the Data availability section of the manuscript, the code is fully available upon request and is the compilation of the procedure described step by step in the Methodology. The sample datasets are also already available as we added all input data as supplementary for each year and referred to the open access website of INGV-OV. This allows any reader to test the procedure and the code with the used data.

4. There is no discussion of the influence of event numbers on the technique. The study began in 2019 with 536 events, and the number of events increased each year until they tripled in 2022. In 2023, the number of events is approximately seven times that of 2019 and more than twice that of the previous year. The distribution sampling in the diffusive and non-diffusive years is thus very different. The number of earthquakes should influence the analysis and should be tested by random sampling of the available earthquakes in the most numerous years.

Ok we have added a sentence in the main text at p. 7, lines 19-23 and added the random sampling analysis for the diffusive years in the supplementary material S2a.

As expected the variance is independent on the number of samples when the total number is statistically significant.

The influence of the number of events could be significant only for the non-diffusive years, which, as expected do not converge on a solution.

5. The authors state that Scotto di Uccio et al. (2024) provided a qualitative interpretation of the fault planes based on correlation with geomorphology. However, these authors tested their novel locations using an updated version of NonLinLoc against those obtained with older versions, other methods, and locations provided by the Osservatorio Vesuviano. They conclude that their locations exhibit higher quality in terms of uncertainty compared to other location methods. The clustering obtained here depends on the quality of the locations routinely gathered by the Osservatorio Vesuviano. The same analysis should be conducted on more than one location dataset to demonstrate the reliability of the technique.

See reply to - P4-L25 REV1, who raised a similar question.

We added the following sentences at p. 5, lines 10-33 to clarify our choice as compared with relative location catalogues:

“We chose to use the catalog provided by the Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Vesuviano because it is an institutional product, continuously updated and validated by the official monitoring authority of the area. Its certified and standardized nature ensures the consistency, transparency, and reproducibility of our analysis over time, which we consider essential for the scope of our work. We acknowledge that relocated catalogs (e.g. Tramelli et al. 2022; Scotto di Uccio et al. 2024, Giacomuzzi et al. 2025), obtained through relative location techniques such as double-difference methods or source-specific corrections, can offer improved clustering and lower location uncertainties, which can facilitate the identification of seismicity patterns. However, such catalogs are often not available continuously or systematically over the entire time window of interest and may introduce a bias toward artificially increased clustering due to the nature of the relocation algorithm itself.

The goal of our study is to offer a statistical, unsupervised approach to identify potential temporal clustering of earthquakes aligning along a main fault structure. Several authors have previously mapped multiple fractures and faults in the area using both seismic and geological data; an overview of these structures is summarized in Iervolino et al. (2024). In that same work, the authors define the upper bound of reference magnitude scenarios as the simultaneous activation of multiple faults. In a similar spirit, our method aims not just to detect individual small-scale faults, but their possible merging or interaction over time, and for this reason we preferred to use a catalog that does not implicitly cluster events through a double-difference approach.

To ensure the reliability of the seismic locations used in the analysis, we applied a completeness magnitude threshold of 0.5, which allowed us to select events for which 95% of the catalog has a location quality of B or better. This quality code incorporates several factors, including RMS residuals, horizontal and vertical errors, number of phase picks, and azimuthal gap.”

## Results and presentation

The stated objective is to determine whether, when, and where seismicity has transitioned from diffuse microfracturing to localization along a well-defined fault plane. This assessment relies solely on the quantitative approach developed in the materials, without comparison to surface features, as in Scotto di Uccio et al. (2024). I have the following comments:

6. I view this lack of comparison as detrimental to the authors' inferences. Instead of stating that no fault appears to correlate with the (quite extensive) inferred deep fault, it would be much better to show surface features in a way that allows the reader to draw this

conclusion. There have been numerous recent studies detailing faults at Campi Flegrei, beginning with those cited in Scotto di Uccio et al. (2024).

We here disagree with Rev3. Actually, as already explained at various points in this rebuttal letter, we think that our unsupervised method is the main step ahead respect to any other preceding work attempting to correlate qualitatively 3D earthquake clusters (relocated) and 2D geomorphological features such that of Scotto di Uccio et al 2024. Our group blends physical volcanologists and seismologists and we all know very well that what is mapped at surface as a fault on active volcanoes is very often the integration of mild to elusive field evidence such as outcrop scale microfaults or fractures, alignments of vents/dikes and/or other geomorphological features, inferences from stratigraphic correlations. The reliability of such surface expressions in terms of lateral and vertical extent of real faults is highly questionable and not surprisingly results in features that are from slightly to significantly different in each subsequent publication based on field data (cf Cosentino et al. 1984; Acocella et al., 1999; Acocella 2010; Selva et al. 2012; Vitale and Isaia 2014; Isaia et al. 2015, 2021; Sbrana et al. 2022). Even more so is the inference of how those mapped structures would project at depth which is instead the realm where our study is performed. We confirm that no clear structures with the direction, dip and extent of the one highlighted by our study have been mapped in previous works unless we take into account very generic and partial overlaps.

7. The only geomorphological features (caldera rim bounds) are presented in Fig. 1. However, the information it provides, given the short format and length restrictions, is limited to station distribution. Is this figure necessary, considering it is cited only once and not referenced for station distribution (stations are also in Fig. 2)? Why are Vesuvius and Ischia Island included, yet only mentioned in the figure caption and shown so prominently? This figure could be reworked into a single panel above Figure 2, focusing solely on Campi Flegrei.

We think that a general view of the active volcanic field in the Neapolitan area may help the reader to understand the level of risk of the area. However we agree with Rev3 that this figure could be improved so we have added the lines that enclose the area most at risk according to the Italian Civil protection and overlaid the density of population from NASA. This way Fig. 1 provides an excellent framework for the reader to understand the need to improve our ability to timely track the evolution of seismicity, that is at the core of our work

8. Perhaps due to the final manuscript's transformation into the journal format, Figures 2-4 have low quality, with labels that are small and sometimes unreadable. Figure 2, in particular, has all its internal labels unreadable. Moreover, it would be more sensible to show a geomorphological map with the discussed geological features rather than one that shows what looks like roads. Seismicity generally occupies less than half of the figure area, so the panel could be made smaller or, ideally, only two years per row could be shown. This figure needs to be completely redrawn.

Rev3 is correct and we have now modified Figs 1, 2, 3, 4 and increased the resolution of all figures

9. I am a big fan of bird's-eye views, like those in Figs. 3-4. However, these views make it challenging to understand the exact shape and directionality of the PIF plane. A more standard WE/SN perspective on the PIF would greatly enhance understanding of its features.

We agree with Rev3 that this figure needs improvement, so we have made the requested changes

10. Looking at Fig. 5, I would have guessed downthrow toward SSE; the authors should indicate the directionality of the profile, as it was intuitive for me to view it from the SSW.

Ok we corrected the figure to make it clearer

Interpretation

I have the following comments:

11. As the author states, an increasing number of scientific works are now suggesting the direct involvement of magma at relatively shallow levels. However, there are recent papers that either discard by any means the rise of magma as the cause of the current unrest (Vanorio et al., 2025, Science Advances) or show the effect of pore-fluid pressure and thermoporoelastic processes as the underlying mechanism triggering the unrest (Nespoli et al., 2023; De Siena et al., 2024). Faults like those inferred from the analysis do not require, in my experience, the presence of magma: they can develop at the boundary of any thermo-poroelastic reservoir, which stresses the weaker surrounding fault. This does not mean that the PIF inference is any weaker, but the interpretation in terms of rupture should take this into account.

Our study and its significance are independent from the interpretation of the causes that may promote the development of a fault from initial diffuse microfracturing. We have added a sentence at p. 13 lines 27-28 to acknowledge the various interpretations available but also that whether or not there is magma at depth (what else though???) the interconnection of a new fault may increase the implications for the hazards.

12. The area intersected by the PIF has been the target of several investigations, suggesting the existence of a stressed boundary, for example, through InSAR measurements via the THD method (Pepe et al., 2019 and especially Tizzani et al., 2024 – see particularly their Fig. 17). The inferred dip seems to correspond to several earthquake migrations existing at least since 2018-2019, corresponding to a change from compressive towards the central reservoirs to extensive in GPS measurements (De Siena et al., 2024, see their Figs. 2-3 and supplementary materials). These results appear to support the

opening of the structure, with the deformation anomaly exhibiting similar responses prior to 2023. Deformation is expected to precede earthquakes, which involve rupture. The lack of discussion of time-dependent deformation features is detrimental to the drawn conclusions.

We agree with Rev3 that discussion of time dependent deformation is essential to the interpretation. This is why we have shown in Fig 5b the area identified by Giudicepietro et al 2025 of relative slower uplift, which matched with the inferred PIF location and kinematics derived from associated focal mechanisms. This anomaly in the perfect axisymmetric uplift pattern appears exactly when the PIF appears. Other time-dependent geophysical changes could be of interest and are now cited

I finally note these two typos:

13. Line 26, page 4, (Ricciolino et al. 2024).

14. Line 29, page 15, “farer”?

OK done

References in this review, not in the text - they act as a sample to discuss uncertainties about interpretation and deformation features. The author might find others more appropriate.

De Siena, L., Amoroso, A., Petrosino, S., & Crescentini, L. (2024). Geophysical responses to an environmentally-boosted volcanic unrest. *Geophysical Research Letters*, 51, e2023GL104895. <https://doi.org/10.1029/2023GL104895>

Pepe, S., De Siena, L., Barone, A., Castaldo, R., D'Auria, L., Manzo, M., ... & Tizzani, P. (2019). Volcanic structures investigation through SAR and seismic interferometric methods: The 2011–2013 Campi Flegrei unrest episode. *Remote Sensing of Environment*, 234, 111440.

Tizzani, P., Fernández, J., Vitale, A., Escayo, J., Barone, A., Castaldo, R., ... & Camacho, A. G. (2024). 4D imaging of the volcano feeding system beneath the urban area of the Campi Flegrei caldera. *Remote Sensing of Environment*, 315, 114480.

Vanorio, T., Geremia, D., De Landro, G., & Guo, T. (2025). The recurrence of geophysical manifestations at the Campi Flegrei caldera. *Science Advances*, 11(18), eadt2067.

We thank the reviewer and we have added De Siena et al 2024, Tizzani et al 2024 and Vanorio et al 2025 (not published yet at the time of first submission)

## RESPONSE TO REFEREES

### Reviewer #1 (Remarks to the Author):

The authors have addressed the comments raised in the former version, supporting their analysis and significantly improve the quality of the figures.

Again, as already pointed out in the former comments, I ask the authors to correctly refer to moment magnitude and not duration magnitude when discussing about the maximum magnitude expected in the area, since this is what was inferred in Scotto di Uccio et al. (2024) and Iervolino et al. (2024)

With this final modification, I support the manuscript for publication.

**WE THANK REV1 AND WE HAVE CORRECTED THE MAXIMUM EXPECTED MAGNITUDE TO MW=4.4, AS REQUESTED**

### Reviewer #2 (Remarks to the Author):

I appreciate the efforts made to address my comments on the earlier version and to revise the manuscript, which I think has been very substantially improved.

My main concern regarding the first version of this manuscript was a 'lack of delivery' (or a lack of balance) regarding how the proposed earthquake clustering method and its results relate to and improve upon the Failure Forecast Method. To rectify this imbalance, I suggested that the manuscript's Introduction section might be reorientated a bit more toward imaging of seismogenic structures and the emergence of potential magma conduits, rather than application of the FFM. The authors have responded that they prefer to maintain focus on the FFM in the introduction and to rebalance the Discussion section by better explaining the study's implications for use of the FFM. I fully respect the authors' decision; their rationale is well explained in their rebuttal letter, and they have clearly attempted to better articulate how their method can augment or improve upon the FFM approaches.

Nonetheless, the Abstract and Introduction could still be more direct about the aims and scope of the paper with respect to the FFM. I suggest a restructuring of the Introduction to facilitate focus, to eliminate some repetition and to remove some potentially redundant text. A restructured paragraph order could be (i) risk and current activity at Campi Flegrei; (ii) the principles of FFM and the past application of FFM to Campi Flegrei; (iii) the problem with FFM (iv) the contribution of the present study. I also suggest some more minor restructuring of the first few paragraphs of the Discussion section to achieve a similar streamlining. The attached document with tracked changes should help the authors to gauge the impact of this suggested editing, BUT, for clarity, please first read the suggestions with tracked changes turned off.

**OK WE THANK REV2 AND WE HAVE MODIFIED AND RESTRUCTURED THE TEXT OF BOTH THE INTRODUCTION AND THE DISCUSSION AS SUGGESTED**

A second concern I raised regarding the overall annual (non-planar) distribution of seismicity and its bearing

on the use of planar fault estimations has been dealt with adequately in the revised Approach section. Similarly, my major comment 3 on the original manuscript regarding the addition of cross-sections to show the three-dimensional distribution of the seismicity has been well addressed in the revised Figure 2. In general, all the figures have been greatly improved in terms of clarity and quality.

THANKS

My suggestions for more comparison to other restless calderas (comments 4 and 5 on the previous manuscript version) were not adopted in the revised version, given the abovementioned decision to retain focus on the FFM. I appreciate the authors' perspective here. The short note at the start of the revised Discussion section alerting the reader to the existence of similar phenomenon at other calderas, and the note at the end of the Discussion on the transferability of the methodology proposed here, are both fine. However, I do think it important to acknowledge explicitly that other studies have similarly - if not exactly in the same way - been able to delineate the geometry and evolution of intracaldera faults systems from earthquake hypocentre locations (see suggested edits on the attached doc).

Overall, my comments/critiques of the revised manuscript are thus mainly of an editorial nature. I congratulate the authors on their fine work. I hope the above suggestions and those in the attached document will help to finalize the paper.

THANKS

Reviewer #3 (Remarks to the Author):

The authors correctly addressed most of the critical comments, improving the manuscript. Figures now clarify extension and depth of the PIF, and I am convinced by the authors' responses to my doubts regarding the technique and interpretation.

I report here a simple reference to the numbered point of my previous review, to show where they answered satisfactorily and where more discussion is needed.

**Technical Points 1, 2, 4, 6-10, 12 and 13:**

The additions to the paper and responses fully address my comments.

THANKS

**Point 3:**

This is more of an editorial and policy matter - if CE&E accepts that the code must be asked to the authors I have no further issue. I report below regulations regarding reporting of computer codes in Nature journals (<https://www.nature.com/nature-portfolio/editorial-policies/reporting-standards>) so that the authors and editor can better resolve any matter regarding code availability:

THE CODE IS FREELY AVAILABLE UPON REQUEST. HOWEVER WE REMARK THAT THE MCC METHOD IS DESCRIBED ANALYTICALLY STEP BY STEP IN THE METHOD SECTION AND ANY RESEARCHER CAN COMPILE IT IN ANY PREFERRED LANGUAGE OR TOOL (C, R, PYTHON, MATLAB, EXCEL, OTHERS) AND RUN THE DATASET.

**Point 5:<\b>**

The importance of assessing the PIF to understand Campi Flegrei current unrest is undeniable, as is a test with other location datasets that are available at the caldera. The implementation of the algorithm on the mentioned datasets still offers snapshots on the PIF, allowing the authors to evaluate technically how reliable the structure might be and consistent with that obtained so far. There are obvious problems affecting routine locations at the Osservatorio Vesuviano even above the chosen magnitude threshold that might corrupt the definition of the PIF structure. As the three mentioned datasets (Tramelli, Giacomuzzi and Scotto di Uccio) are available from repositories (one from a co-author) and the code can be swiftly implemented, I still see this lack of comparison as detrimental. The author can discuss this further in their response, but this will certainly be a question that the wider community will ask.

WE AGREE THAT THE STUDY SUGGESTED BY REV3 WOULD BE INTERESTING BUT, CONSIDERING OUR PREVIOUS RESPONSE, FOR WHICH THE DATASETS ARE IN FACTS NOT COMPARABLE, WE FEEL THAT SUCH REQUEST IS OUT OF THE SCOPE OF THE PAPER IN ITS PRESENT FORM AND MAY INSTEAD BE PART OF A FUTURE DEVELOPMENT

**Point 11:<\b>**

I acknowledge the work can disregard differences between interpretations and the PIF is independent of such interpretations. My comment was more about the impact that such a structure could have in the context of a magmatic or non-magmatic unrest. While it is challenging to explain the current unrest without magma for many, it has been done recently (Vanorio et al., 2025, Science Advances; De Landro et al., 2025, Nature: Communications). Explaining how the PIF would interact with this scenario could add impact and reach, but I understand if the authors believe this to be unnecessary.

AGAIN WE AGREE WITH REV3 THAT THIS IS CERTAINLY A TOPIC OF INTEREST FOR FUTURE DEVELOPMENTS BUT OUT OF THE SCOPE OF THE CURRENT WORK