nature portfolio

Peer Review File

Modelling of earthquake swarms suggests magmatic fluids in the upper crust beneath the Eger Rift

Corresponding Author: Dr Pinar Buyukakpinar

This manuscript has been previously reviewed at another journal. This document only contains information relating to versions considered at Communications Earth & Environment.

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

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

Version 0:

Decision Letter:

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Dear Dr Buyukakpinar,

Your manuscript titled "Revived Earthquake Swarms: The Role of Magma in NW Bohemia/Vogtland" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

In particular, please ensure that the revised manuscript meets the following editorial thresholds:

* Present a robust and compelling case that the 2024 seismic swarm in the Bohemia/Vogtland region was caused by ascension of magmatic fluids and that this can be demonstrated by the dense-array seismic observations.

* Ensure that your conclusions are fully supported by the data and results and fairly account for alternative explanations.

* Describe your methods in detail to the extent that your work is fully reproducible. Please note that we allow up to 5,000 words in the main text plus unlimited space in the methods section.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers’ comments. Please submit your 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.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

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

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Joe Aslin

Deputy Editor,
Communications Earth & Environment

Consulting Editor,
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For your information, you can find some guidance regarding format requirements summarized on the following checklist:
(https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide
(https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

see attachment

Reviewer #2 (Remarks to the Author):

Dear authors,

thank you for your insightful study into the potential role of magma in NW Bohemia/Vogtland earthquake swarms. Your study could be an important contribution to the debate about which role fluids, and more specific magma, might play in the process of swarm earthquake activity. At the present stage the manuscripts would benefit from moderate to major revisions, as I will express below. More detailled comments you will find in the annotated manuscript.
At first, you should make more clear what it means that a volume of "undisturbed rock" got activated during the studied 2024 earthquake swarm. As it can be seen from you figures, the area was active over the last decades and most probably the last century. Therefore, I would assume, that an existing fault zone got reactivated. What would be different, if actually an existing fault zone gets reactivated instead of fracking an undisturbed volume of rock? What is the general fault inventory of the study

area?
Many aspects mentioned in the manuscript are not yet fully documented, e.g., the double-difference Wadati plots. Also, uncertainties are not yet presented and discussed.
Can you provide more information on the physical state of relevant fluids at mid-crustal levels, e.g., CO2, water or more realistic brines, magma. What about host rock density variations throughout the studied crustal section? Could a change from lithostatic to hydrostatic pressure regime have an influence on the fluid/seismic activity? When/where CO2 dissolves from fluids/brines?
Which parameters beside the density of the fluid can have a strong influence on the studied dynamics?
To me it is not yet clear at all, why you stack waveforms, and especially amplitude spectra (Fig. S2). Having similar magnitudes, that could in principle make sense for P and S waves individually, but not for P and S waves combined.
The conclusions do not yet fit to the title. I would expect a more general discussion and conclusion about the potential role of magma in the earthquake swarm generation in NW Bohemia/Vogtland region. Until now, it is a bit too much focused on the 2024 swarm. Furthermore, it would be benefitial for the impact of your study, if you could provide also a more global perspective at the end.
The manuscript text and especially the figures need some more elaboration. Some figures are very difficult to read (e.g., due to small font sizes, used color scales). You should also check the references. In my opionion, some relevant ones are missing.
Please give reference to all station/data providers, including the institutes from Czech Republic. Are there dois available that could be referenced to?
In summary, your manuscript has a high potential to become an important reference in the debate on the role of magma/fluids in the generation of earthquake swarms, but it has to be improved in many aspects before. I hope my comments and questions will help you to improve your manuscript and the impact of the study.

With best regards, Wolfram Geissler

Additional technical comment: the layout of the manuscript file was not great for review.

Reviewer #3 (Remarks to the Author):

Review of “Revived Earthquake Swarms: The Role of Magma in NW Bohemia/Vogtland” by P. Bükükakpinar and others

In this paper, the authors analyze the structural symmetry of an energetic swarm that occurred in the Vogtland after a long period of quiescence. This is an important region for studying and learning about swarms and the authors observe that this is a unique swarm in that for this region it was the first time that a swarm evolved in undisturbed rock. The authors conclude that the swarm resulted from hydro-fracturing and hydro-shearing from two different ascending magmatic fluids with differing buoyancies.

The analysis of the observations is very nice, and I have no comments on the data analysis. There is a complete analysis of the magnitude time history, locations, and source properties. The relation to Vp/Vs is solid and draws out nice attributes of the sequence. However, the link between observations and conclusions is weak. I attribute this to the short format of this paper and too much of a reliance on referring to other papers.

I recommend rejecting this paper and encourage the authors to develop this as a long format paper that has a detailed motivation of the proposed models. so that the observations can more clearly be compared. I understand that some of this information is in the Methods section, but in this short format, the paper is too disjoint to follow the arguments.

If this paper is to be accepted, I strongly recommend that the section Hydro-fracture model for bilateral and radial growth in Methods be moved to the body of the paper or at least the discussion around Figure 5. This is not really a Method and in my opinion that discussion would be better used as an introduction to the models for structuring the discussion surrounding Figure 3 and the conclusions in the paper. I am also confused by Figure 4, specifically, I do not understand what the gray shading is representing; also the offset in the horizontal layer does not correlate with the fault—there appear to be multiple offsets. It is not clear what my takeaway from this cartoon should be.

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Version 1:

Decision Letter:

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Dear Dr Buyukakpinar,

Your manuscript titled "Modelling of earthquake swarms indicates magmatic fluids in the Upper Crust Beneath the Eger Rift" has now been seen again by 3 reviewers, and we include their comments at the end of this message. They remain interested in your work, but some important points are retained. We also remain 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.

In particular please ensure that you adapt the interpretations and conclusions to match the level of support available, as questioned and highlighted by Reviewer #1.

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

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

Best regards,

Joe Aslin

Deputy Editor,
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If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. 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 pdf file

Reviewer #2 (Remarks to the Author):

Dear authors,

thank you very much for your detailed response to the reviews and all the revisions made to the manuscript. In my opinion, the manuscript got very much improved. I would agree with reviewer 3 that the format of the selected journal is very challenging to present your study. Some disadvantages of this format remain after the revisions, e.g., I find it not perfect to have the figures illustrating parts of the methods then only in the supplementary material, and there these figures are presented without much context. Maybe it could be possible to place a few figures also in the methods section?

I very much appreciate that you included a comparison to the 1897 earthquake that occurred in the same area as the 2024 earthquake swarm.

I have only some minor additional comments and suggestions. You will find them in the annotated manuscript. The most relevant to me I will list below:

Which definition of the local Magnitude ML do you use? How this definition compares to standard regionally applied ML formulas?

When you calculate the changes in the Vp/Vs ratios in the swarm volume, do you assume point sources for the individual events? How do you derive/define the uncertainties of the regional and source volume Vp/Vs ratios?

Which peridotitic melts are you thinking of, basalts/nephelinites, or just more general?

In some paragraphs, and also in parts of the Supplementary Materials, you should provide also references. Overall, the reference list looks very comprehensive.

With best regards, Wolfram Geissler

Reviewer #3 (Remarks to the Author):

Review of revision for “Revived Earthquake Swarms: The Role of Magma in NW Bohemia/Vogtland” by P. Bükükakpinar and others

The re-organization of this paper and addition of a supplement directly responds to my past review. My additional comments below are editorial. The new paper is clearer with a consistent argument. I now recommend publishing.

One editorial comment that should be addressed. Lines 166 to 178 cite Figure 3 but refer to Figure 4. I recommend swapping Figure 3 and 4 so that the observations come first. Lines 179 to 189 also cite Figure 3, if you reorder figures as suggested these should be updated to Figure 4. Lines 220 to 231 would then reference figure 3 and Line 258.

I note a few other minor editorial comments below for the authors to consider (line numbers correspond to track changes version):

Line 106: suggest changing to “progressively extends bidirectionally”

Line 112: suggest changing to “down-dip directions along the fault”

Line 122: suggest Reykjanes Peninsula, Iceland”

Version 2:

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 Dr. Buyukakpinar,

Your manuscript titled "Modelling of earthquake swarms suggests magmatic fluids in the Upper Crust Beneath the Eger Rift" has now been seen by our reviewer, 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 reviewer. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Best regards,

Joe Aslin

Deputy Editor,
Communications Earth & Environment

Consulting Editor,
Communications Sustainability

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Dear authors,
Thank you for the detailled responses on my comments. In my previous comments, I can just regret that the noise level has

been added in an extra figure and not directly in fig. S8, and that a schematic Brune model (plateau + f^-2) was not added in this fig. These are still suggestions, up to the authors to follow them or not, but it may help to convince the readers on the change of the corner frequency. Exept this minor suggestion, I think the ms is now clear enough, giving strong and balanced results, and in good shape for being published. I therefore recommand publications for this article.

Revived Earthquake Swarms: The Role of Magma in NW Bohemia/Vogtland

Dear editors, dear authors,

Please find below my comments on the ms by Büyükakpinar et al., submitted for publication in Communications Earth & Environment. This article presents a nice, comprehensive and detailed study of a seismic swarm occurring in 2024 in Bohemia/Vogtland area. This area show regular swarm activity, studied in pioneering articles on swarms. Therefore, this area is a perfect place to gain insights on swarm processes. This study includes detection and localization through novel IA algorithm, focal mechanisms and analysis of the migration patterns. It then compares the data with mechanical models to build a comprehensive story about the swarm processes. Overall, this study use up-to-date methods and concepts and it is clear and well-written.

However, I find that the model they develop is overly complex (involving several phases of injection, with different types of fluids and pressure levels) and it is poorly supported by the observations. It sounds correct and interesting, but the link between the data and the models does not allow to exclude other potential mechanisms. In particular, the presence of a magmatic dike propagation seems to be an a priori in this analysis, but not justified by data or references. Therefore, the interpretation goes beyond what can be proven/shown, leading to very strong and not fully justified statements (eg: role of magma in the title). At least, some discussion about alternative possibilities for the swarm processes, and why they can be discarded, may help convincing the reader on the validity of the interpretations.

I therefore suggest major revisions for this article. Please find below my detailed comments, in addition to major comments stated above.

Detailed comments

General comments: please add line numbers to help the review process.

- P2: "Our findings provide key insights for understanding fluid-driven deformation in geodynamically active regions worldwide.", or similar statement in the conclusion (p11). It is not straightforward as it stands, especially given the very complex you suggest at this end. please precise (other locations?, what insights? Etc.)
- P2: "As this is the first time a swarm has evolved in undisturbed rock" is not clear, please reformulate.
- Fig 1: for what Neunhofer, Webnet and oseek stand for? How to you define the red area in c (all the seismicity in the KK square?)?
- P4: a few lines (in the main text, appendixes or supp) on the seismic stations (numbers, geometry, types of sensors, etc) may be useful.
- P4: "unprecendented spatial resolution": Could you comment in the method section on the resolution of the location? How does it compare to relative double-difference location?
- P4: "Conventionnal approaches … through the crust". I do not get the aim of this sentence, please reformulate.
- P4-P5 "fracture developpment", "hydro-shearing", etc are already interpretations, not justified so far. Same in P6: "hydroshearing is prominent … larger hydrofracturing components", but following your interpretation, stress drops are just showing higher pressure in the 1st phase than in the second one (even though variations of stress drop can be related to other interpretations, such as the differences in depth).

- Fig. S2: I am a bit confused, more details on this analysis may be needed. If you stack waveforms having different fc, you do not get a waveform that follows a Brune-type model (ie having a single corner frequency). Moreover, you can compare only events with same magnitude, so how do you select the events? Finally, as Phase 1 are deeper than Phase 2 events, differences in attenuation may lead to differences in spectrum.
- P5: such low value of Vp/Vs are highly uncommon, and should be discussed more extensively. What mechanical models may explain such values, corresponding to null or negative Poisson's ratio?
- P6: Bilateral (non radial) migration may be explained by several processes. In particular, control from the fault structure, such as intersection of faults lead to 1D migration. Moreover, considering the first points of the swarms, migration is dominantly downward. So, even if I fully agree with the model you propose, a bit more justification and discussion on alternative processes may be useful.
- P6: You mention several times hydro-fracturing. However, a pressure of 6MPa seems quite small to generate hydro-fracturing at this depth. If estimation of the stress level exist in this area, comparing it with the inferred overpressure through a simple failure criterion may help.
- P8: In your model, you have a relation between v and r. Are you observing it with this data? The existence of an aseismic slip makes that migration may strongly differ from a purely diffusive law (see e.g. paper from Danré et al, 2022, 2024).
- P8: no back-front… Please add references, as there are several papers discussing about the existence of back-front during or after the injection stops.
- P8: The discussion of the two fluid batches with different types of fluids contents sounds like overinterpretation given the evidences from the data. I fully agree that dike propagation, as you propose is a possibility. However, based on your observations, could you discard that this seismicity pattern may be induced by water or CO_2 with differences between both phases explained by eg a fault structural control?
- Fig. 4: something very hard to understand in this 3D view, as part of it is cut N-35°, while another part is cut E-W.
- P9: The assumption of having the seismic cloud of the same size as the ascending fluid batch is odd, especially for phase 2 where you consider having fluid diffusion on the fault. The assumption of having the same structure size for both batches may seem geologically meaningful (especially since the pressure is lower for the second batch), leading to a same density for both batches. Please better justify your assumptions, and evaluate how it make change your interpretation.
- P10: with your model, a overpressure of 6MPa and a density of 1200 kg/m3 produces bilateral migration because of buoyancy-induced pressure gradients, hence hydro-fracturing. How to make this observation consistent with EGS stimulation, where pressure is higher and fluid density lower (water), but migration is globally radial? Is it a matter of viscosity?

Revived Earthquake Swarms: The Role of Magma in NW Bohemia/Vogtland

Pinar Büyükakpinar[1*], Torsten Dahm[1,2], Sebastian Hainzl[1,2], Marius Isken[1], Matthias Ohrnberger[2], Jana Doubravová[3], Siegfried Wendt[4], Sigward Funke[5]

[1*]Physics of Earthquakes and Volcanoes, GFZ Helmholtz Centre for Geosciences, Potsdam, Germany.
[2]Institute for Earth and Environment, University of Potsdam, Potsdam, Germany.
[3]Institute of Geophysics, Czech Academy of Sciences, Prague, Czech Republic.
[4]Geophysical Observatory Collm, Institute for Earth System Science and Remote Sensing, Leipzig University, Leipzig, Germany.
[5]Institute for Earth System Science and Remote Sensing, Leipzig University, Leipzig, Germany.

*Corresponding author(s). E-mail(s): pinar@gfz.de;
Contributing authors: torsten.dahm@gfz.de; hainzl@gfz.de; isken@gfz.de; Matthias.Ohrnberger@geo.uni-potsdam.de; doubravka@ig.cas.cz; wendt@rz.uni-leipzig.de; sfunke@uni-leipzig.de;

Abstract

Earthquake swarms are enigmatic seismic phenomena that occur across diverse tectonic settings, from volcanic to intraplate regions, and are often associated with fluid migration, magmatic activity, or stress redistribution. The Northwest Bohemia/Vogtland region is a globally recognized hotspot and natural laboratory for such activity. This study examines the awakening of a new earthquake swarm in 2024 after decades of dormancy. The structural symmetry and temporal evolution of the swarm indicate the activation of a pre-existing fault by natural hydro-fracturing and hydro-shearing under the influence of ascending magmatic fluids. Seismicity modeling shows that the month-long swarm begins with a high-pressure CO_2-rich fluid intrusion, followed by transitions to low-pressure hydro-shearing on the fault, likely associated with CO_2 magma mixtures. Our

you mean locally?

? what is that?

results highlight the critical role of fluid overpressure and fault zone weakening in controlling swarm dynamics. By integrating high-resolution seismicity patterns and earthquake source mechanisms with models of fluid migration, we provide a detailed reconstruction of the temporal and spatial evolution of the swarm. Our findings provide key insights for understanding fluid-driven deformation in geodynamically active regions worldwide.

Main

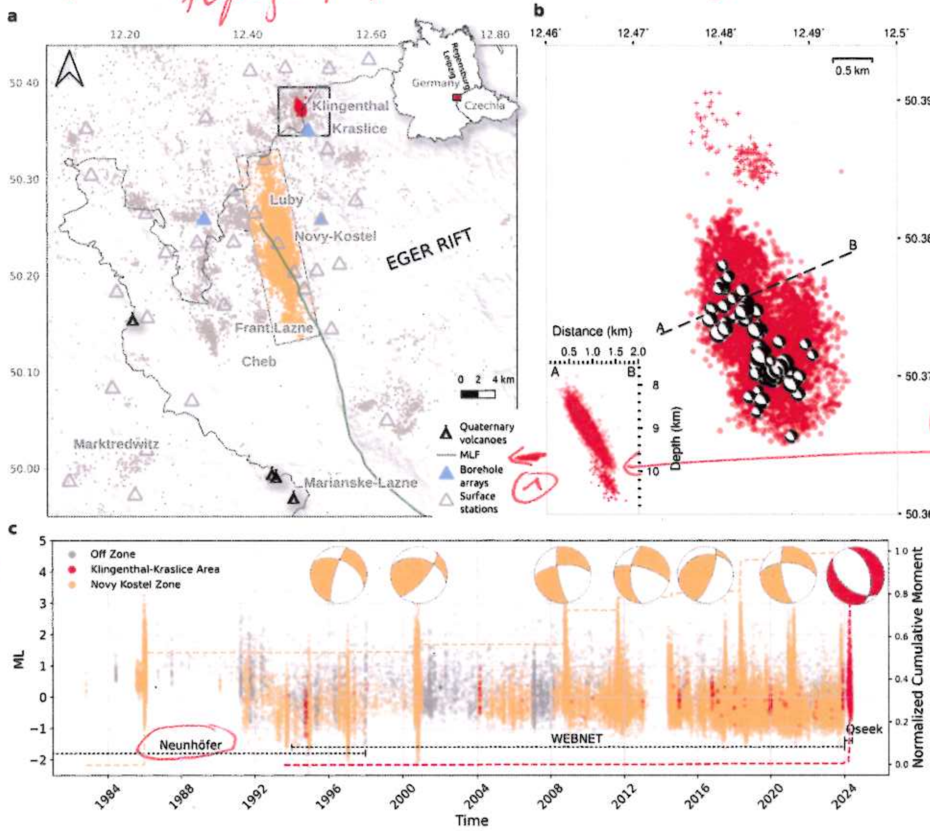
Located within the Bohemian Massif, one of the largest outcrops of Variscan basement in Europe, the Northwest Bohemia/Vogtland region (Figure 1) hosts one of the most active seismic zones in Central Europe. This region is where the term "earthquake swarm" was first introduced [1], highlighting its significance in seismology. Persistent seismic activity makes this region a key site for swarm studies. In addition, widespread CO_2 emissions associated with crustal underplating provide an exceptional natural laboratory for investigating interactions between tectonics, magmatism, and fluid migration. The Cheb Basin, situated at the intersection of the Eger Rift and the Mariánské Lázně Fault Zone (Figure 1), is the center of seismicity and gas emissions [2] and is characterized by high heat flow, alkaline volcanism, and five Quaternary volcanoes [3]. Since 1985, an NS trending zone crossing Nový Kostel (NK) (Figure 1) has episodically produced intense swarms with the largest seismic moment release in the entire region [4]. However, in March 2024, an intense seismic swarm emerged in the Klingenthal-Kraslice (KK) zone northeast of NK. This marks a striking shift in regional seismicity, raising key questions about its underlying mechanisms.

The mid-crustal earthquake swarms are commonly attributed to fluid transfer from the upper mantle and pore pressure perturbations [5]. However, the relative roles of magma, CO_2, and water in triggering swarms and driving upper crustal deformation remain less understood. The new KK swarm began in December 2023 and continues in episodic bursts. It stands for the first significant seismic activity in the area since 1994, with historical records indicating only minor seismicity over the past century [6]. As this is the first time a swarm has evolved in undisturbed rock, its relatively simple spatiotemporal patterns provide a unique opportunity to fill the knowledge gaps mentioned above.

Our seismic analysis benefits from exceptionally dense observations in close proximity to the swarm, including high-frequency borehole arrays with a sampling rate of 1 kHz. By combining seismicity and seismic source studies with fluid intrusion models, we identify a transition from highly buoyant fluids at high overpressure to less buoyant fluids at lower overpressure, e.g. from CO_2-rich fluids to CO_2-magma mixtures, which cause first hydraulic fractures followed by growth of hydro-shearing on the activated fault. These findings highlight the critical role of magmatic processes in swarm dynamics, offering broader implications for fluid-driven seismicity in tectonically and volcanically active regions.

epicentres difficult to identify on grey-shaded topography

(1) ↓ fonts very small?



not possible to see if crossed or dots

← yellow line difficult to see

references missing in caption

Fig. 1: **a** Regional map showing the tectonic setting and seismicity from 1982 to 2024. Triangles represent the seismic stations used. The Mariánské Lázně Fault Zone (MLF) is marked. Recent swarm activity in the Klingenthal-Kraslice region (red) and the most prominent seismically active area, Nový Kostel (orange), are highlighted. **b** A zoomed-in view of the Klingenthal-Kraslice swarm, with centroid moment tensors (CMTs) for events with $M_W > 1.2$ (lower hemisphere projections of double-couple components). The December 2023 activity is marked with plus symbols, while the main swarm (March–June) is shown as red circles. **c** Temporal variation of seismicity (1982–2024), showing event magnitudes (M_L) and composite moment tensors for larger events [7, 8]. Colors indicate the regions: Klingenthal-Kraslice (red), Nový Kostel (orange), and off-zone events (gray). The normalized cumulative moment is plotted on the right axis for both regions.

(2)

references?

High-Resolution catalog and moment tensors

In recent years, as part of an ICDP (International Continental Scientific Drilling Program) initiative, a unique network of surface and multiple borehole high-frequency

(2) Why don't you code it by color? (or intensity)

arrays has been established in the study area, in addition to the existing [9] monitoring networks. The infrastructure is located only a few kilometers from the swarm earthquakes, and the sampling rate is up to 1 kHz, which allows a detailed investigation of subsurface processes. Using this network in combination with machine learning, we have created a high-resolution earthquake catalog. This process yielded 9,456 seismic events from Dec 2023 to June 2024, including those as small as $M_L = -0.5$, which is 10 times as many as the agency catalogs, achieving unprecedented spatial resolution for seismicity in the region.

The earthquakes, confined in a narrow NW-SE trending zone of about 1.2 km width and 2 km length, show systematic spatiotemporal migration patterns. To probe the source mechanisms, we applied a Bayesian inversion approach to generate centroid moment tensor (CMT) solutions for the first time for this region. We obtain 64 CMT solutions for events with $M_W > 1.2$. This approach accounts for uncertainties, providing robust estimates of the fault characteristics (see the Methods section). The solutions reveal the activation of a previously unrecognized fault segment, predominantly normal faulting, with strike = 329° ± 27, dip = 60° ± 6, and rake = -62° ± 12 (Figure 1b) aligning with the spatial extend of the swarm, likely influenced by localized stress accumulation. This discovery is remarkable because other earthquake swarms in the region, such as at NK, have been dominated in the past by strike-slip and thrust faulting (Figure 1c) [7, 8]). The regional variation of mechanisms and activated faults suggests significant heterogeneity in the stress field, likely influenced by transient deformation and fluid migration within the crust.

The sudden activation of geological fault zones with different orientations at different locations is challenging seismic hazard assessment. Conventional approaches fall short in the swarm earthquake region because they generally do not consider the interaction between tectonic stress input, fault zones of different orientations, and fluid transfer through the crust.

Swarm phases

While the first micro-earthquakes occurred in December 2023, the swarm exhibited an unprecedented rate of seismicity between March and June 2024. Since then, the activity has been greatly reduced, but micro-earthquakes occasionally appear and disappear for a few days. Figure 2 illustrates the spatiotemporal and magnitude distribution of events and CMT results (M_W >1.2) for the earthquakes, revealing two distinct temporal phases with contrasting seismic patterns.

Figure 2a highlights the spatiotemporal distribution of events projected onto the strike and up-dip directions. The activity starts at (0, -0.5) km and progressively extends, first bilateral in up- and down-dip directions (Phase I), and later radial with a central point at (0,0) (Phase II). After two months of activity, the distribution forms an almost circular cluster with slight asymmetry along the strike axis.

The spatiotemporal patterns (Figure 2b and Figure S1) reveal distinct episodic bursts of activity, with two main phases, Phase I and II, marked by the vertical dashed lines and shading. Smaller magnitudes dominate the initial Phase I of bilateral growth until March 29, corresponding to the early stages of fracture development and fault activation. As the growth mode of the swarm becomes radial in Phase II, larger magnitudes emerge, reflecting the increasing role of fault slip and hydro-shearing on the activated fault.

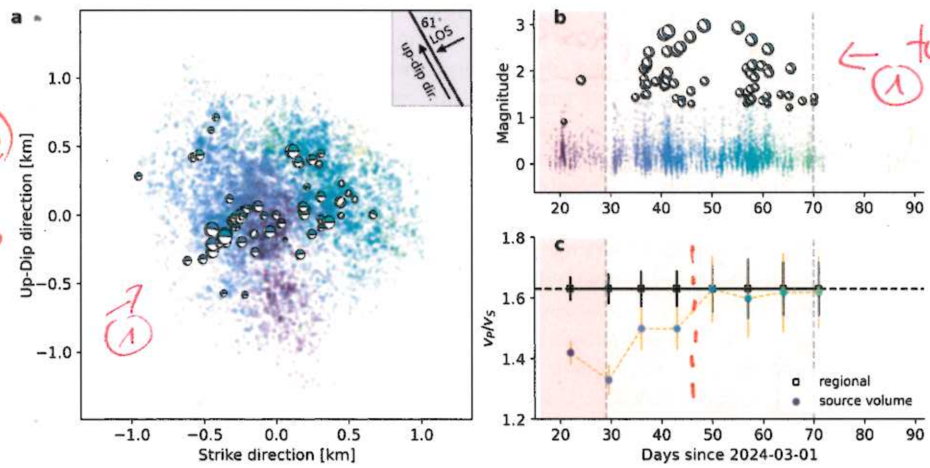


Fig. 2: Spatiotemporal and magnitude distribution of the swarm and CMT inversion results. Panel **a** displays the spatial distribution of events projected onto the strike and up-dip directions, forming an elliptical cluster along the fault plane. Panel **b** shows temporal clustering and magnitude evolution, with dashed lines and background shading marking distinct phases linked to fluid dynamics. Panel **c** compares the regional and source volume v_P/v_S as a function of time. The pink and yellow shaded areas indicate the first 29 days and the subsequent 29–70 days, corresponding to Phase I and II, respectively.

Interestingly, the ratio of P- to S-wave velocity (v_P/v_S) resembles the different phases (Figure 2c). We use a double-difference Wadati method in moving windows to distinguish v_P/v_S between the source region (source) and averaged over the path between the swarm and seismic stations (regional) [10]. While the regional v_P/v_S remains constant at 1.64 over the course of the swarm, the source-related v_P/v_S is strongly reduced in the initial phase of the swarm and returns to background values during Phase II. Such behavior has been observed for NK swarms before [e.g. 10, 11], and has been explained by the sudden flushing of the source volume with gaseous fluids in the initial phase of a swarm, which gradually diffuses away over periods of days and weeks.

The reduced v_P/v_S ratios in the early phase of the swarm correlate with a change in the relative corner frequencies, or stress drops, between earthquakes during Phase I and II. Earthquakes of, e.g., M_W 0.8 have a smaller corner frequency, i.e. stress drop, during Phase I than during Phase II (Figure S2). An anti-correlation between stress drops and pore pressure has been previously reported for the hydraulic stimulation in Basel [12], supporting our model that hydro-shearing is prominent during the low-pressure Phase II as opposed to larger hydro-fracturing components during Phase I [e.g. 13].

Chronology of ascending fluids

The observed patterns and sequences of the growing seismicity cloud tell us a lot about the cause and the physical processes during the swarm. In particular, bilateral growth of seismicity occurs in injection experiments under stress gradients [14]. Therefore, the observed bilateral upward and downward growth in the fault zone indicate buoyancy-induced pressure gradients, which are caused by the intrusion of a light fluid into a dense rock [e.g. 15]. An intrusion associated with an injection under high, almost constant overpressure that abruptly ceases leads to a seismicity front initially growing bilaterally with higher velocities upwards than downwards. Then, in the so-called 'bleed-off' phase, there is a one-sided growth of the seismicity front upwards, which is accompanied by a so-called 'back-front of seismicity generation', which only propagates upwards from the center of the opening fracture. The event density is asymmetric, with a thick bulge at the top.

The seismicity cloud of the KK swarm shows exactly this predicted pattern (Figure 3 a,c), and can therefore be simulated with the bilateral growth model. Our modeling results indicate an injection phase lasting 5 days (from day 16.8 – March 16, 2005, at 19:00 UTC, to day 22 – March 22, 2005) at an overpressure of about 6 MPa, followed by a bleed-off phase over 7 days until March 29, 2005. Although the fluid viscosity is difficult to determine because the fracture mechanics modeling makes simplified assumptions about the crack opening, the modeling shows that viscosities as small as a few tens of $Pa \cdot s$ are sufficient to reproduce the observed growth of the seismicity cloud.

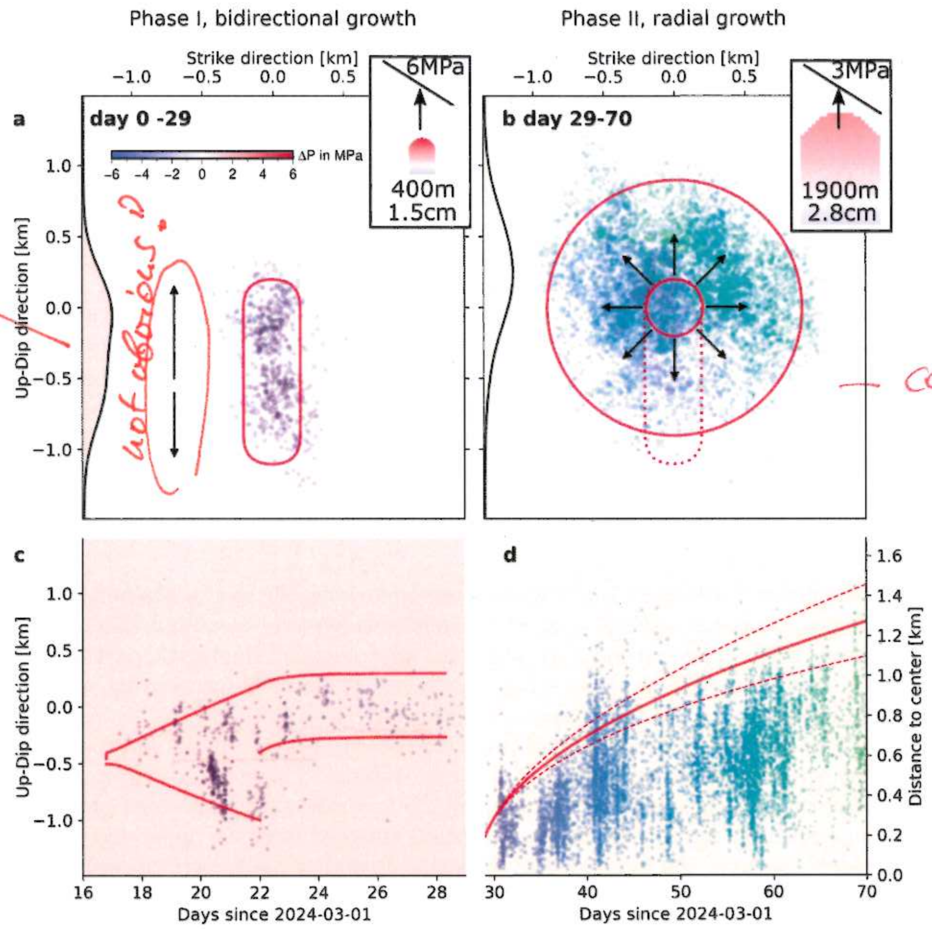


Fig. 3: Evolution of seismicity patterns during fluid injection phases. **a** The seismicity in Phase I projected onto the fault plane, illustrating bilateral growth. **b** The seismicity in Phase II, highlighting radial growth. The inset curves in both panels show the normalized event densities as a function of up-dip. The inlet figures at the top right of **a** and **b** show numerical simulations of the vertical and lateral shape of an ascending batch of buoyant fluid with $\Delta\rho$ of 1597 and 167 kg/m^3, respectively. The color scale indicates the overpressure of the fluid in MPa. The numbers indicate the static overpressure at impact, the lateral extend, and the mean opening of a rising batch. The observed spreading of seismic events is compared with theoretical growth models: **c** Bilateral growth model, with a fluid density difference of $\Delta\rho = 1597\,kg\,m^{-3}$; and **d** radial growth model, with a fluid density of $\Delta\rho = 167\,kg\,m^{-3}$. Red curves indicate model predictions, showing good agreement with observed patterns.

use different colors to illustrate evolution?

color scale?

make caption more clear? (observations?)

Model or observation?

(1) This is the interpretation?

(2) really? not first to left and then to right?

In Phase II (t > 29d, March 29, 2024), the seismicity cloud continued to grow, but now radially, starting from the upper end of the previously fractured segment on the fault Figure 3b,d). Slow radial growth of a seismic cloud is often explained by pore pressure diffusion inducing both shear and opening mode fractures. Aseismic slip may also play a role [16]. Such radial growth is expected when both buoyancy forces and injection pressures are lower [e.g. 17]. In the following, we argue why the overpressure and the density difference to the host rock could have been lower in Phase II.

In terms of growth rate, the circumferential length of the crack increases with time, in contrast to the bilateral growth in Phase I. So, the speed of the seismicity front decreases with increasing radius of the activated fault patch, even if the inflow is constant. Pore pressure diffusion models suggest radial growth with time proportional to $\sqrt{t}$ or velocity v proportional to r^{-1}. A similar relation is obtained if we extend the 1D hydrofracture growth to cylindrical 2D growth due to constant pressure at radius r_1. According to Eq. 3, the expected velocity is proportional to $\left[(r-r_1)/(r^4\ln(r/r_1))\right]^{1/3} \sim r^{-4/3}$. The event density in the upward direction is symmetrical about the center in the middle. Our modeling shows good agreement with the observed growth of the seismicity cloud. In contrast to Phase I, no significant back-front is theoretically predicted for low-pressure injections after the inflow has stopped.

Overall, our results suggest that the overpressure driving the swarm was generated by the subsequent ascent of fluid batches from depth, which were silent and undetected in the ductile lower crust but induced seismicity after entering the brittle part of the crust and interacting with a pre-existing fault zone. The first batch arriving on the fault may have contained a large proportion of low-density CO_2, which has a larger buoyancy and arrives before the second batch consisted of heavier fluids, which ascent slower and with lower overpressure but a larger volume. Therefore, the first phase led to bilateral growth of the activated patch up and down from the high-pressure injection point in the fault, while the second phase emerged from the upper end of the already activated zone and generated hydro-shearing and radial growth of seismicity on the fault (Figure 4).

The final size of the cloud at the end of each phase can tell us about the overpressure at the beginning of the phases. Fluids can rise from great depths as batches of (almost) constant volume. The size of the volume, i.e. the lateral and vertical dimensions, the opening, and the overpressure of the batch, depends crucially on the density of the fluid, the fracture toughness of the rock, and the stresses in the crust. For example, a fluid batch can break away from a deep reservoir and rise if light fractions of the reservoir fluids continuously accumulate under the overburden, generating increasing overpressure at the highest point until the rock fractures and a fluid-filled dike forms and rises. An obvious candidate for the unstable reservoir layer is CO_2 since carbon dioxide can dissolve from melts at great depths. However, the release of a CO_2 package from a reservoir can lead to the subsequent flow of magmatic melts, as the CO_2 has already opened a channel through the crust that is subsequently available for melts to rise. This process can also lead to the cyclical ascent of several fluid packages, as was observed at Reykjanes in 2020 [18]. Another process to explain the episodic ascent of melt batches together with CO_2 is carbonatite metasomatism [19].

(1) What is the state of the fluids?
What happens if lithostatic pressure decreases? (when)

(2) What is "low-density CO_2" at mid-crustal level?

(3) Why "heavier"? Why not CO_2 rich fluid under lower overpressure?

not yet clear to me ?

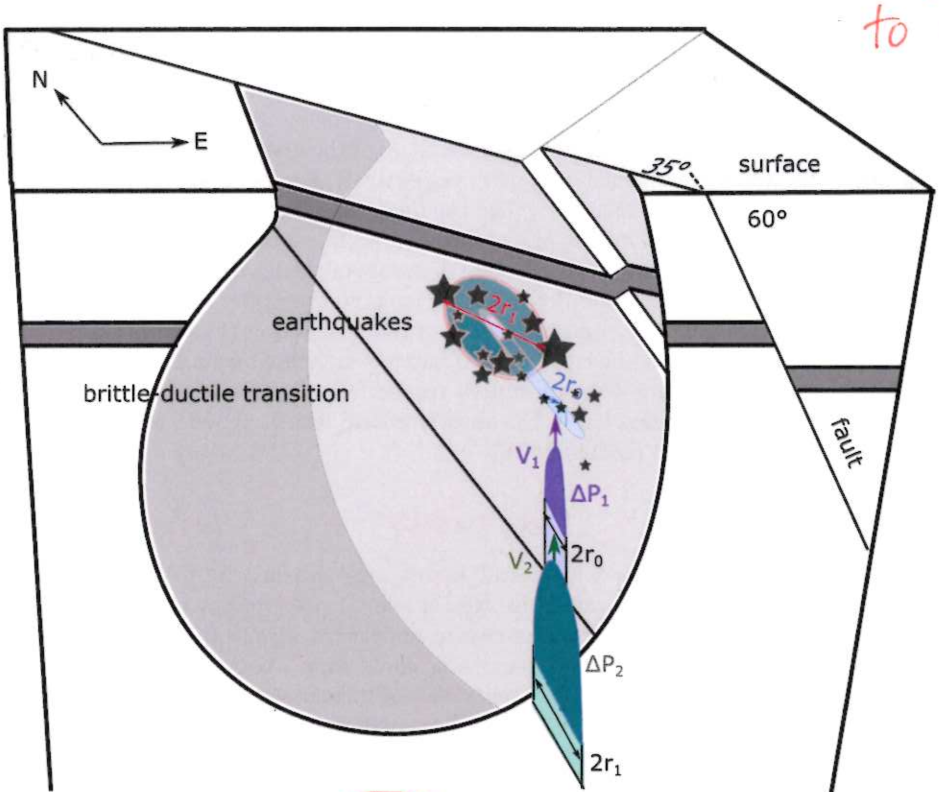


Fig. 4: Sketch of a subsequent cyclic intrusions into a pre-existing fault inducing the KK swarm. The smaller batch (Phase I) arrives first and has a larger overpressure ΔP_1. The batch feeding Phase II of the swarm has a larger lateral size $2r_1$, a smaller overpressure ΔP_2, and a smaller ascent velocity v_2. Both the small overpressure in Phase II and the small density-related buoyancy facilitate hydro-shearing in the fault zone, triggering larger earthquakes.

right term? circular ?

magnitude differences ?

The size and shape of such fluid batches are self-similar and depend only on the density difference between the fluid and the surrounding rock, $\Delta\rho$, and the fracture toughness K_c [13, 20]. The overpressure in the batch is a linear function of depth z given by $P = P_0 + \gamma z$, where P_0 is the overpressure at the center of the batch and γ is the gradient, $\gamma = \Delta\rho g$, with g being the gravitational acceleration. For a critical 3D batch, the batch size and the gradient are related by $\gamma = \sqrt{\pi} K_c / \left(4r^{1.5}\right)$, where $r \approx 3a/4$, and a and r are the vertical and lateral half-widths of the ascending 3D batch, respectively [13, 20].

→ (1)

We propose that the lateral extent of the seismic cloud in Phase I and II, $r_0 = 200$ m and 900 m, respectively, resembles the lateral extent of the ascending fluid batch prior to contact with the fault. From this, the density difference of the trapped fluid can be

(phases)

how it migrated towards the fault ?
→ not along the fault ??

(1) density of surrounding rock changes throughout the crust (along the pathway). how this could influence the process ?
→ function not linear anymore
what about change from lithostatic to hydrostatic pressure regime ?

estimated by

$$\Delta\rho \approx \frac{\sqrt{\pi}}{4g}\frac{K_c}{r_0^{3/2}}$$

Assuming $K_c \approx 100\,\mathrm{MPa\,m^{1/2}}$, the density differences of the first and second phase are estimated to be $1597\,\mathrm{kg\,m^{-3}}$ and $176\,\mathrm{kg\,m^{-3}}$, respectively. For example, if the density of the granitic host rock is $2800\,\mathrm{kg\,m^{-3}}$, then the fluid densities in the first and second batches are $1200\,\mathrm{kg\,m^{-3}}$ and $2632\,\mathrm{kg\,m^{-3}}$, respectively. The lower buoyancy in Phase II can also be seen in the different distribution of events in the up-dip direction. While the distribution of Phase I is asymmetric with a focus in the upper region, the event density in Phase II is almost symmetrical in the up-dip direction (Figure 2).

The static overpressure at the tip of the 3D batch is estimated from $\Delta P = 2r_0\Delta\rho g$ at $\approx 6\,\mathrm{MPa}$ and $\approx 3\,\mathrm{MPa}$ for Phase I and II, respectively. It represents a minimum overpressure because the rising batch has an overcritical length. 3 MPa is typical for hydro-shearing in numerical modeling [21].

Conclusions

The 2024 Klingenthal-Kraslice mid-crustal earthquake swarm, the first significant seismic activity at this location after decades of silence, exemplifies mantle-derived fluid-induced seismicity. The earthquake swarm underwent an unexpected evolution from a bilateral to a radial growth of the seismic cloud over a period of 70 days. The centroid moment tensors of $M_W > 1.2$ events manifest shear stress release during the second phase of the swarm, suggesting the activation of a previously unidentified normal fault in the region. The fit of a hydro-fracture model reveals the role of magmatic fluid ascent in generating seismicity. Magmatic fluids in the NW Bohemia/Vogtland swarm region develop and accumulate in the upper mantle, at the crust-mantle boundary, and possibly in the lower crust. If such a deep reservoir becomes unstable, fluid batches may separate and ascend further through the crust. When they encounter the brittle-ductile boundary, the buoyancy-driven fluid batches can form classical dike or sill-type intrusions or interact with pre-existing fault zones, causing opening and co-seismic shearing along the faults. The process is typically accompanied by swarms of micro-earthquakes, where the gradual release of overpressure controls the migration and seismicity pattern in a pre-existing fault under shear.

Our analysis suggest that such fluid-fault interaction occurred during the KK swarm and caused the three months of intense earthquake activity. Fluid overpressure was acting in both seismic phases, but Phase I was characterized by a larger overpressure associated with a higher buoyancy force in the ascending fluid batch containing fluids with a smaller average density, likely related to a high water- and CO_2-content. This first phase is characterized by a bilateral, sub-vertical crack growth within a previously unknown normal fault. In Phase II, the density difference between intruded fluids and host rock is smaller, possibly explained by the influx of melts, and the seismicity grows radially over a broader area. The intruding fluids are still assumed to rise because of buoyancy. However, the realized overpressure is smaller than the least deviatoric stress, leading to hydro-shearing of the pre-existing fault, generating larger magnitude earthquakes.

This work advances the understanding of fluid-induced seismicity, its impact on fault reactivation, stress redistribution, and unusual fluid-melt-fault interaction. The findings provide valuable insights into the dynamics of earthquake swarms in magmatically active regions and may aid in the monitoring and prediction of similar seismic phenomena.

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Methods

Earthquake detection and localization

We generated the earthquake catalog using *Qseek*, an automatic waveform-based earthquake detector and locator, as detailed in [22]. *Qseek* combines seismic phase arrival annotations provided by neural network phase pickers and waveform stacking with an efficient adaptive octree search. The resolution of the search volume is iteratively refined toward the seismic source location, enabling fast and accurate detection. Moment and local magnitude calculations from peak ground motions are included [23]. Location accuracy is further enhanced by incorporating station-specific corrections (SST) and source-specific station terms (SSST). The method has been validated for multiple large seismic datasets across various regions and geological settings [18, 22].

The seismic catalog was created using the local velocity model from [24], which is a modified version of the model in [25]. Waveform data were sourced from three borehole

↳ which stations were used for the study?
↳ list + map
= Data, not Method

(explanation) +BW?

arrays (6A.LWS00, 1D.TIS00, 1D.STC00) of the ICDP Eger virtual network, along with surface stations operated by WEBNET, SXNET, and TSN (Thuringia Seismic Network), as described in the Data Availability section.

Centroid moment tensor inversion

We applied moment tensor inversion to earthquakes with $M_W > 1.2$ for the 2024 KK swarm (Figure 1) using a joint inversion of waveform and first motions [18]. Uncertainties were estimated using a Bayesian bootstrap approach implemented in the open source software *Grond* [26], which combines nonlinear inversion and bootstrapping. documented?

The source model parameterization includes centroid location, depth, time, moment tensor components, and optional source duration. Green's functions (GFs) were precomputed using *Qseis* [27] for a sampling rate of 100 Hz, covering distances of 0-80 km and source depths of 7-13 km with 100 m spacing, based on the velocity model of [24]. Theoretical travel times and phase polarities were calculated using the Pyrocko *Cake* tool [28]. The inversion minimizes the L1 norm misfit between observed and synthetic data [29], balancing weights for signal amplitude, source-receiver distance, phase type, and data type.

Waveforms were inverted in time windows of ±0.25 s around P- and S-wave arrivals in the time domain, with shifts of ±0.15 s allowed for synthetic traces. Approximately 4,000 manually verified P- and S-wave arrivals were used, with a frequency range of 1.0-3.0 Hz. After 100,000 iterations, 64 earthquakes with robust centroid locations, low misfits, and sufficient azimuthal coverage were selected for further interpretation (Figure 1). Full waveform fits are available as online reports and interactive web-based visualizations (see Data Availability).

Temporal changes in v_P/v_S ratios in the swarm volume

The double difference Wadati method has been developed independently by [30] and [10] to estimate $\gamma = v_P/v_S$. The traditional Wadati diagram uses the arrival time difference between the S- and P-wave, $t_S - t_P$ plotted over t_P, for all stations recording the event, which linearly depends on γ and the origin time of the event. Averaging γ for many events provides an average ratio of the crust beneath the seismic network. A modified Wadati diagram plots all combinations of the station-wise difference between S-wave arrivals and P-wave arrivals, which depends only on γ and is independent of the origin time of the event. Therefore, picks from multiple events can be easily stacked. A third approach to stack multiple events was suggested in [10].

In order to derive γ representative for the source volume of the earthquake swarm, we calculate time differences between P-wave arrivals at each station for pairs of events. The same for S-wave arrivals. These double differences are then used with either of the three introduced methods, final plots are based on [10].

The challenge of the double difference Wadati approach is to have precise pick times available with an accuracy below 0.05 seconds, in order to resolve variations in arrival time differences over a path length of 1-2 km. In our case, we take advantage of the high sampling rate, which is 1000 Hz at the three borehole chains in Landwüst, Tisova and Studenec, and 250 Hz on all WEBNET stations. Arrival time differences were

map/table?

- all not really documented, e.g. by figures
- what are the uncertainties

calculated by waveform cross-correlation. Additionally, outliers were strictly removed based on the analysis of the regional Wadati approach.

Hydro-fracture model for bilateral and radial growth

Fluid-induced seismicity in faults is modeled either by hydraulic fractures or pore pressure diffusion in the fracture zone. Hydro-facture models have mostly been developed for controlled injection experiments, for example, in cases where fluids are injected into the rock at a constant downhole pressure or flow rate from a sealed wellbore. In our case, we are dealing with natural injections when an ascending fluid batch hits or intrudes a fault. Natural fluid ascent is a well-studied phenomenon. Constant-volume batches ascend when their radial or vertical length exceeds a critical threshold, depending on the density difference $\Delta\rho$ between the fluid and the surrounding rock and the fracture toughness K_c. During ascent, their shape, volume, and tip overpressure ΔP are conserved [e.g. 13]. If the batch encounters a fault with lower fracture toughness, the fluid will intrude into the fault. The injection pressure is initially high until most of the volume in the upper, thicker part of the batch is intruded. To simplify the problem, we assume a constant injection pressure during the initial intrusion phase. (references?)

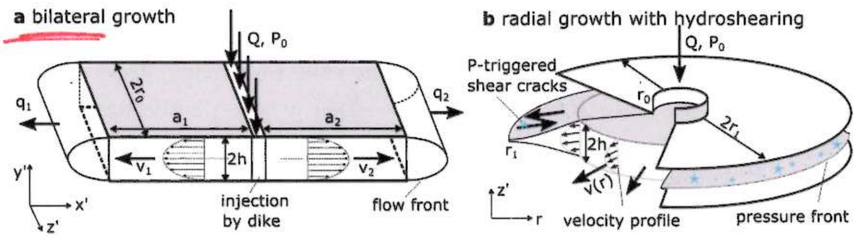


Fig. 5: **a** Bidirectional crack growth by fluid injection with high overpressure and buoyancy, and **b** radial growth under low overpressure and buoyancy, leading to hydro-shearing in the tip region of the penny-shaped crack. For simplified analysis, cracks are replaced by theoretical models with constant half-width h. Crack growth is considered quasi-static, where crack size is associated with the fluid or pressure front, respectively.

We study and compare hydro-fracture models and directed pressure diffusion for bilateral and circular growth. Both models assume that the fluid overpressure in the fracture zone spreads slowly from the injection zone (point x_0 or injection radius r_1) (Fig. 5). The front of seismicity spreads with the pressure front and fracture tip. While hydraulic diffusion models often assume a constant permeability in the fracture zone, hydraulic fracture models consider the change in permeability (crack thickness) as the crack grows. The bilateral growth model [14] (Fig. 5a) assumes laminar viscous flow within the crack with time- or length-dependent opening. The model is suitable when the overpressure is so large that the mode I stress intensity factor exceeds K_c. The circular growth observed in Phase II occurred dominantly at low overpressure and grows by shear motion induced by increased pore pressure, known as hydro-shearing

(1) see comments above, Bidirectional seems to be a better term, compared to Bilateral
see also [14]

(Fig. 5b). In both fracture models, we assume that pressure is suddenly "increased" at a specific point, line, or radius, and the fault opening and shearing start growing from this point bilaterally or radially.

Bilateral flow in a rectangular channel:

In the bilateral fracture model, the laminar fluid flow in the growing crack is controlled by the (over-) pressure at the injection point, the average half-thickness of the crack, h, the fracture toughness K_c, and the geometry of crack growth (curvature of the crack tip line). If an effective stress gradient γ is present, the growth may additionally be asymmetric. The over-pressure at the injection point is large at the beginning of crack growth, and zero when growth stops. In between, the over-pressure function is largely unknown. For simplicity, we divide the pressure function into two regimes: (1) a constant over-pressure P_0 during the injection phase (constant 2D flux Q), and zero over-pressure during after-growth. If an effective driving stress gradient exists, unilateral growth can develop after injection. We assume an injection line source at the center. During the injection phase, the steady-state viscous flow is described by laminar Hagen-Poiseuille flow with total volume flux Q and the mean velocity [14] (1)

$$v = \mp \left[\frac{Q^2}{48\eta} g^{\text{eff}}\right]^{1/3} . \tag{1}$$

Here, η is the intrinsic permeability and g^{eff} is the effective driving stress gradient, $g^{\text{eff}} = \gamma + \partial P/\partial x = \gamma + (P_a - P_0)/a = -\frac{\pi}{2a}\left(P_0 - \frac{K_c}{\sqrt{\pi a}}\right)$, where γ is the static driving stress gradient (e.g. buoyancy, $\Delta\rho g$, or an external stress gradient), P_0 is the injection pressure, and P_a is the pressure in the channel at length a from the injection point.

Although the solution represents a steady-state flow, it can be used to approximate the slow crack growth for hydro-fracture experiments. Therefore, we assume that the hydro-fracture has a time-dependent length a that increases with velocity v so that the laminar flow behind is not disturbed. Such a process requires that the pressure at the tip of the fracture wing adjusts such that for each instantaneous time the stress intensity $K^{\pm}$ at the crack tips in both wings equals the fracture toughness K_c of the rock. As shown in [14], the asymmetric growth velocity $v_{u/d}$ of the two wings during the injection phase from time t_1 to t_2 can be equated by

$$v_{u/d}(a) = \pm v \left[1 \pm \frac{g}{g^{\text{eff}}}\right] \text{ with } v = \left[\frac{Q^2}{96\eta}\frac{\pi}{a}\left(P_0 - \frac{K_c}{\sqrt{\pi a}}\right)\right]^{1/3} . \tag{2}$$

The back-front of seismicity develops after the injection stops when the over-pressure in the fracture re-organizes into a linear function with depth. With further growth at the longer wing, the point of maximal opening migrates together with the crack tip and marks the seismicity back-front behind which the Coulomb stress in the surrounding rock reduces and no longer increases.

(1) You use γ in two different ways in the manuscript. That is a bit not so good.

Low-pressure injection leading to radial diffusion and hydro-shearing:
The pressure function from injection with pressure P_1 at radius r_1 and constant total flux Q into a confined aquifer with half thickness h is described by the Thiem equation, where $P(r) - P_1$ varies logarithmically with radial distance $\ln(r/r_1)$. The functional form is similar to the problem of radial flow between two parallel disks.

Using the same concept of a quasi-static growth of the fractured, penny-shaped area on the fault growing together with the pressure front and considering the stress intensity factor of a penny-shaped crack, the growth velocity can be described by

$$v(r) \approx \left[\frac{Q^2}{12\pi^3 \eta} \frac{(r - r_1)}{r^4 \ln \frac{r}{r_1}} \left(P_1 - \frac{\pi}{2} \frac{K_c}{\sqrt{\pi r}} \right) \right]^{1/3} \quad \text{for} \quad r > r_1 \,. \tag{3}$$

Note that the total flux has a unit of m^3/s. The time needed to fracture a radius r_x is calculated by the integral $t(r_x) = \int_0^{r_x} v^{-1} dr$.

Supplementary information. Supplementary information can be found here: Supplementary Information (supplement.tex file)

Acknowledgments. This work utilized high-performance computing resources made possible by funding from the Ministry of Science, Research and Culture of the State of Brandenburg (MWFK). It is operated by the IT Services and Operations unit of the Helmholtz Centre Potsdam. for Geosciences.

Declarations

Funding

We acknowledge the funding of the borehole and surface array by ICDP (ICDP-EGER project). Additional stations were built in the framework of the Central European Volcanic rovince Observatory (CVO) of GFZ. PB was funded by the DFG project "Characterizing source properties of NW Bohemia/Vogtland earthquake swarms exploiting novel network and waveform processing tool (Chasing)", BU4346/1-1, project number: 517982028.

Conflict of interest

The authors have no conflict of interests.

Data availability

The seismic data used in this study are available from FDSN (TH; Thüringer Seismologisches Netz (TSN), SX; SXNET Saxon Seismic Network, BW; BayernNetz (BW)). The online resulting reports of each earthquake resolved by moment tensor inversion can be interactively accessed via the link https://data.pyrocko.org/publications/grond-reports/2024-klingenthal.

What about Czech data providers and stations?

doi for station networks? references?

Code availability

The software used are all open-access. The earthquake detection and localization framework "Qseek" can be found under the link (https://pyrocko.github.io/qseek). The probabilistic source inversion method with the Grond framework is available at the link (https://pyrocko.org/grond) under the Pyrocko environment (https://pyrocko.org). The maps are prepared using the pyGMT, (https://www.pygmt.org, GMT ([31], Python (http://www.python.org), MatPlotLib (https://matplotlib.org) visualization packages and QGIS software (https://www.qgis.org). This work utilized high-performance computing resources made possible by funding from the Ministry of Science, Research and Culture of the State of Brandenburg (MWFK). It is operated by the IT Services and Operations unit of the Helmholtz Centre Potsdam.

Author contribution

Conceptualization: P.B., T.D.; **Data curation:** M.P.I., M. O., J.D., S.F.; **Formal analysis:** P.B., M.P.I., S.W.; **Funding acquisition:** P.B.; **Investigation:** P.B., T.D., S.H., S.W.; **Methodology:** P.B., M.P.I.; **Project administration:** P.B.; **Resources:** ; **Software:** P.B., M.P.I.; **Supervision:** ; **Validation:** P.B., T.D., S.H.; **Visualization:** P.B., T.D., S.H.; **Writing – original draft:** P.B., T.D.; **Writing – review & editing:** P.B., T.D., M.P.I., S.H., M. O., J.D.

Supplementary Information
Revived Earthquake Swarms: The Role of Magma in NW Bohemia/Vogtland

Pinar Büyükakpinar[1*], Torsten Dahm[1,2], Sebastian Hainzl[1,2], Marius Isken[1], Matthias Ohrnberger[2], Jana Doubravová[3], Siegfried Wendt[4], Sigward Funke[5]

[1*]Physics of Earthquakes and Volcanoes, GFZ Helmholtz Centre for Geosciences, Potsdam, Germany.
[2]Institute for Earth and Environment, University of Potsdam, Potsdam, Germany.
[3]Institute of Geophysics, Czech Academy of Sciences, Prague, Czech Republic.
[4]Geophysical Observatory Collm, Institute for Earth System Science and Remote Sensing, Leipzig University, Leipzig, Germany.
[5]Institute for Earth System Science and Remote Sensing, Leipzig University, Leipzig, Germany.

*Corresponding author(s). E-mail(s): pinar@gfz.de;
Contributing authors: torsten.dahm@gfz.de; hainzl@gfz.de; isken@gfz.de; Matthias.Ohrnberger@geo.uni-potsdam.de; doubravka@ig.cas.cz; wendt@rz.uni-leipzig.de; sfunke@uni-leipzig.de;

The Supplementary Information contains two additional figures (Figs. S1 and S2) that provide further detail and support the interpretations presented in the main text.

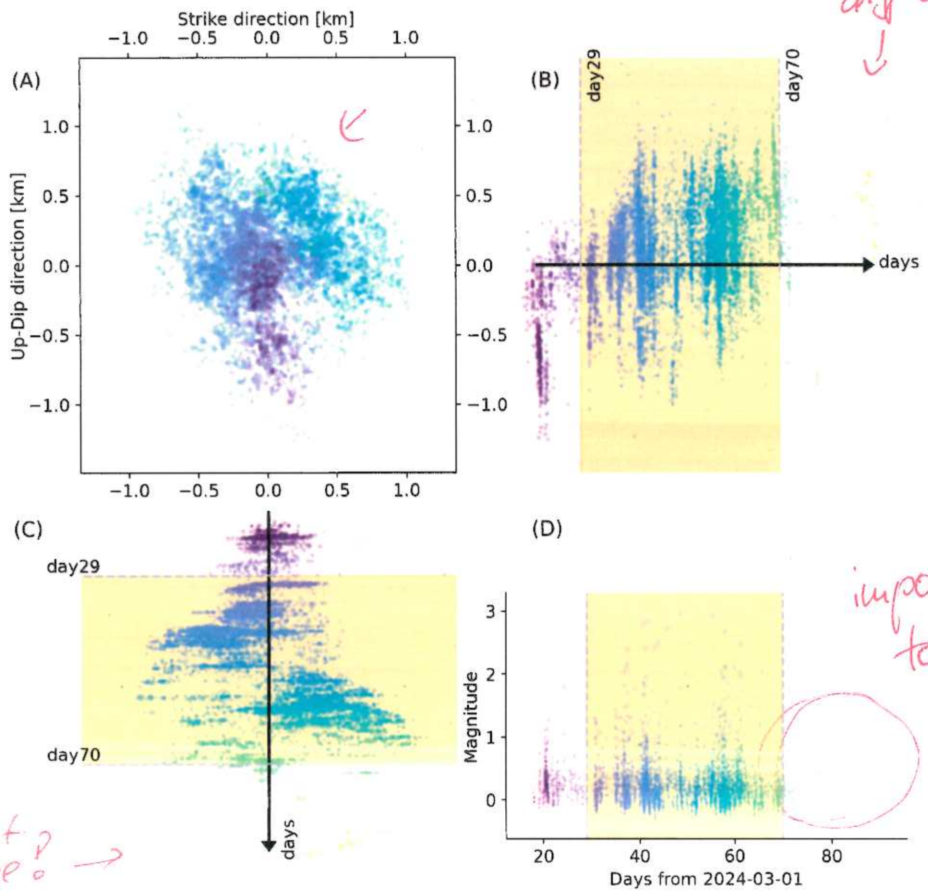


Fig. S1: Spatiotemporal and magnitude distribution of seismicity. (A) Hypocenter locations projected onto the fault plane, showing the up-dip versus strike directions. (B) Temporal evolution of events along the strike direction overlaid with highlighted time windows (pink and yellow shading indicate the first 29 days and the subsequent 29–70 days, respectively). (C) Temporal evolution of events along the up-dip direction, emphasizing the same time windows. (D) Magnitude distribution as a function of time, with the same highlighted intervals.

difficult to see

impossible to see

difficult to see? →

add "phase 1" "phase 2"

→ add movie to better illustrate
→ expand color scale to improve visibility

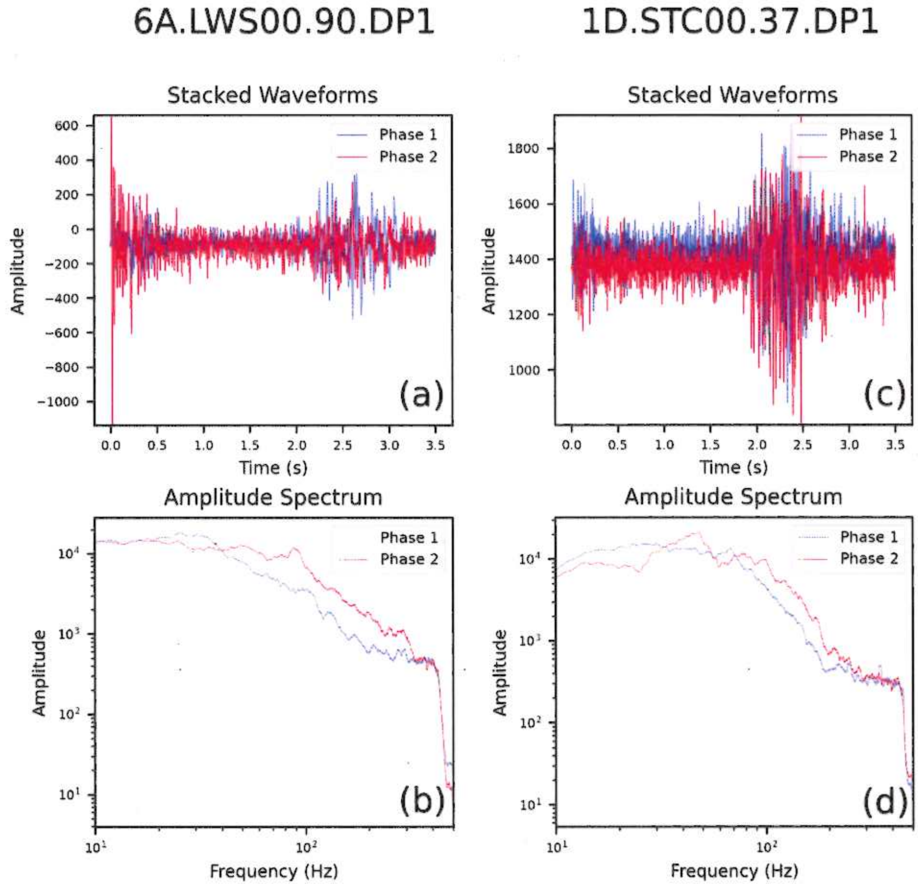


Fig. S2: Stacked waveforms and amplitude spectra for two different seismic stations. (a) and (b) correspond to station 6A.LWS00.90.DP1, while (c) and (d) correspond to station 1D.STC00.37.DP1. The top panels (a, c) display the stacked waveforms for Phase 1 (blue) and Phase 2 (red) over a time window of 3.5 seconds. The bottom panels (b, d) show the corresponding amplitude spectra, illustrating the frequency-dependent amplitude variations for the two phases. ‖ (1)

location of stations?

- uncertainties (variations within the individual phases)?
- differences for P and S waves? (different Q)

(1) all events, not considering different magnitudes?

Modelling of earthquake swarms indicates magmatic fluids in the Upper Crust Beneath the Eger Rift

Pınar Büyükakpınar[1*], Torsten Dahm[1,2], Sebastian Hainzl[1,2], Marius Isken[1], Matthias Ohrnberger[2], Jana Doubravová[3], Siegfried Wendt[4], Sigward Funke[5]

[1*]Physics of Earthquakes and Volcanoes, GFZ Helmholtz Centre for Geosciences, Potsdam, Germany.
[2]Institute for Earth and Environment, University of Potsdam, Potsdam, Germany.
[3]Institute of Geophysics, Czech Academy of Sciences, Prague, Czech Republic.
[4]Geophysical Observatory Collm, Institute for Earth System Science and Remote Sensing, Leipzig University, Leipzig, Germany.
[5]Institute for Earth System Science and Remote Sensing, Leipzig University, Leipzig, Germany.

*Corresponding author(s). E-mail(s): pinar@gfz.de;
Contributing authors: torsten.dahm@gfz.de; hainzl@gfz.de; isken@gfz.de; Matthias.Ohrnberger@geo.uni-potsdam.de; doubravka@ig.cas.cz; wendt@rz.uni-leipzig.de; sfunke@uni-leipzig.de;

Abstract

Earthquake swarms are enigmatic seismic phenomena that occur across diverse tectonic settings, from volcanic to intraplate regions, and are often associated with fluid migration, magmatic activity, or stress redistribution. The Northwest Bohemia/Vogtland region is a globally recognized hotspot and natural laboratory for such activity. This study examines the recent reawakening of an earthquake swarm in the region after a century of dormancy. By integrating high-resolution seismicity patterns and earthquake source mechanisms with models of fluid migration, we provide a detailed reconstruction of the swarm's temporal and spatial evolution. Our seismicity modeling indicates the activation of a pre-existing fault by natural hydro-fracturing and hydro-shearing under the influence of ascending magmatic fluids, beginning with a high-pressure $\mathbf{CO_2}$-rich fluid intrusion, followed by transitions to low-pressure hydro-shearing on the fault, likely associated with $\mathbf{CO_2}$ magma mixtures. Our results emphasize the pivotal role of fluid overpressure and fault zone weakening in controlling swarm dynamics.

Main

Located within the Bohemian Massif, one of the largest outcrops of Variscan basement in Europe, the Northwest Bohemia/Vogtland region (Figure 1) hosts one of the most active seismic zones in Central Europe. This region is where the term "earthquake swarm" was first introduced [1], highlighting its significance in seismology. Persistent seismic activity makes this region a key site for swarm studies. In addition, widespread carbon dioxide (CO_2) emissions associated with magmatic crustal underplating provide an exceptional natural laboratory for investigating interactions between tectonics, magmatism, and fluid migration. The Cheb Basin, situated at the intersection of the Eger Rift and the Mariánské Lázně Fault Zone (Figure 1), is the center of seismicity and gas emissions [2] and is characterized by elevated heat flow, alkaline volcanism, and five Quaternary volcanoes [3]. Since 1985, an NS trending zone crossing Nový Kostel (NK) (Figure 1) has episodically produced swarms with the largest seismic moment release in the entire region [4]. However, in March 2024, an intense seismic swarm emerged in the Klingenthal-Kraslice (KK) zone northeast of NK, after 125 years of rest [1]. This marks a striking shift in regional seismicity, raising key questions about its underlying mechanisms.

The mid-crustal earthquake swarms are commonly attributed to fluid transfer from the upper mantle and pore pressure perturbations [5]. However, the relative roles of magma, CO_2, and their interaction with water and rock in triggering swarms and driving upper crustal deformation remain less understood. The new KK swarm began in December 2023 and peaked during the March–May 2024 period. Since then, seismic activity has generally subsided, though intermittent bursts continue. It stands for the first significant earthquake swarm near Klingenthal-Kraslice since 1897 [1], which developed into a phase of strong earthquakes distributed over the entire Vogtland swarm region from 1900 until 1915 [1, 6–8]. There is only evidence of a weaker swarm earthquake activity near KK in 1994 [9] (Figure 1c). Since the recent activity is the first high-resolution instrumental observation of a massive swarm near KK after a centuries-long hiatus, it provides a unique opportunity to study the spatiotemporal patterns in detail and to compare them with historical swarms.

Our seismic analysis benefits from exceptionally dense observations in close proximity to the swarm, including high-frequency borehole arrays with a sampling rate of 1 kHz (Figure 1 and Figure S1). By combining seismicity and seismic source studies with fluid intrusion models, we identify a transition from highly buoyant fluids at high overpressure to less buoyant fluids at lower overpressure, e.g., from CO_2-rich fluids to CO_2-magma mixtures, which cause first hydraulic fractures followed by growth of hydro-shearing on the activated fault. These findings are compared with alternative models and shed light on the crucial role of CO_2-rich magmatic fluids in the formation of recurrent earthquake swarms.

• use different line type for border?

• check the locations of Quat. volcanoes? → Komorni Hurka missing

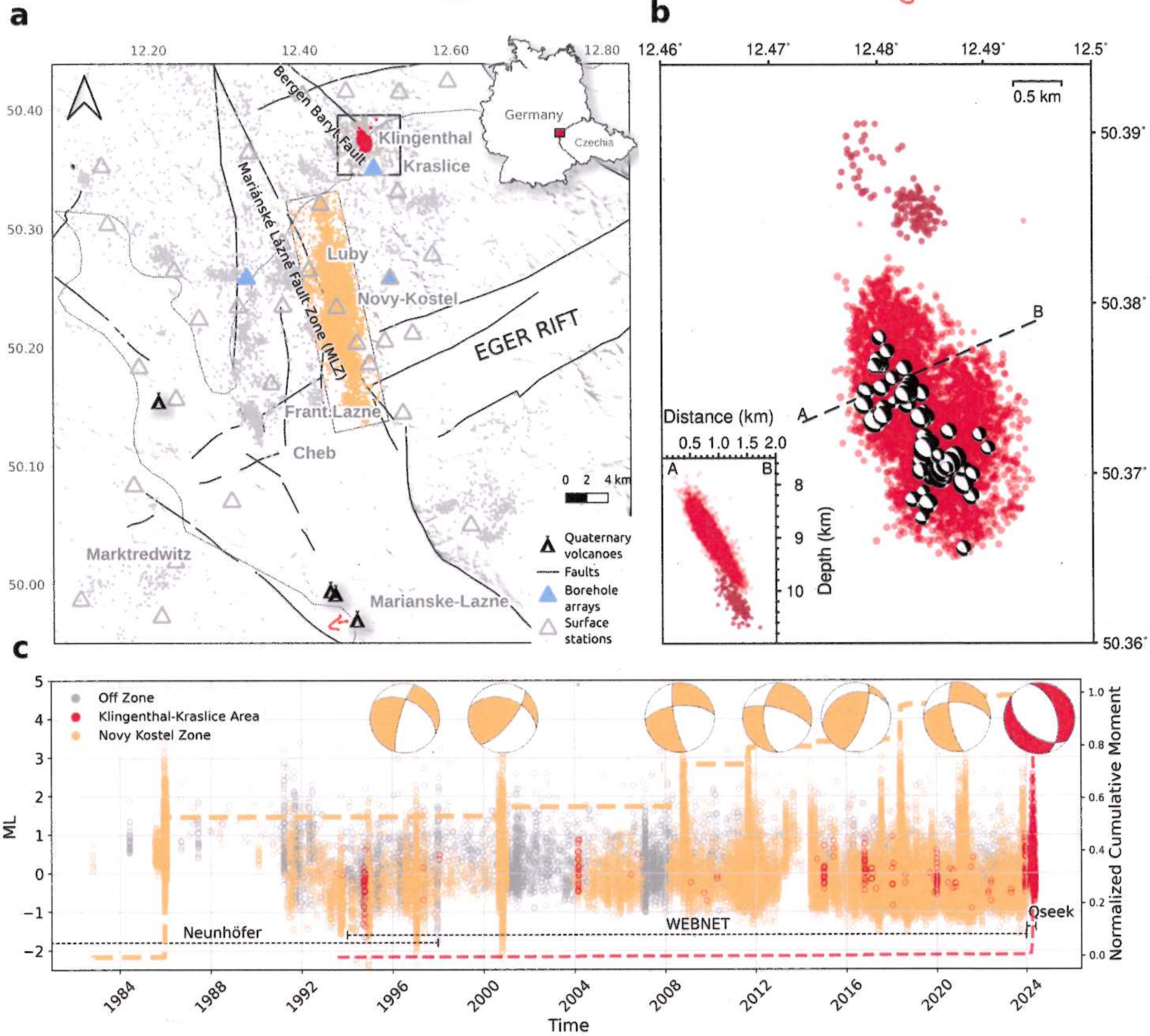


Fig. 1: **a** Regional map showing the tectonic setting and seismic activity from 1982 to 2024. The triangles represent the seismic stations used. The Mariánské Lázně Fault Zone (MLZ) and the Bergen Baryt Fault are marked. The recent swarm activity in the Klingenthal-Kraslice region (red) is defined by the black box, which includes a ±2.5 km buffer around the main cluster to account for location uncertainties, especially when comparing with earlier seismicity. The most prominent seismically active area (Nový Kostel) is also highlighted (orange). **b** A zoomed-in view of the Klingenthal-Kraslice swarm, with centroid moment tensors (CMTs) for events with M_W >1.2 (lower hemisphere projections of double-couple components). The December 2023 activity is marked with dark brown circles, while the main swarm (March–May 2024) is shown as red circles. **c** Temporal variation of seismicity (1982–2024), showing event magnitudes (M_L) and composite moment tensors for larger events from previous studies [10, 11] and this paper. The earthquakes are compiled from three different catalogs: (1) Neunhöfer (1962–1997) [12], (2) WEBNET (1997–2023), (3) *Qseek* (2023–2024), a high-resolution catalog covering 2023–2024, obtained through machine learning (ML)-based detection and analysis method. The indicated regions include the recent Klingenthal–Kraslice swarm (in red; all events located within the black box in panel **a**, the seismically active Nový Kostel area (orange), and off-zone events (gray) outside these highlighted regions. The normalized cumulative moment for the Klingenthal–Kraslice and Nový Kostel regions is shown on the right axis.

dots?
dots?

High-Resolution catalog and moment tensors

In recent years, as part of an International Continental Scientific Drilling Program (ICDP-Eger), a unique network of surface and multiple borehole high-frequency arrays has been established in the study area (Figure 1 and Figure S1), in addition to the existing monitoring networks [13]. The infrastructure is located only a few kilometers from the swarm earthquakes, and the sampling rate is up to 1 kHz, which allows a detailed investigation of subsurface processes such as fluid migration and fault zone dynamics. By integrating this network with ML algorithms, we have built a high-resolution earthquake catalog, recording 8,071 seismic events from December 2023 to June 2024, including the smallest-size events with magnitudes of $M_L = -0.5$. This represents a tenfold enhancement of events resolved in classical agency catalogs and provides unprecedented spatial and temporal resolution. The enhanced dataset specifies fine-scale fault geometries, detects intricate seismicity patterns that were not formerly resolvable, and documents the detailed history of the swarm with high accuracy.

The earthquakes, confined in a narrow NW-SE trending zone of about 1.2 km width and 2 km length, show systematic spatiotemporal migration patterns. To investigate the source mechanisms, we computed centroid moment tensors (CMT), the first for this region, using a Bayesian inversion approach [10, 14, 15]. We obtain 64 CMT solutions for events with $M_W > 1.2$. This approach accounts for uncertainties, providing robust estimates of the fault characteristics (see the Methods section). The solutions reveal the activation of a previously unrecognized fault segment, predominantly normal faulting, with strike = 329° ± 27, dip = 60° ± 6, and rake = -62° ± 12 (Figure 1b) aligning with the spatial extend of the swarm, likely influenced by localized stress accumulation. This discovery is remarkable because other earthquake swarms in the region, such as at NK, have been dominated in the past by strike-slip and thrust faulting (Figure 1c) [10, 11]). The regional variation of mechanisms and activated faults suggests significant heterogeneity in the stress field, likely influenced by transient deformation, fluid migration, and metasomatic processes within the crust.

Swarm phases

The first micro-earthquakes occurred in December 2023, about 2 km north of the later KK swarm center, at a depth between 10 and 11 km (Figure 1b). These were the deepest events in the entire sequence. After a period of about 3 months, the swarm moved slightly south to shallower depths and exhibited an unprecedented rate of seismicity between March and June 2024. Since then, the activity has been greatly reduced, but micro-earthquakes occasionally occur for a few days. Figure 2 illustrates the spatiotemporal and magnitude distribution of all events and the CMT results for the earthquakes $M_W > 1.2$, revealing two distinct temporal phases with contrasting seismicity patterns (Figures 2 and S2).

Figure 2a highlights the spatiotemporal distribution of events projected onto the strike and up-dip directions. The activity starts at (0, -0.5) km and progressively extends, first bidirectional in up- and down-dip directions (Phase I), and later radial with a central point at (0,0) (Phase II). After two months of activity, the distribution forms an almost circular cluster with slight asymmetry along the strike axis.

The magnitude versus time plot in Figure 2 reveals distinct episodic bursts of activity. The two main phases, Phase I and II, are marked by the vertical dashed lines and shading. Smaller magnitudes dominate the initial Phase I of bidirectional growth in up- and down-dip direction in the fault until March 29, corresponding to the early stages of fault activation. As the growth mode of the swarm becomes radial in Phase II, larger magnitudes emerge.

project ? (1) (2) focal area year ?

(1) abbreviation introduced before → necessary? (unfortunately ML also stands for the local magnitude)
(2) in principle yes, for specific swarms such low magnitudes were reported by manual data analysis automatic procedures reduced sensitivity late oc

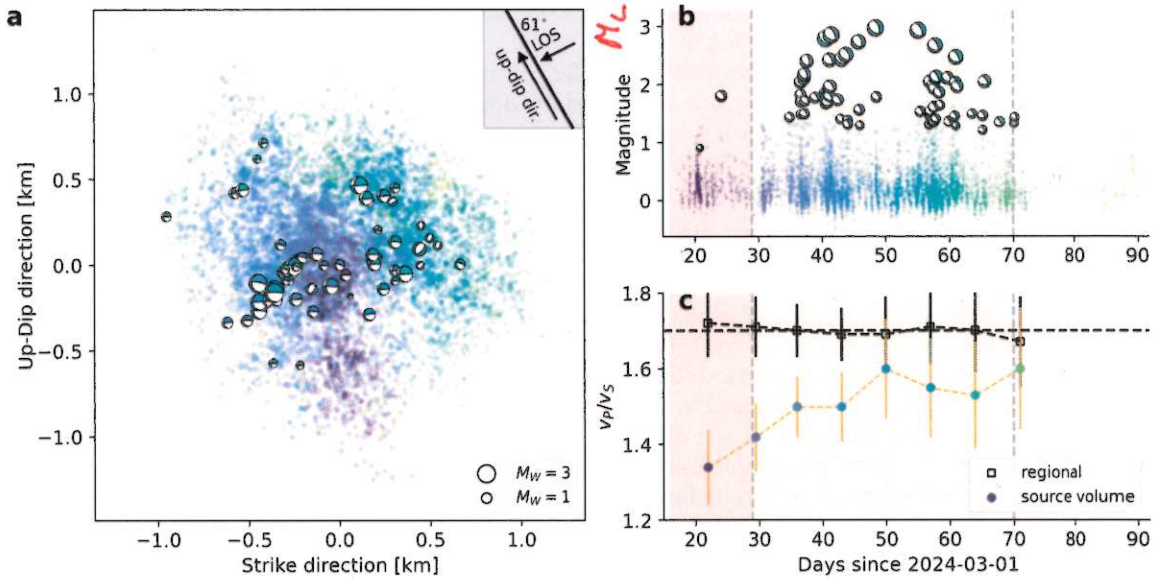


Fig. 2: Spatiotemporal characteristics of the swarm and CMT inversion results. Panel **a** displays the spatial distribution of events projected onto the strike and up-dip directions, forming an elliptical cluster along the fault plane. M_W of moment tensors is indicated in the legend; *Qseek* magnitudes scale non-linear to enhance the visibility of small events. Colors are related to the occurrence times in panel **b**, which shows temporal clustering and magnitude evolution, with dashed lines and background shading marking distinct phases linked to rupture dynamics. Panel **c** compares the regional and source volume v_P/v_S as a function of time. Uncertainties are plotted as vertical bars. The dashed line indicates a reference ratio of 1.7. The pink and yellow shaded areas indicate the first 29 days in March and the subsequent 29–70 days, corresponding to Phase I and II, respectively.

Interestingly, the ratio of P- to S-wave velocity (v_P/v_S) reflects the different phases (Figure 2c). We use a double-difference Wadati method [16] in moving windows to distinguish v_P/v_S at the activated fault (source) and averaged over the path between the swarm and seismic stations (regional). While the regional v_P/v_S remains constant at 1.7 over the course of the swarm, the source-related v_P/v_S is strongly reduced in the initial phase of the swarm and returns to background values during Phase II. Such behavior has been observed for NK swarms before [e.g., 16, 17], or during dike intrusions on Reykjanes Peninsula in Iceland [18], and may be explained by the flushing of newly formed pore space close to the intrusion with gaseous fluids in the initial phase of a swarm, which gradually diffuses away over periods of days and weeks.

The reduced v_P/v_S ratios in the early phase of the swarm correlate with a change in the relative corner frequencies, or stress drops, between earthquakes during Phases I and II. Earthquakes of, e.g., $M_L = 0.7-0.8$ have smaller corner frequencies—i.e., lower stress drops— during Phase I than during Phase II (Figure S3). This analysis is based on the largest events that are available within Phase I, as magnitudes were typically small during that phase. The same magnitude range was also used in Phase II to ensure a consistent comparison. Both full waveform analyses and independent spectral analyses of the P and S waves support the consistent variations in corner frequency between the two phases. An anti-correlation between stress drops and pore pressure has been previously reported for the hydraulic stimulation in Basel [19]. This refers to a higher pressure in Phase I than Phase II, which could indicate that shearing was prominent during Phase II, while opening or hydro-fracturing acted during Phase I.

Hydro-fracture model for bidirectional and radial growth

The first occurrence of earthquakes at greater depths and the subsequent bursts of activity and phases at shallower depths between March and June 2024 indicate that fluids rising from greater depths may have triggered the activity. The reduced v_P/v_S ratios in Phase I of the 2024 swarm indicate a temporary reduction in P-wave velocities in the source region, and the increase in corner frequencies between Phase I and II suggests that the initial Mode I ruptures were increasingly overwhelmed by shear ruptures. This and the spatio-temporal patterns of the swarm phases can be discussed in the context of pore pressure diffusion [e.g. 20, 21] and hydro-fracture models [e.g. 22].

Hydro-facture models have mostly been developed for controlled injection experiments, for example, in cases where fluids are injected into the rock at a constant downhole pressure or flow rate from a sealed wellbore. Few natural processes are known to generate overpressure, the most important being geochemical process chains during metasomatism, e.g. in the vicinity of carbonatitic melts [e.g., 23], or physical buoyancy effects in closed fracture networks when fluids have lower densities than the host rock. Estimating the overpressure in natural systems at 10 km depth seems challenging at first sight. However, if injection-like processes are observed, we can base our estimate on laboratory experiments for buoyant fluid injections, e.g. in brittle gelatin [e.g., 24, 25]. With increasing injected volume, e.g. in the fault beneath KK, an initially penny-shaped circular fracture becomes vertically elongated until the overpressure at its upper tip is sufficient to propagate the fluid-filled fracture further upwards. After that, the fracture will not increase in lateral width and will only grow upward. Therefore, the lateral width of a fracture, together with the fracture toughness of the rock, can be used to estimate the first-order overpressure at the tip.

The static overpressure at the tip of the 3D batch is given by $\Delta P = 2r_0 \Delta\rho g$, where $2r_0$ is the lateral width of the fracture, g is the gravitational acceleration, K_c is the fracture toughness, and $\Delta\rho$ is the density difference between the fluid and the surrounding rock, which itself can be related to K_c and r_0 by [equation A2 in 25, setting $P_g = \Delta\rho g$]

$$\Delta\rho \approx \frac{\sqrt{\pi}}{4g}\frac{K_c}{r_0^{3/2}}.$$

The volume of the fluid entrapped in a buoyant 3D fracture is $V = \frac{4}{3} r A \approx \frac{2(1-\nu)}{G}\frac{K_c r^{5/2}}{\sqrt{\pi}}$ [see appendix in 25], where ν is the Poisson ratio and G the shear modul of the host rock. The measured lateral extent of the seismic cloud is $r_0 = 200$ m in Phase I and $r_0 = 900$ m in Phase II (Figure 3a,b). Assuming $K_c \approx 100\,\mathrm{MPa\,m^{1/2}}$ [e.g. 26], the density differences of the first and second phases are estimated to be $1597\,\mathrm{kg\,m^{-3}}$ and $176\,\mathrm{kg\,m^{-3}}$, respectively. For example, if the density of the deep Eibenstock granite host rock is $2620\,\mathrm{kg\,m^{-3}}$ [see figure 5 in 27], then the fluid densities in the first and second batches are $1020\,\mathrm{kg\,m^{-3}}$ and $2440\,\mathrm{kg\,m^{-3}}$, respectively. With these density differences and the measured lateral extent, the overpressures are estimated at ≈ 6 MPa and ≈ 3 MPa for Phase I and II. The values represent a minimum. They are independent of the question of whether the injection is driven from a self-similar, constant volume fluid batch ascending through the crust, or build-up by metasomatic processes in the contact of melt and rock. The lower buoyancy in Phase II is also reflected in the different distribution of events in the up-dip direction. While the distribution of Phase I is asymmetric with a focus in the upper region (Figure 3a), the event density in Phase II is almost symmetrical in the up-dip direction (Figure 3b).

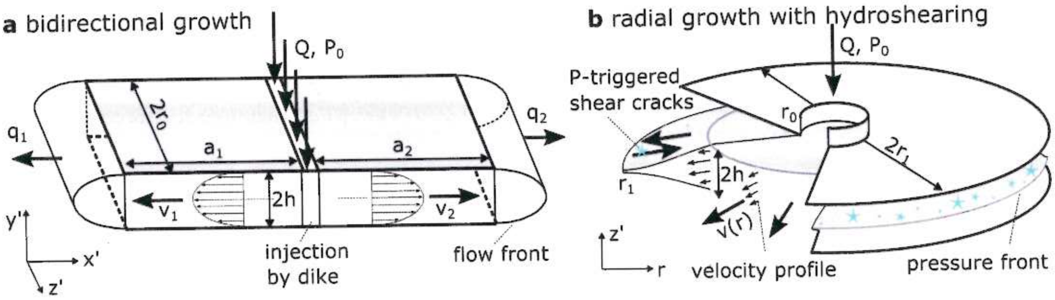


Fig. 3: **a** Bidirectional crack growth by fluid injection with high overpressure and buoyancy, and **b** radial growth under low overpressure and buoyancy, leading to hydro-shearing in the tip region of the penny-shaped crack. For a simplified analysis, cracks are replaced by theoretical models with constant half-width h. Crack growth is considered quasi-static, where the crack size is associated with the fluid or pressure front, respectively.

In the following, we discuss hydro-fracture models and directed pressure diffusion for bidirectional and circular growth in more detail (Fig. 3). Both models assume that the fluid overpressure in the KK fault spreads slowly from the injection zone (point x_0 or injection radius r_0). To simplify the problem, we assume a constant injection pressure during the injection (intrusion) phase. The front of seismicity spreads with the pressure front and the fracture tip. While hydraulic diffusion models often assume a constant permeability in the fracture zone, hydraulic fracture models consider the change in permeability (crack thickness) as the crack grows. The bidirectional growth model [22] (Fig. 3a) assumes a laminar viscous flow within the crack with time- or length-dependent opening. The model is suitable when the overpressure is so large that the mode I stress intensity factor exceeds K_c. A circular growth as observed in Phase II occurs dominantly at low overpressure and grows by shear motion induced by increased pore pressure, known as hydro-shearing (Fig. 3b).

Bidirectional flow in a rectangular channel:

In the bidirectional fracture model, the laminar fluid flow in the growing crack is controlled by the (over-) pressure at the injection point, the average half-thickness of the crack, h, the fracture toughness K_c, and the geometry of crack growth (curvature of the crack tip line). The over-pressure at the injection point is large at the beginning of crack growth, and drops to zero when growth stops. In between, the over-pressure function is largely unknown. For simplicity, we divide the pressure function into two regimes: (1) a constant over-pressure P_0 during the injection phase (constant 2D flux Q), and zero over-pressure during after-growth. If an effective driving stress gradient exists, unilateral growth can develop after injection. We assume an injection line source at the center. During the injection phase, the steady-state viscous flow is described by laminar Hagen-Poiseuille flow with total volume flux Q and the mean velocity [22]

$$v = \mp \left[\frac{Q^2}{48\eta} g^{\text{eff}} \right]^{1/3} . \tag{1}$$

Here, η is the intrinsic fluid viscosity and g^{eff} is the effective driving stress gradient, defined as $g^{\text{eff}} = \gamma + \partial P/\partial x = \gamma + (P_a - P_0)/a = -\frac{1}{a}\left(P_0 - \frac{3}{4}\sqrt{\pi/a}K_c\right)$, where $\gamma = \Delta\rho g$ is the static driving stress gradient due to buoyancy, P_0 is the injection pressure at the injection point, and P_a is the pressure in the channel at length a from the injection point.

Although the solution represents a steady-state flow, it can be used to approximate slow crack growth for hydro-fracture experiments. Therefore, we assume that the hydro-fracture has a time-dependent length a that increases with velocity v so that the laminar flow is not disturbed. Such a process requires that the pressure at the fracture tips adjusts such that for each instantaneous time, the stress intensity $K^{\pm}$ at the crack tips of both wings equals the fracture toughness K_c of the rock. As shown in [22], the asymmetric growth velocity $v_{1/2}$ of the two wings during the injection phase from time t_1 to t_2 can be equated by

$$v_{1/2}(a) = \pm v \left[1 \pm \frac{g}{g^{\text{eff}}}\right] \text{ with } v = \left[\frac{Q^2}{96\eta}\frac{\pi}{a}\left(P_0 - \frac{K_c}{\sqrt{\pi a}}\right)\right]^{1/3} . \tag{2}$$

An intrusion associated with an injection under high, almost constant overpressure that abruptly ceases leads to a seismicity front initially growing bidirectionally with higher velocities upwards than downwards. Then, in the so-called 'bleed-off' phase, there is a one-sided growth of the seismicity front upwards, which is accompanied by a so-called 'back-front of seismicity generation', which only propagates upwards from the center of the opening fracture. The back-front develops when the internal pressure in the fracture re-organizes into a linear function with depth. With further growth at the longer wing, the point of maximal opening migrates together with the upper crack tip and marks the seismicity back-front behind where the Coulomb stress in the surrounding rock reduces and no longer increases. As shown in [22], the time evolution of the back-front and the final length of the hydro-fracture are independent of other parameters and cannot be varied.

The seismicity cloud of the KK swarm shows during Phase I exactly this predicted pattern (Figure 4 a,c) and can therefore be simulated by the bidirectional growth model. Our modeling results indicate an injection phase lasting 5 days (from day 16.8 – March 16, 2024, at 19:00 UTC, to day 22 – March 22, 2024) at an overpressure of about 6 MPa (pressure above normal stress on the fault) and $K_c \approx 100\,\text{MPa}\,\text{m}^{1/2}$, followed by a bleed-off phase over 7 days until March 29, 2024. Although the fluid viscosity is difficult to determine because the fracture mechanics modeling makes simplified assumptions about the crack opening, the modeling shows that viscosities as small as a few $Pa \cdot s$ are sufficient to reproduce the observed growth of the seismicity cloud. The observed one-sided back-front agrees with the predictions. This is a strong indication that hydro-fracturing was the dominant process in Phase I, resulting from the intrusion of a low-viscosity light fluid into a dense rock. As expected from this model, the observed earthquake density in Phase I is asymmetric in the up-dip direction, with a thick bulge at the top (Figure 4a).

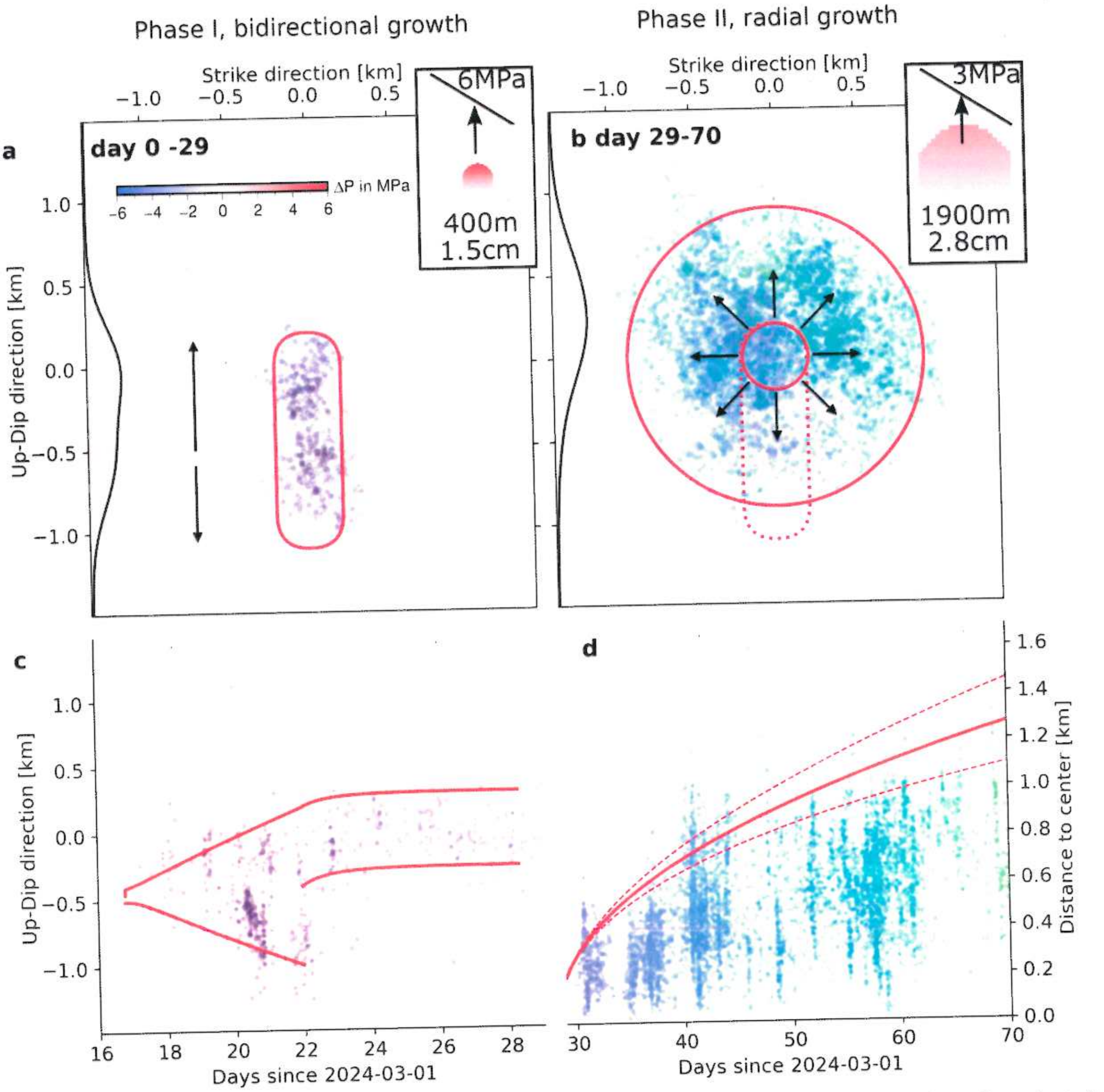


Fig. 4: Evolution of seismicity patterns during fluid injection phases. **a** Seismicity in Phase I projected onto the fault plane, illustrating bidirectional growth. **b** Seismicity in Phase II, highlighting radial growth. The inset curves in both panels show the normalized event densities as a function of the up-dip direction. The inlet figures at the top right of **a** and **b** show numerical simulations of the vertical and lateral shape of an ascending batch of buoyant fluid with $\Delta\rho$ of 1597 and 167 kg/m^3, respectively. The color scale indicates the overpressure of the fluid in MPa. The numbers indicate the static overpressure at impact, the lateral extent, and the mean opening of the rising batch. The observed spreading of seismic events is compared with the theoretical growth models: **c** bidirectional growth model, with a fluid density difference of $\Delta\rho = 1597\,kg\,m^{-3}$; and **d** radial growth model, with a fluid density of $\Delta\rho = 167\,kg\,m^{-3}$. Red curves indicate model predictions, showing good agreement with observed patterns.

Low-pressure injection leading to radial diffusion and hydro-shearing:

In Phase II (t > 29d, March 29, 2024), the seismicity cloud continued to grow, but now radially, starting from the upper end of the previously fractured segment on the fault (Figure 4b,d). Slow radial growth of a seismic cloud is often explained by pore pressure diffusion [e.g., 28], inducing both shear and opening-mode fractures. Aseismic slip may also play a role [29–31]. Diffusion models suggest a radial growth proportional to $\sqrt{t}$, equivalent to a radial growth velocity v proportional to r^{-1}. In a fracturing model, radial growth is expected when both buoyancy forces and injection pressures are lower [e.g. 32]. In terms of growth rate, the circumferential length of the crack increases with time, in contrast to the bidirectional growth in Phase I. Therefore, the speed of the seismicity front decreases with increasing radius of the activated fault patch, even if the inflow is constant.

The pressure function from injection with pressure P_0 at radius r_0 and constant total flux Q into a confined aquifer with half thickness h is described by the Thiem equation, where $P(r) - P_0$ varies logarithmically with radial distance $\ln(r/r_0)$. The functional form is similar to the problem of radial flow between two parallel disks. Using the same concept of a quasi-static growth of the fractured, penny-shaped area on the fault growing together with the pressure front and considering the stress intensity factor of a penny-shaped crack, the radial growth velocity can be described by

$$v(r) \approx \left[\frac{Q^2}{12\pi^3\eta} \frac{(r - r_0)}{r^4 \ln \frac{r}{r_0}} \left(P_0 - \frac{\pi}{2} \frac{K_c}{\sqrt{\pi r}} \right) \right]^{1/3} \quad \text{for} \quad r > r_0 \, . \tag{3}$$

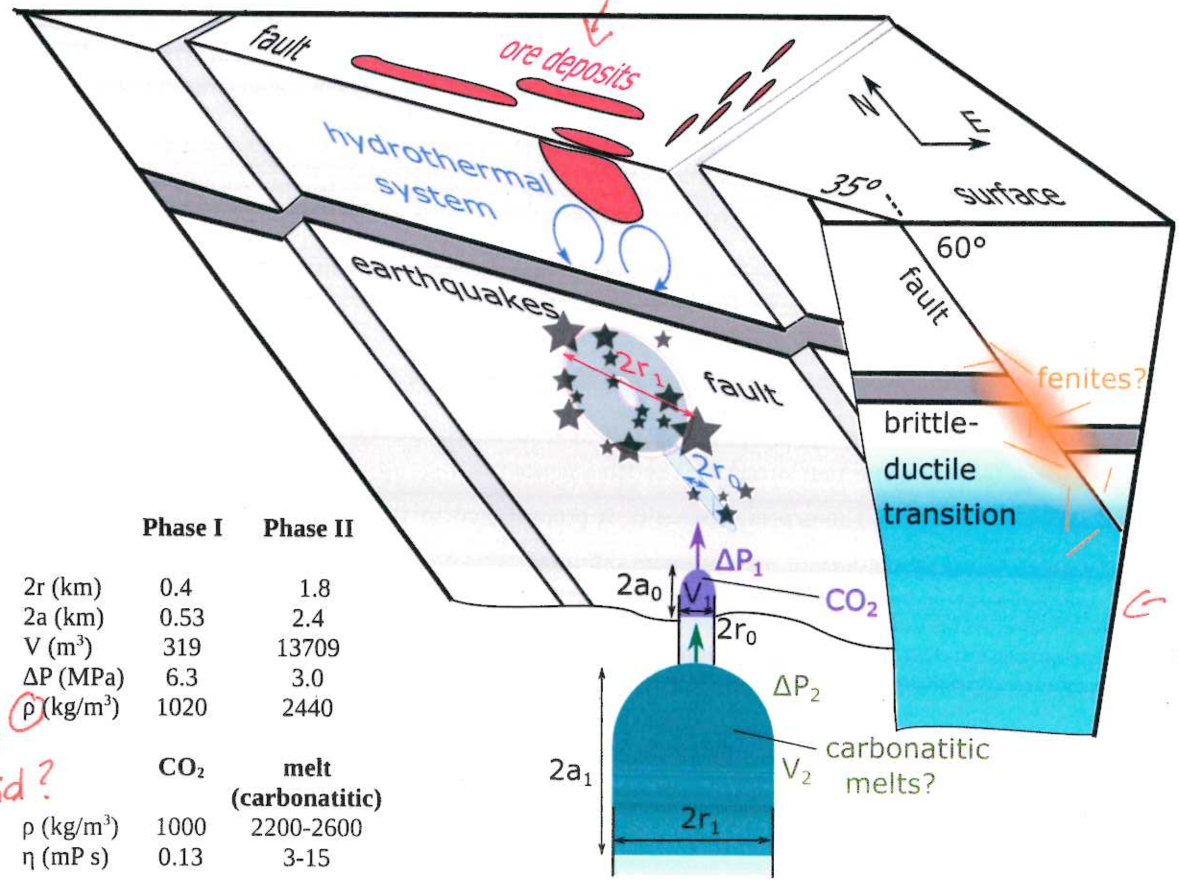
Note that the total flux has a unit of m^3/s. The time needed to fracture a radius r is calculated by the integral $t(r) = \int_0^r 1/v(r')dr'$. The expected velocity is proportional to $\left[(r - r_0)/(r^4 \ln(r/r_0))\right]^{1/3} \sim r^{-4/3}$, which is similar to the predictions of pore pressure diffusion.

Our modeling shows good agreement with the observed growth of the seismicity cloud in Phase II (Figure 4d), if a lower injection pressure of about 3 MPa and $K_c \approx 100\,\mathrm{MPa\,m}^{1/2}$ are used. The radial instead of bidirectional growth is explained by a higher density of the inflowing fluid. This, together with the lower injection pressure, could also explain that no significant back-front is observed after the inflow has stopped, contrary to borehole injection experiments [e.g., 33]. The injection under low overpressure predicts a symmetrical event density around the center in the up-dip direction, as observed (Figure 4b).

The role of magmatic fluids in driving swarms - discussion

Swarm activity also occurred in the KK region in 1897, exhibiting multiple phases and similar source mechanisms to the 2024 sequence, allowing for a meaningful comparison between the two swarms (Figure S4). The first events of the recent KK swarm occurred three months before the swarm itself (December 2023). These earthquakes were located approximately 1 km deeper and 2 km north of the subsequent swarm activity, which intensified on 16 March 2024. During the first five days of the main activity, a high rate of small-magnitude earthquakes indicated the injection of low-density fluids into a pre-existing normal fault, with bidirectional fracture growth over a lateral width of 400 m and a vertical length of about 1.1 km. According to our modeling, the initial overpressure was about 6 MPa. After the cessation of injection, the fracture continued to grow upward in the fault by about 100 m for 7 days, where a back-front of ceasing seismicity developed behind the upper seismicity front. This asymmetric pattern strongly supports the injection of light fluids with an estimated density of around 1020 kg/m^3, assuming a density of the granitic host rock of 2620 kg/m^3 [27].

The pressurization of the fault could be explained by different processes accumulating CO_2. For instance, a buoyancy-driven fracture could have arrived (Fig. 5), originally formed from the degassing of carbonatitic melts at great depth or during ascent. Alternatively, pressurization could have formed by metasomatic processes close to the fault when carbonatitic melts interact with host rocks [e.g. 34].



	Phase I	Phase II
2r (km)	0.4	1.8
2a (km)	0.53	2.4
V (m^3)	319	13709
ΔP (MPa)	6.3	3.0
ρ (kg/m^3)	1020	2440

	CO_2	melt (carbonatitic)
ρ (kg/m^3)	1000	2200-2600
η (mP s)	0.13	3-15

Fig. 5: Sketch of a subsequent cyclic intrusion into a pre-existing fault, inducing the KK swarm. The smaller batch with volume V_1 (Phase I) arrives first, with a larger overpressure ΔP_1. The batch with volume V_2 feeding Phase II of the swarm has a larger lateral size $2r_1$ and a smaller overpressure ΔP_2. Estimated parameters and literature values for the density and viscosity of CO_2 (see supplementary material) and carbonatitic melt [e.g., 35] are given in the upper and lower table on the left, respectively. Both the small overpressure in Phase II and the small density-related buoyancy facilitate hydro-shearing in the fault zone, triggering larger earthquakes.

The filling of pore space by CO_2 or water could eventually explain the sudden decrease in v_P while v_S remains less affected. However, very small ratios below 1.4 indicate possible vaporization of fluids associated with an expansion of pore space. Because CO_2 is in a supercritical state at a depth of 10 km, only the water component can eventually vaporize (Figure S5) in the region of the crack tip cavity where tensional suction forces can become extremely large if the host rock pore space is undrained [36]. Distributed hydro-fracturing and brecciation in the aurora of carbonatitic intrusions can be violent [e.g., 23] and may play a role. Such zones have been highlighted by a reduction of gravity and low v_P [37]. Fracture-induced anisotropy may also affect v_P/v_S, but studies on this topic are beyond the scope of this article.

After 29 March, the swarm experienced a second phase of activity in which it grew radially within the fault to a radius of about 950 m, starting at the upper end of the seismicity in Phase I. Using a similar modeling approach as before, we estimate an initial overpressure during Phase II of only 3 MPa and a fluid density of about 2440 kg/m^3. This indicates that after the injection of CO_2, a heavier melt or melt brine flowed into the fault (Figure 5). During this phase, the earthquakes became larger and the corner frequency of their rupture increased, indicating that shearing was more prominent than opening. The lower injection pressure could explain why hydro-shearing became dominant [see 38, for mechanism]. A more detailed analysis of the source spectra and corner frequencies could support these interpretations, but this lies outside the objectives of the present study.

To date, a number of alternative models have been proposed for the Vogtland region. Purely tectonic models based on the interaction of fault networks [e.g., 39, 40] have now been ruled out, as modern geodetic data show only minor tectonic deformations, difficult to explain repeating swarms. Proposals that the swarms are triggered by exogenous environmental factors can also be ruled out [41]. Most proposals assume transients of CO_2 flow, sometimes linked to so-called valve mechanisms in fault zones [e.g., 42]. However, decades of extensive measurements in Vogtland region mofettes show that flow transients can be triggered by different mechanisms and are difficult to interpret [e.g. 43]. A possible problem with the flow-controlled valve model is that already small volumes of CO_2 are sufficient to build up the excess pressure to reopen sealed fault patches, making it difficult to explain month-long swarms alone. However, detailed analyses show that the swarm patterns result from a combination of fluid intrusion and earthquake interactions driven by co- and postseismic stress transfer, which can explain their duration [44–46]. Similarly, CO_2 alone, which is light and tends to move upwards, cannot explain the incremental growth of the NK swarms in about 9 km depth horizontally over the length of more than 20 km since 1985, if not an unbroken sealed layer is assumed at approximately 7 km depth.

Massive CO_2 emissions at mofettes and springs extend over an area of 60 x 40 km^2, including the locations of different swarms. Helium isotopes in springs indicate that the CO_2 is mantle-derived, facilitated by the upwelling and magmatic underplating [47]. Mantle xenoliths from the tephra deposits in maars indicate that alkaline melts intrude at depths of 45 to 25 kilometres [48, 49], which is a favourable condition for the development of light and low-viscosity carbonatitic melts during ascent. Such magmatic processes at Moho depths have long lifecycles, which could also explain the persistent occurrence of swarms, including the reactivation of the KK swarm after a hundred years. Some previous studies suggested that melts were present at the depths of the swarms. This is supported by geological maps that indicate that earthquake swarms occur predominantly close to old magmatic intrusions [e.g., 50]. [32] studied the aspect ratio of the seismicity cloud of individual swarms beneath NKC and suggested that melts and CO_2 separate during a swarm to explain both upwards and lateral/downwards migration of earthquakes. The analyses estimated a mean overpressure during the later phase of a swarm in 2000 to be around 5 MPa, while a shear stress between 9-17 MPa was effective. Other investigations of repeating seismicity clouds yielded an initial overpressure at the beginning of the NK swarm in 2008 of 15-25 MPa [5].

Non-differentiated peridotitic melts do not align well with our observations. They typically have high densities, meaning large volumes of melt must accumulate in vertical fractures before the overpressure at the tip is sufficient to cause instability and the entire batch to ascend through the crust. These large-volume intrusions induce relatively strong earthquakes, up to magnitude $M_W \sim 5$, when they penetrate the brittle part of the crust. However, our maximum magnitudes are below $M_W \sim 3$. Additionally, the viscosity of silicate-rich melts may be too high for them to propagate through grain boundaries and faults in the brittle crust to generate hydro-shearing.

This suggests that small volumes of light, low-viscosity melts have been available in our case, from which CO_2 is also released. Alkaline or calcium carbonatites could fulfill these conditions. The rise of carbonatite melts to the upper crust overcomes some of the limitations mentioned above. Carbonatites have very low viscosities, similar to water, and can therefore migrate slowly through the crust in small volumes and penetrate grain boundaries and faults without causing strong earthquakes. Their ascent along pre-existing weak zones or in the vicinity of existing intrusions or plutons may explain why earthquake swarms reawaken in the same place after a long time. Another characteristic of carbonatite melts is that they produce CO_2 and H_2O during their ascent and in contact with the surrounding rock [e.g., 51]. The time scales of this interaction are not fully understood, but can possibly be violent [e.g. pneumatic jackhammer model, 51] as networks of hydraulic fractures and breccia zones are documented in fenite deposits in the volume around carbonatitic intrusions.

Melt-rock interaction and the related hydrothermal systems may lead to the formation of ores and minerals, which have been mined for centuries in the Vogtland and close to Klingenthal. For example, the KK swarm is located on the border of the Eibenstock granite pluton, which covers an area of more than 30 km^2, on the edge of which feldspar, barite, and apatite were mined [52].

Conclusions

Magmatic fluids in the NW Bohemia/Vogtland swarm region develop and accumulate in the upper mantle and at the crust-mantle boundary. When such deep reservoirs evolve and become unstable, the lower density melts and fluids may separate and rise further through the crust. When these magmatic fluids encounter the brittle-ductile boundary and interact with pre-existing fault zones, seismic swarms can occur.

Our analysis suggests that the 2024 Klingenthal-Kraslice earthquake swarm—the first significant seismic activity in the area in over 125 years—was driven by such fluid-fault interaction, providing a concrete example of mantle-derived, carbonate-rich fluids interacting with bedrock at the brittle-ductile boundary.

This interaction caused three months of intense earthquake activity, activating a previously unidentified normal fault at a depth of 10 km. The swarm underwent an unexpected evolution from vertical bidirectional growth to radial growth of the seismic cloud over a period of 70 days. The v_P/v_S ratio in the source region decreased significantly during bidirectional growth. Source spectra also indicate a different fracture mode during this phase.

The spatial and temporal evolution of the swarm could be modeled using a hydro-fracture model that provides constraints on overpressure, viscosity, and density of the injected fluids. The first phase, which lasted five days and involves bidirectional vertical growth, is characterized by very low viscosity and an overpressure of about 6. MPa associated with a higher buoyancy force in the intruding fluid batch of a volume of about 320 m^3 ascending from below. This indicates a high H_2O or CO_2 content with an average density of about 1040 kg/m^3.

During the second phase of radial growth, the density difference between the intruded fluids and the host rock decreases, which can be explained by the influx of melt or melt brine with a density of about 2440 kg/m^3 but still a very low viscosity. Although the estimated intruded volume is larger at about 13,700 m^3, the realized overpressure is smaller at only about 3 MPa, favoring hydro-shearing events and generating earthquakes of magnitude greater than 1.2. Carbonatitic melts would explain such parameters.

Our study exemplifies how seismicity patterns can identify sequential injections of light CO_2 and melt-brines of very low viscosity and with densities much smaller than that of the host rock in 10 km depth. We propose that the NW Bohemia/Vogtland swarm region is an area where the ascent of low-viscosity melts into the upper crust, as well as the metasomatism and fenitization of carbon-rich melts, can be studied as they develop today.

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Methods

Earthquake detection and localization

We generated the earthquake catalog using *Qseek*, an automatic waveform-based earthquake detector and locator, as detailed in [53]. *Qseek* combines seismic phase arrival annotations provided by neural network phase pickers and waveform stacking with an efficient adaptive octree search. The resolution of the search volume is iteratively refined toward the seismic source location, enabling fast and accurate detection. Moment and local magnitude calculations from peak ground motions are included [54]. Location accuracy is further enhanced by incorporating station-specific corrections (SST) and source-specific station terms (SSST). The method has been validated for multiple large seismic datasets across various regions and geological settings [53, 55].

Methods implementing SSST can achieve relative locations similar to double difference methods [e.g., 56, 57]. In our case, SSSTs were derived from a regional application of *Qseek* to NW Bohemia and Vogtland for the years 2018 to 2024, including the KK swarm. The waveform attribute stacking approach with static station correction terms, a preliminary version of the *Qseek* approach, was directly compared to a high-resolution double difference relative location applied to a NW Bohemia earthquake swarm in 2008 using stations from WEBNET [58]. Results showed very comparable high precision relative and absolute locations, where data errors were in the range between 0.2-0.5 km. Compared to 2008, the density and coverage of stations have significantly improved, so we estimate that the uncertainties from the updated *Qseek* application are in the range of 0.1 km.

location ?

The seismic catalog was created using the local velocity model from [59], a modified model version in [60]. Waveform data were sourced from three borehole arrays (6A.LWS00, GX.TIS00, GX.STC00) of the ICDP (Drilling the Eger Rift) Eger Virtual Network [61], along with surface stations operated by WEBNET [62, 63], SXNET [64], TSN [65], and BW [66], as described in the Data Availability section.

Centroid moment tensor inversion

We applied moment tensor inversion to earthquakes with $M_W > 1.2$ for the 2024 KK swarm (Figure 1) using a joint inversion of waveform and first motions [55]. Uncertainties were estimated using a Bayesian bootstrap approach implemented in the open source software *Grond* [67], which combines nonlinear inversion and bootstrapping.

The source model parameterization includes centroid location, depth, time, moment tensor components, and optional source duration. Green's functions (GFs) were precomputed using *Qseis* [68] for a sampling rate of 100 Hz, covering distances of 0-80 km and source depths of 7-13 km with 100 m spacing, based

-> which definition of local Magnitude ?

on the velocity model of [59]. Theoretical travel times and phase polarities were calculated using the *Cake* tool [69]. The inversion minimizes the L1 norm misfit between observed and synthetic data [70], balancing weights for signal amplitude, source-receiver distance, phase type, and data type.

Waveforms were inverted in time windows of ±0.25 s around P- and S-wave arrivals in the time domain, with shifts of ±0.15 s allowed for synthetic traces. Approximately 4,000 manually verified P- and S-wave arrivals were used, with a frequency range of 1.0-3.0 Hz. After 100,000 iterations, 64 earthquakes with robust centroid locations, low misfits, and sufficient azimuthal coverage were selected for further interpretation (Figure 1). Full waveform fits are available as online reports and interactive web-based visualizations (see Data Availability).

Temporal changes in v_P/v_S ratios in the swarm volume

The double difference Wadati method was developed by [16] to estimate temporal changes of $\gamma = v_P/v_S$ in the source region of an earthquake swarm. The traditional Wadati diagram uses the arrival time difference between the S- and P-wave, $t_S - t_P$ plotted over t_P, for all stations recording the event, which linearly depends on γ and the origin time of the event. Averaging γ for many events provides an average ratio for the crust beneath the seismic network.

We use time differences between P-wave arrivals at each station for pairs of events. The same applies to S-wave arrivals. These double differences are sensitive for velocity changes between the different sources, as effects between the swarm and the stations are canceled out. The challenge of the double difference Wadati approach is to have precise pick times, T_P and T_S, with accuracies of 4 or 8 ms, respectively, in order to resolve variations in arrival time differences over a path length of 1-2 km. In our case, we take advantage of the 250 Hz sampling rate on all WEBNET stations. Note that borehole chains in Tisova (GX.TIS00), Landwüst (6A.LWS00) and Studenec (GX.STC00) sample with 400 or 1000 Hz.

The theory and inversion approach is described in [16], where the following equations are minimized,

$$\begin{aligned} \|T_{Sij} - \gamma T^d_{Pij} - \delta_i\| &\quad \text{is minimal} \quad \text{(regional ratio)} \\ \|\Delta T_{Slj} - \gamma_l \Delta T^d_{Plj} - \Delta\delta_l\| &\quad \text{is minimal} \quad \text{(source region ratio)}\,, \end{aligned}$$

where T_{Sij} and T_{Pij} are S and P wave arrival times at station j from event i, T^d_{Pij} is the event-wise demeaned P arrival time. δ_i is a constant that can be estimated for each event. The symbol Δt refers to arrival time differences. The index l refers to unique permutations of event pairs. The minimum is found from a grid search over possible values of γ, where an L_1 norm was implemented.

We only considered earthquakes within a $2^3\,km^3$ cube centered on the swarm that with at least 14 accurate picks with probabilities greater than 0.8. Stations with a T_S-T_P difference of more than 4 s and outliers with a deviation of more than 0.05 s from the Wadati curve in a regional (conventional) Wadati plot were removed. We also ensured a systematic input dataset by selecting a set of stations that consistently provided picks for every included earthquake. We tested different station ensembles. Stations from which rays emerge perpendicular to the fault result in very small (or zero) arrival time differences for event pairs and are therefore not suitable for studying velocity ratios. Those associated with rays along the activated fault produced larger arrival time differences that exceeded the pick accuracy. We tested different ensembles of stations. While the general result and trend in v_P/v_S remained unchanged, the most convincing examples involved stations located approximately 15 km from the sources. We ultimately employed stations WB.LOUD, SX.WERN and SX.WERD for the analysis (see Figure S1, S6-S9).

Supplementary information. Supplementary information can be found here: Supplementary Information (supplement.tex file)

Acknowledgments. This work utilized high-performance computing resources made possible by funding from the Ministry of Science, Research and Culture of the State of Brandenburg (MWFK) and are operated by the IT Services and Operations unit of the Helmholtz Centre Potsdam.

Declarations

Funding

We acknowledge the funding of the borehole and surface array by ICDP (ICDP-EGER project). Additional stations were built in the framework of the Central European Volcanic Province Observatory (CVO) of GFZ. PB was funded by the DFG project "Characterizing source properties of NW Bohemia/Vogtland earthquake swarms exploiting novel network and waveform processing tool (Chasing)", BU4346/1-1, project number: 517982028.

Conflict of interest

The authors have no conflicts of interest.

Data availability

The seismic data used in this study are available through the FDSN data center network under the following codes: ICDPEGER (ICDP Eger Virtual Network, DOI: 10.14470/SN852091), operated as part of the International Continental Scientific Drilling Program (ICDP); TH (Thüringer Seismologisches Netz – TSN, DOI: 10.7914/SN/TH), operated by Friedrich Schiller University Jena, Germany; SX (SXNET – Saxon Seismic Network, DOI: 10.7914/SN/SX), operated by the University of Leipzig; BW (Bayern-Netz – BW, DOI: 10.7914/SN/BW), operated by the Bavarian Seismological Network, Germany; and WEBNET (DOI: 10.7914/SN/WB), operated by the Institute of Geophysics, Czech Academy of Sciences, Czech Republic. The fault inventory in Figure 1 is compiled from three different sources: (1) Bayerisches Landesamt für Umwelt – LfU Bayern (https://www.lfu.bayern.de/gdi/wms/geologie/dgk25), (2) Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie (https://www.geologie.sachsen.de/artus-2-aktive-stoerungszonen-27587.html), and (3) Czech Geological Survey (https://cgs.gov.cz/en/maps-and-data/web-services).

The online reports of the results of each earthquake resolved by moment tensor inversion (e.g., waveform fits and uncertainties) can be accessed interactively via the following link: (https://data.pyrocko.org/publications/grond-reports/2024-klingenthal)

Code availability

The software used is all open-access. The earthquake detection and localization framework *Qseek* can be found under the link (https://pyrocko.github.io/qseek). The probabilistic source inversion method with the Grond framework is available at the link (https://pyrocko.org/grond) under the Pyrocko environment (https://pyrocko.org). The maps are prepared using the pyGMT, (https://www.pygmt.org, GMT ([71], Python (http://www.python.org), MatPlotLib (https://matplotlib.org) visualization packages and QGIS software (https://www.qgis.org).

Author contribution

Conceptualization: P.B., T.D.; **Data curation:** P.B., M.P.I., M. O., J.D., S.F.; **Formal analysis:** P.B., M.P.I., S.W., S.F.; **Funding acquisition:** P.B.; **Investigation:** P.B., T.D., S.H., S.W.; **Methodology:** P.B., T.D., M.P.I.; **Project administration:** P.B.; **Resources:** ; **Software:** P.B., M.P.I.; **Supervision:** ; **Validation:** P.B., T.D., S.H.; **Visualization:** P.B., T.D., S.H.; **Writing – original draft:** P.B., T.D.; **Writing – review & editing:** P.B., T.D., S.H., M. O., J.D.

Supplementary Information
Modelling of Earthquake Swarms Indicates Magmatic Fluids in the Upper Crust Beneath the Eger Rift

Pinar Büyükakpinar[1*], Torsten Dahm[1,2], Sebastian Hainzl[1,2], Marius Isken[1], Matthias Ohrnberger[2], Jana Doubravová[3], Siegfried Wendt[4], Sigward Funke[5]

[1*]Physics of Earthquakes and Volcanoes, GFZ Helmholtz Centre for Geosciences, Potsdam, Germany.
[2]Institute for Earth and Environment, University of Potsdam, Potsdam, Germany.
[3]Institute of Geophysics, Czech Academy of Sciences, Prague, Czech Republic.
[4]Geophysical Observatory Collm, Institute for Earth System Science and Remote Sensing, Leipzig University, Leipzig, Germany.
[5]Institute for Earth System Science and Remote Sensing, Leipzig University, Leipzig, Germany.

*Corresponding author(s). E-mail(s): pinar@gfz.de;
Contributing authors: torsten.dahm@gfz.de; hainzl@gfz.de; isken@gfz.de; Matthias.Ohrnberger@geo.uni-potsdam.de; doubravka@ig.cas.cz; wendt@rz.uni-leipzig.de; sfunke@uni-leipzig.de;

The Supplementary Information includes nine additional figures (Figs. S1 and S9) and one table (Table S1), which offer more details and support the interpretations in the main text.

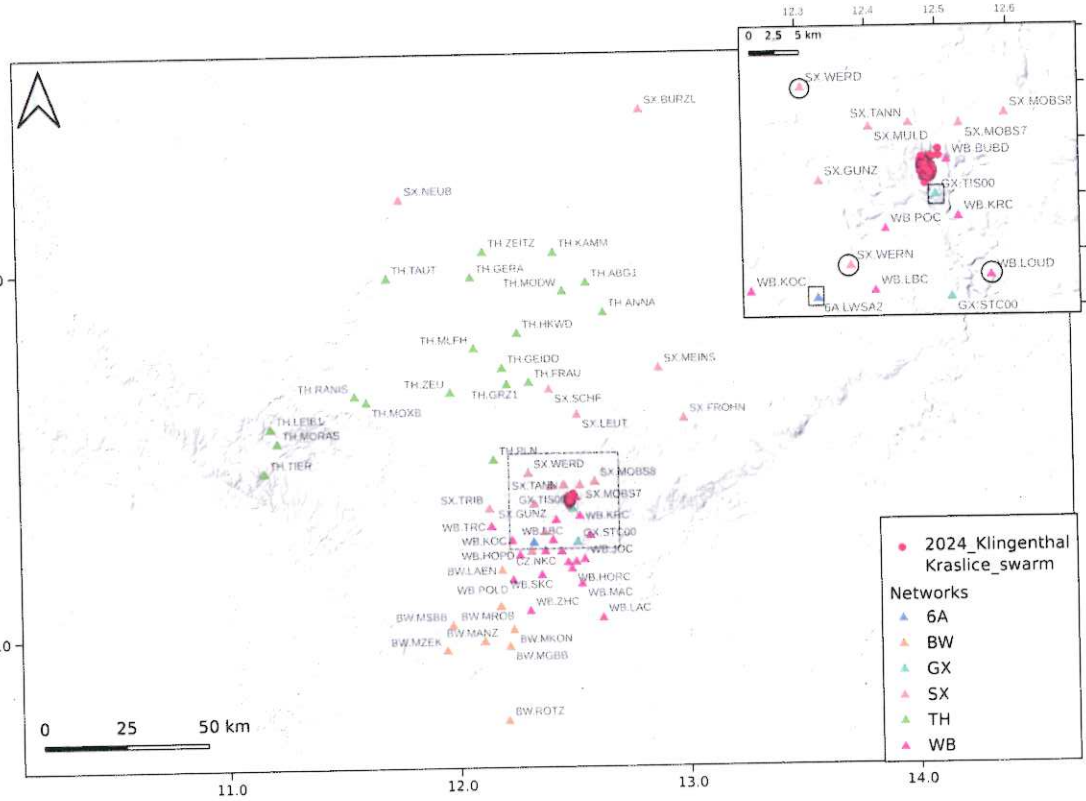

Fig. S1: Map of seismic stations that recorded the 2024 Klingenthal-Kraslice swarm (red circles), labeled in NET.STA format. The inset shows a zoomed-in view highlighting closely spaced stations. Black circles indicate the stations used in the V_P/V_S calculations (see the method section in the main text), while rectangles mark borehole stations used for spectral analysis.

Table S1: List of seismic stations used in this study, including their network codes, names, geographic coordinates, and elevations.

No	Network	Station	Latitude (°)	Longitude (°)	Elevation (m)
1	6A	LWS00	50.258014	12.328517	217.82
2	6A	LWS00	50.258014	12.328517	245.72
3	6A	LWSA2	50.25804	12.328452	614.15
4	BW	LAEN	50.182812	12.185856	675.0
5	BW	MANZ	49.986198	12.1083	635.0
6	BW	MGBB	49.971962	12.214974	650.0
7	BW	MKON	50.018635	12.23383	614.0
8	BW	MROB	50.083145	12.178588	570.0
9	BW	MSBB	50.031429	11.972771	622.0
10	BW	MZEK	49.962593	11.94743	627.0
11	BW	ROTZ	49.766899	12.207	430.0
12	GX	STC00	50.258054	12.518528	335.0
13	GX	TIS00	50.350277	12.497441	369.0
14	SX	FROHN	50.59483	12.98856	401.0
15	SX	GUNZ	50.3635	12.3316	669.0
16	SX	LEUT	50.6072	12.52309	411.0
17	SX	MEINS	50.73247	12.88118	501.0
18	SX	MOBS7	50.41433	12.53191	750.0
19	SX	MOBS8	50.42344	12.59578	906.0

? boreholes? sensors distributed?

No	Network	Station	Latitude (°)	Longitude (°)	Elevation (m)
20	SX	MULD	50.4118	12.4039	693.0
21	SX	NEUB	51.1942	11.7719	200.0
22	SX	ROHR	50.234	12.317	629.0
23	SX	SCHF	50.6772	12.4031	384.0
24	SX	TANN	50.415	12.461	802.0
25	SX	TRIB	50.352	12.137	510.0
26	SX	WERD	50.448	12.307	596.0
27	SX	WERN	50.2874	12.3761	672.0
28	TH	ABG1	50.96532	12.57208	247.0
29	TH	ANNA	50.88399	12.64365	249.0
30	TH	FRAU	50.69544	12.31685	362.0
31	TH	GEIDO	50.7353	12.1999	346.0
32	TH	GRZ1	50.6908	12.21964	401.0
33	TH	HKWD	50.8297	12.26811	313.0
34	TH	KAMM	51.0476	12.43147	179.0
35	TH	LEIB1	50.57607	11.1978	451.0
36	TH	MLFH	50.78982	12.08091	220.0
37	TH	MODW	50.94269	12.46844	242.0
38	TH	MOXB	50.64523	11.61447	359.0
39	TH	MORAS	50.53608	11.2247	618.0
40	TH	PLN	50.4852	12.1573	432.0
41	TH	RANIS	50.66236	11.56432	383.0
42	TH	TAUT	50.98161	11.71074	331.0
43	TH	TIER	50.45468	11.16721	661.0
44	TH	ZEITZ	51.0507	12.12605	158.0
45	TH	ZEU	50.67064	11.97713	331.0
46	WB	BUBD	50.381739	12.513619	745.7
47	WB	HOPD	50.223778	12.265472	731.0
48	WB	HORC	50.18598	12.491	500.0
49	WB	JOC	50.2115	12.5484	510.0
50	WB	KOC	50.264167	12.232878	621.0
51	WB	KOPD	50.20319	12.47473	536.0
52	WB	KRC	50.330692	12.5295	806.0
53	WB	KVC	50.204956	12.51134	666.0
54	WB	LAC	50.049672	12.62396	806.0
55	WB	LBC	50.264608	12.411233	684.0
56	WB	LOUD	50.277533	12.574492	692.0
57	WB	MAC	50.144292	12.535158	609.0
58	WB	NKC	50.2331	12.4479	564.0
59	WB	POC	50.319967	12.426622	841.0
60	WB	POLD	50.156028	12.234972	589.0
61	WB	SKC	50.16911	12.360497	501.0
62	WB	STC	50.257942	12.518492	712.0
63	WB	TRC	50.303444	12.144658	612.0
64	WB	VAC	50.234497	12.376336	581.0
65	WB	ZHC	50.069842	12.308103	677.0

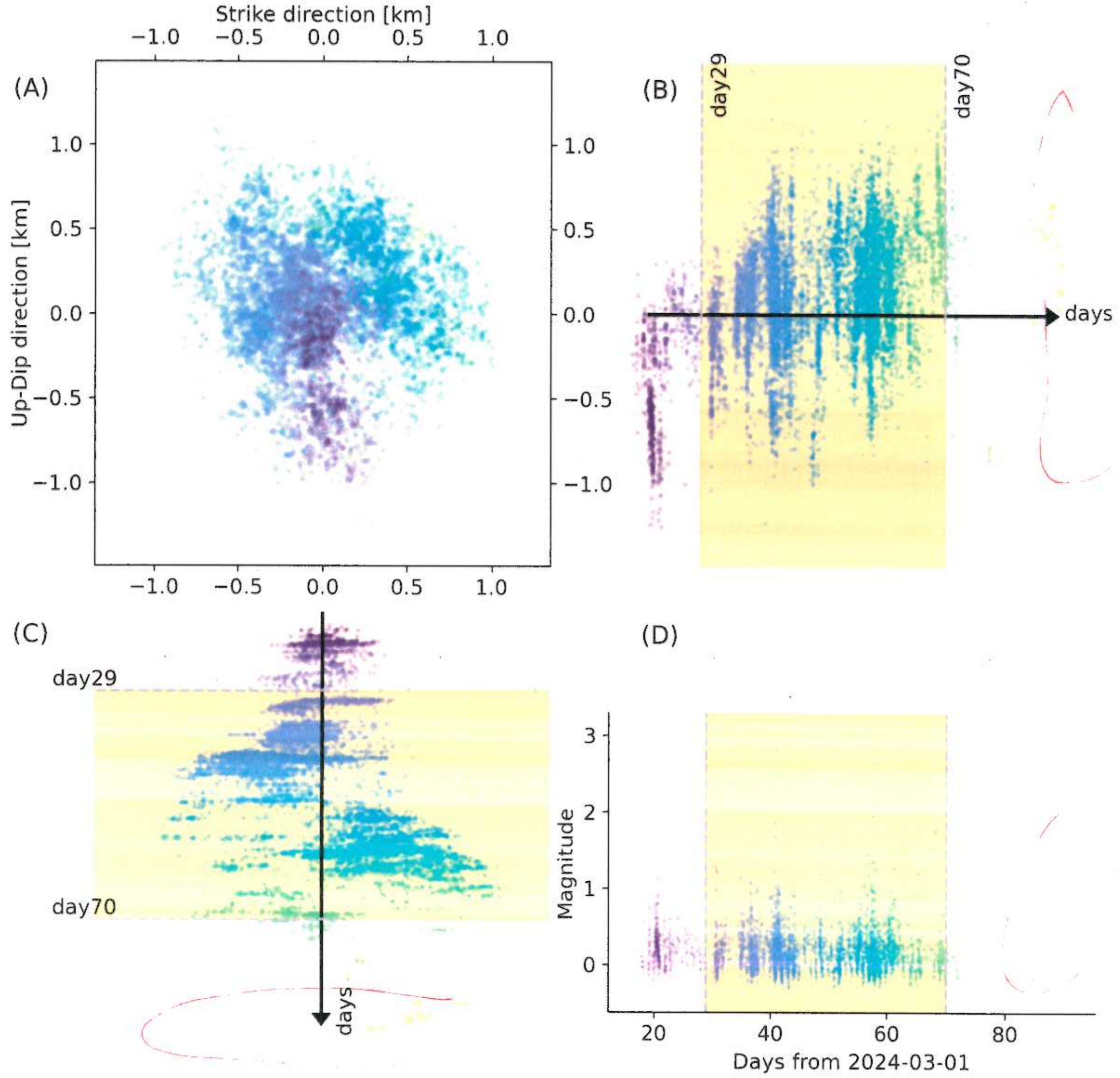

Fig. S2: Spatiotemporal and magnitude distribution of seismicity. (A) Hypocenter locations projected onto the fault plane, showing the up-dip versus strike directions. (B) Temporal evolution of events along the strike direction overlaid with highlighted time windows (pink and yellow shading indicate the first 29 days and the subsequent 29–70 days, respectively). (C) Temporal evolution of events along the up-dip direction, emphasizing the same time windows. (D) Magnitude distribution as a function of time, with the same highlighted intervals.

yellow difficult to see

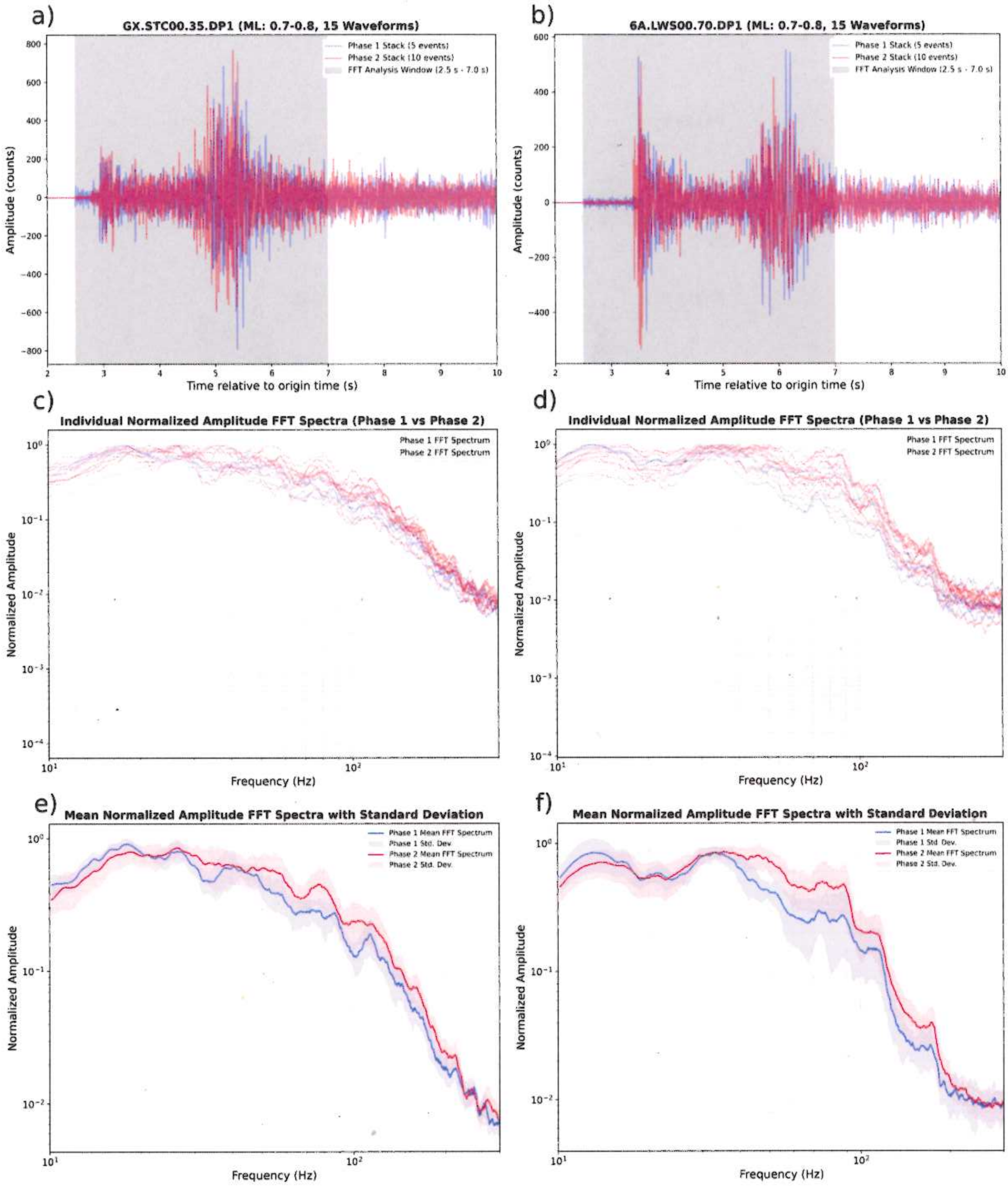

Fig. S3: Comparison of stacked waveforms and amplitude spectra for two borehole seismic stations: (left column) GX.STC00.35.DP1 (Studenec) and (right column) 6A.LWS00.70.DP1 (Landwüst). All panels represent data for events with M_L 0.7–0.8. (a, b) Stacked vertical velocity waveforms aligned to origin time. The blue trace represents the stack of 5 events from Phase 1, and the red trace represents the stack of 10 events from Phase 2. The gray shaded region (2.5 s to 7.0 s after origin time) indicates the window used for Fast Fourier Transform (FFT) analysis. (c, d) Individual normalized amplitude FFT spectra comparing Phase 1 (blue) vs. Phase 2 (red). Each thin line shows a single event's spectrum, illustrating event-to-event variability. (e, f) Mean normalized amplitude FFT spectra with standard deviation for Phase 1 (blue) and Phase 2 (red).

Comparison of the 1897 and the 2024 Klingenthal swarms

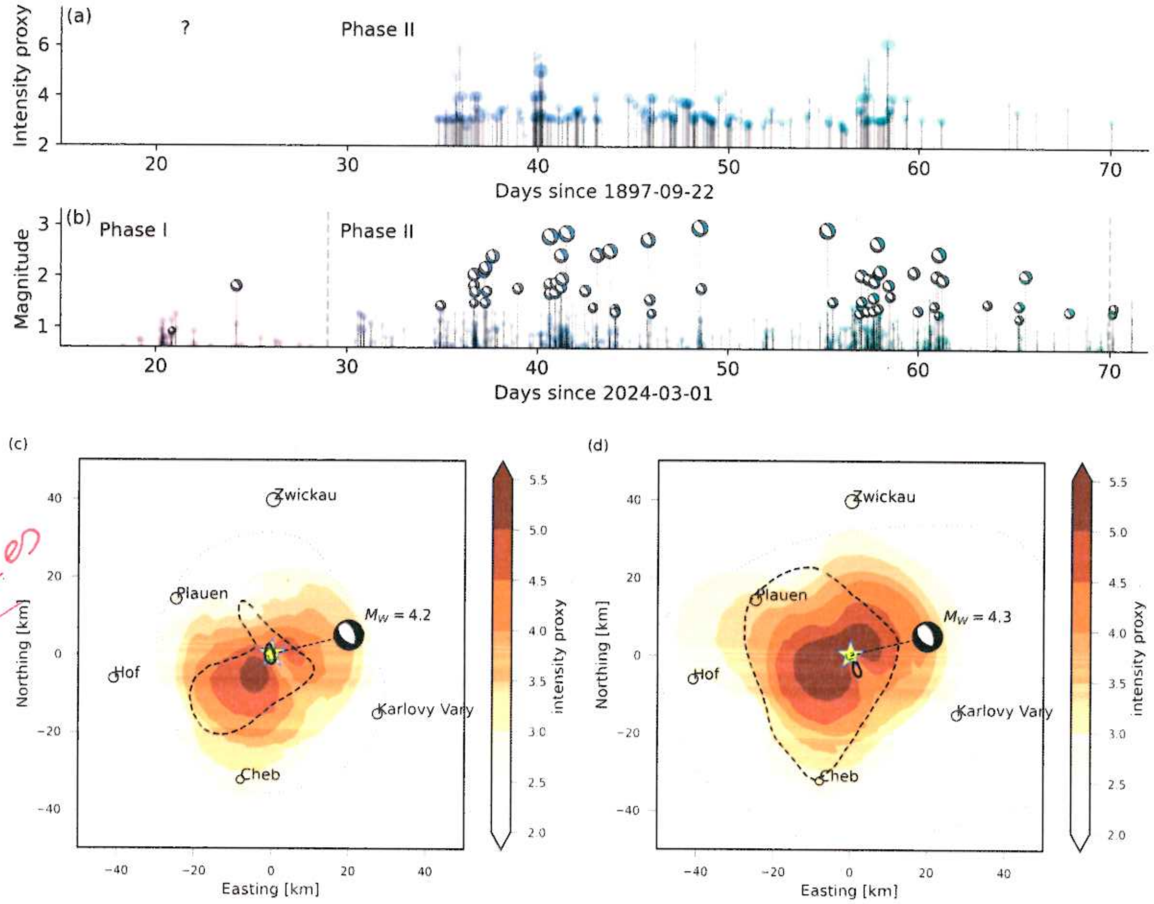

Fig. S4: Comparison of the seismicity and source parameters between the 1897 and 2024 Klingenthal swarms. (a) Events of the 1897 swarm plotted as a function of their occurrence in days. Strength is given by an intensity proxy, as defined in [e.g. 1]. (b) Magnitude over occurrence time of micro-earthquakes of the 2024 swarm. (c) Epicenter location and felt intensity of the the 29th of October 1897 M_W 4.2 earthquake. The hypocentre location and source mechanism of a M_W 2.5 earthquake from 2024 (see focal solution plot) was used to simulate intensities between 0.2 and 4 Hz. The contour lines show isoseisms of highly felt, felt and poorly felt questionnaires. The dashed green lines show the geometry of the rectangular source to simulate peak ground displacement (PGD). PGD was used to derive intensity proxies. (d) Similar as in (c), but simulating the 7th of November 1897 M_W 4.3 Kraslice earthquakes. Moment magnitudes according to [2, appendix]. The mean epicentre location of the 2024 swarm is plotted by the yellow star. According to our simulations, the moment magnitude of the historical earthquakes could have been 4.2 and 4.3, respectively.

Phase diagrams of CO_2 and H_2O

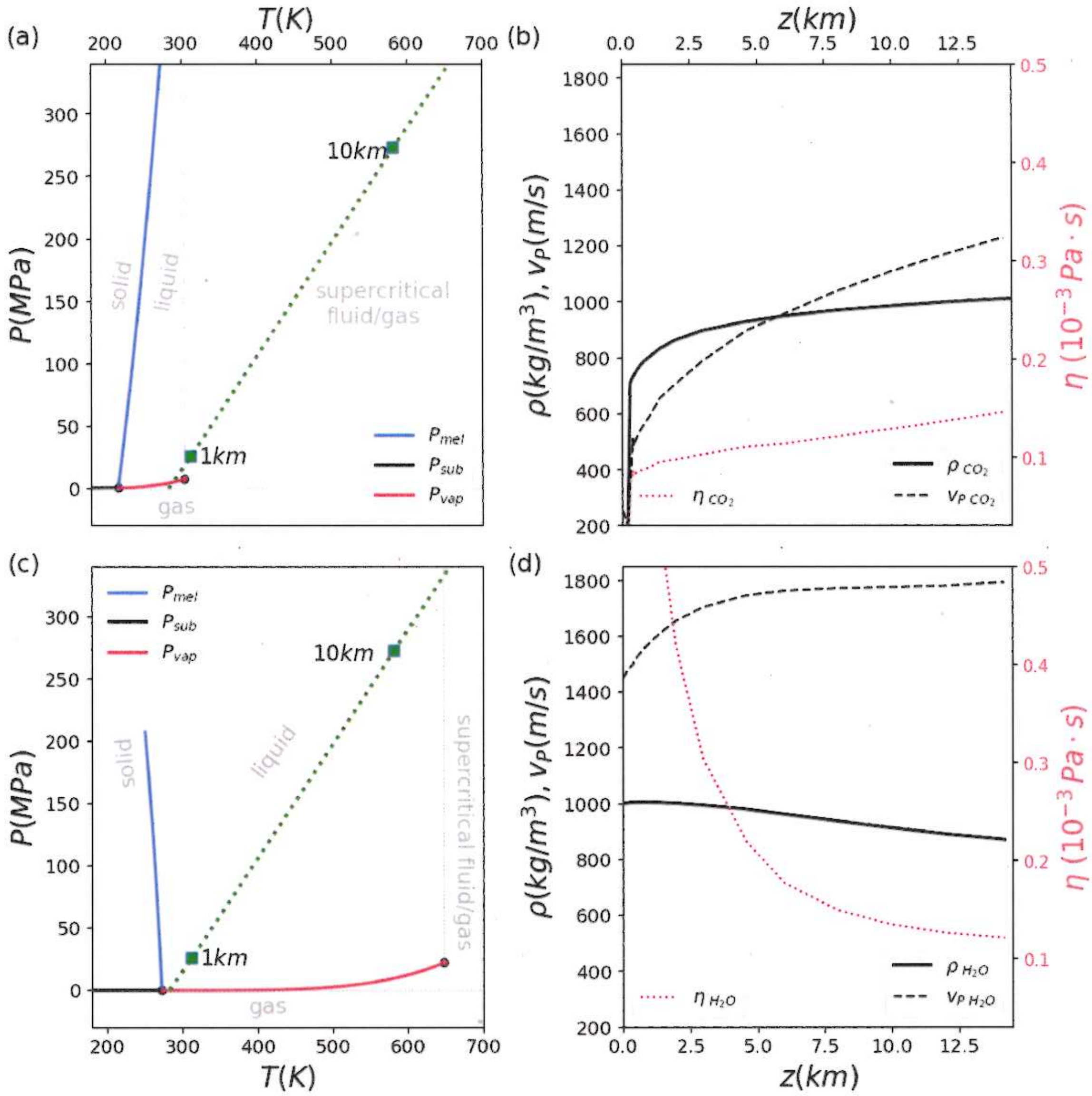

Fig. S5: Phase diagrams ($P - T$) of the state of pure CO_2 (a) and H_2O (c) are plotted together with estimated density ρ, P-wave velocity v_P and viscosity η of CO_2 (b) and H_2O (d) along a depth trajectory from 0 to 10 km (dotted green line). Phase diagrams were calculated from [3, 4]. Density and velocities have been cross-checked against NIST Standard Reference Database 69 for thermophysical properties of fluids [5].

reference?

Double difference Wadati method for v_P/v_S ratio in source region of the swarm

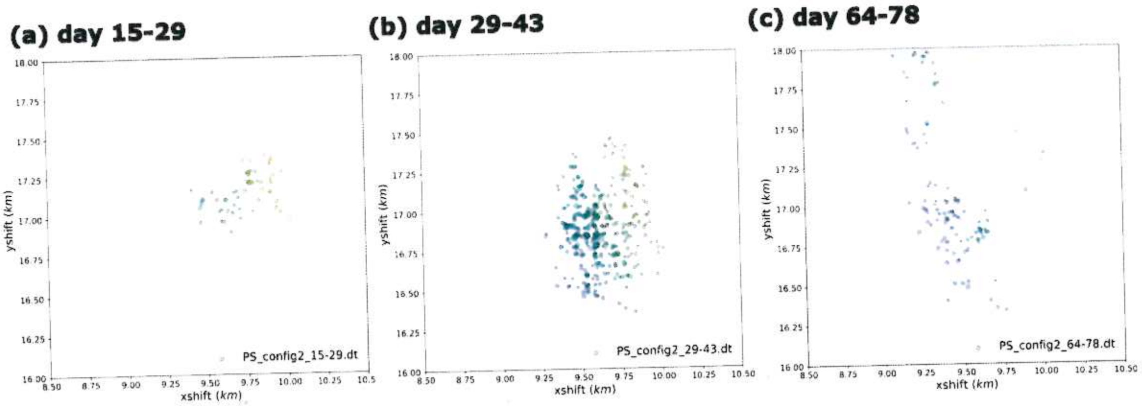

Fig. S6: Epicentral distribution of events considered in the double difference Wadati method (WadatiDD). All events were between 8 and 10 km depth. The panels a-c show the events that occurred during day 15-29, day 29-43 and day 64-78 after 1st of March 2024.

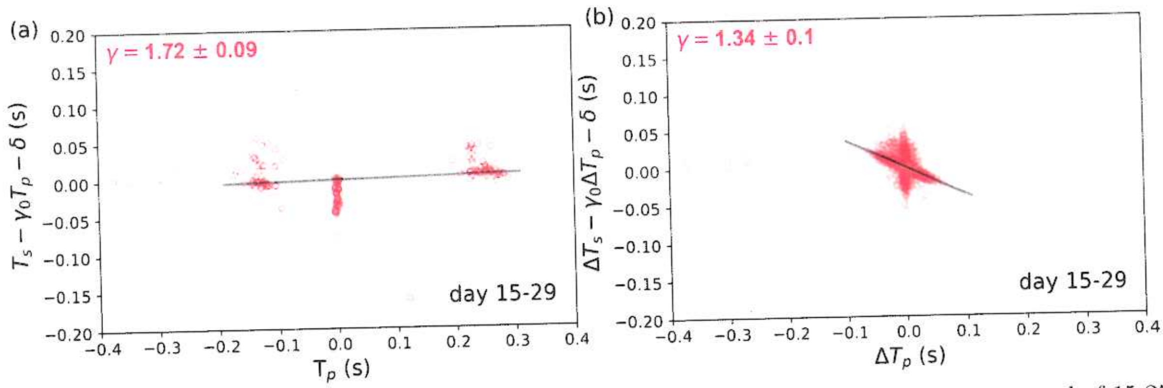

Fig. S7: Example of the regional (a) and source volume (b) WadatiDD plot for the time interval of 15-27 days after the 1st of March 2024. The vertical axis is reduced by a ratio of 1.7. The estimated velocity ratio $\gamma = v_P/v_S$ is annotated in red.

Station(s)?

-> uncertainties? How were they derived?

-> red circles versus grey circles?

-> what is the dimension of individual focal zones?

Station(s)?

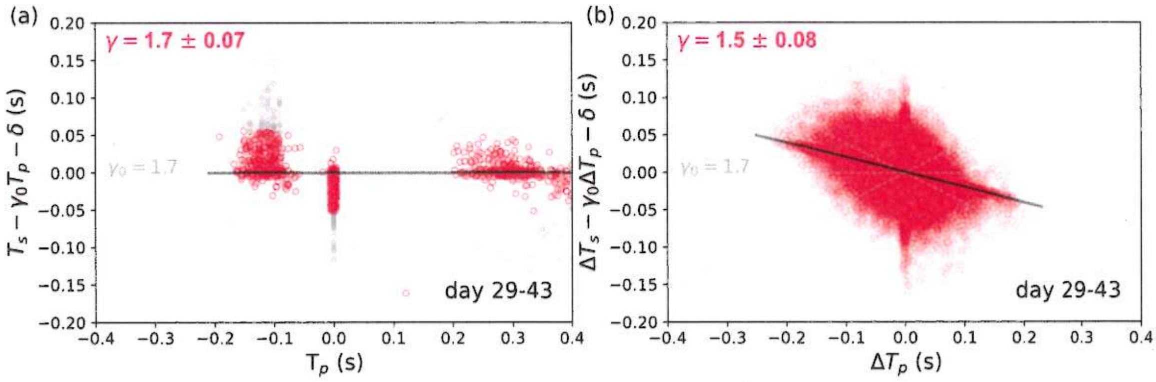

Fig. S8: Same as Fig. S7 but for the time interval of 29-43 days after the 1st of March 2024.

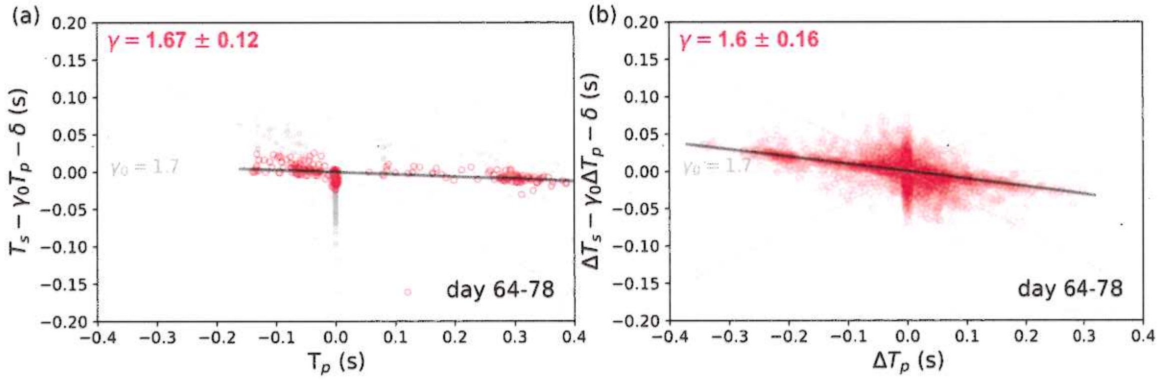

Fig. S9: Same as Fig. S7 but for the time interval of 64-78 days after the 1st of March 2024.

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Dear editors and authors,

Please find my comments on the revised version of the manuscript by Büyükakpinar et al., submitted for publication in Communications Earth & Environment, below. The revisions made by the authors are helpful, as the manuscript is now easier to follow, particularly with regard to the link between the data and the model. However, I am still convinced that the model they proposed (nice and meaningful) is one possibility, among other ones. More specifically, 'fluid diffusion' alone within a pre-existing complex fault network may be consistent with the data results. The data cannot rule out this possibility, given that the main argument lies in the migration pattern of the seismicity. Such complex migration patterns are observed in other contexts worldwide (Japan, California, Greece, etc.) without the need for hydrofracturing or magmatic processes. As I asked in my initial review, these points should be emphasized more in the discussion to avoid readers directly interpreting 1D migration with back-front as hydrofracturing or magmatic fluid processes. I am not fully qualified to judge the scientific quality of the discussion on magmas, but it seems also to go too far given the results of the data. Finally, I have a few minor concerns about the results and the clarity of some points.

Taking these points into account, I still believe that the manuscript is worth publishing, but I apologize for asking again for some major revisions.

Detailed comments

- title: "indicates" might sounds quite strong. Maybe change it by "suggests" (or "is consistent with")
- l20: there is no proof of a reawakening, as the last swarm in this area was one century ago, without strong constraints on its location. 'activation' seems more suitable.
- L100-107: Please refers to the figures in supplementary materials. Maybe you could give more details on the uncertainties to show how robust are these results as fits in Fig. S7b and S8b are not so convincing.
- In Fig. S3: Could you plot a Brune spectrum estimation and the noise level on each station? As you should work with event with same moment, Fig S3c and d should not be normalized.
- L116-117: This sounds as over-interpretation: from one EGS results where most (if not all) the seismicity is due to shearing events, I do not see how you can conclude that phase I is dominantly opening. Do you have evidences of tensile motions in the CMT?
- L118-165: they might be some redudancies with the following sub-sections. Please check.
- L129 and through the text: I was confused in the first set of review by what you call overpressure, sorry for that. It is now defined l199, which is late in the text. Maybe it could be better to speak about effective normal stress of -6MPa, to avoid amibiguity as overpressure commonly designed the pressure above the hydrostatic pressure, and not above the normal stress.
- L245: density of 1020 kg/m3 is here directly associated with CO_2, which is possible according to S5 (not mentioned here). How do you discard water, which seems also possible? Moreover, l251-523 seems to suggest that water may be a better candidate.
- Fig. 5: I still do not get why you consider the batch feeding Phase II has a lateral size of R1. In this case, there is no fluid diffusion on the fault, hence eq 3 and its discussion has no

meaning. Why are you not considering an injection with radius r1, in consequence of phase I?

- L249-253: Thank you for the explanation about the very low Vp/Vs. If I understand correctly, it means that vaporisation occurs dynamically when P-waves is passing, hence with a fluid very close from the transition gas/liquid?
- L257-265: The pressure and the density you use are inferred from a propagating crack (mode I), while you show that seismicity is dominantly shearing with a diffusive fluid (Thiem equation). Are the inferred values are still valid?
- L267-268: I can understand that geodesy rule out a pure tectonic forcing. However, the presence of a complex fault network is an additional difficulty to the processes at play. And complex fault network may lead to complex migration pattern (in particular 1D, bidirectional or unidirectionnal). As mentioned in first review, I think it can be good to discuss a bit more that complex fault networks may also lead to complex migrating patterns. At least, please stress that the model you proposed is one possible interpretation, but that data results cannot fully ruled out other possible models.

Rebuttal Letter for the Manuscript Titled: "Revived Earthquake Swarms: The Role of Magma in NW Bohemia/Vogtland"

To the Editors and Reviewers:

We sincerely thank you for the insightful and constructive feedback on our manuscript. Below, we provide a detailed response to each reviewer's comments in sequential order. Reviewer comments are presented in regular font, followed by our responses in blue. Line numbers refer to the revised version. Before addressing the editor and reviewers' comments individually, we provide below a summary of the major changes implemented in the revised manuscript:

Major Changes

1. **Improved Presentation of the Conceptual Model and Assumptions:** In response to reviewers' request, we revised the presentation of our analytical model. We now clearly define the physical assumptions related to hydrofracturing, hydro-shearing, buoyancy-driven fluid ascent, and overpressure estimations, supported by updated visualizations and model sketches (Figure 3 and 4).
2. **Expanded Discussion on Alternative Models:** We now present a broader and more structured discussion of alternative mechanisms, including CO_2-valve models and tectonic interactions. Furthermore, we discuss the possible **interactions between carbonate-rich melts and surrounding crustal rocks**, and include phase diagrams in the supplement. In particular, we highlight metasomatic processes and fenitization at ~10 km depth as potential contributors to transient overpressure. These mechanisms are presented as plausible alternatives in the revised discussion. Although we cannot provide direct observational evidence, relevant references have been added to support their consideration.
3. **Clarified Interpretation of "Undisturbed Rock" and Historical Context:** The statement regarding "undisturbed rock" has been clarified. We found literature from 1889, 1904 and 1920 describing historical swarms at Klingenthal, where the activity in 1897 appears similar to our observations in 2024. This is now mentioned in the introduction and the text has been reformulated and improved. In this context, we systematically reviewed historical seismicity and identified significant swarm activity in **1897** near the same region. We reconstructed the radiation patterns of the strongest events in the 1897 sequence and observed striking similarities to the 2024 swarm. These findings are now discussed in the main text, with supporting material provided in the supplementary section (Fig. S4).
4. **Expansion of Quantitative Fluid Intrusion Modeling:** We now present a two-phase fluid intrusion model constrained by physical parameters such as density contrast (Δρ), fracture toughness (Kc), and static overpressure (ΔP). The lateral extent and symmetry of the seismic cloud are quantitatively modeled to distinguish **Phase I** (CO_2-rich, high overpressure, bidirectional growth) from **Phase II** (melt/brine-rich, lower overpressure, radial growth). The

results are consistent with both observed Vp/Vs variations and stress drop differences. The method section on the VP/VS ratio in the source has been improved, and the possible mechanisms to explain temporary low VP/VS ratios close to melt intrusions are discussed.

5. **Additional Figures and Supporting Materials:** Several new figures were added including:
    - Phase diagrams and state properties of CO_2 and H_2O at relevant depths (Fig. 5),
    - Plots of regional and source-specific VP/VS ratios in different time windows (Fig. S6-S9),
    - Revised schematic illustrations of fluid batch ascent and swarm evolution (revised Figure 5),
    - Regional geological fault maps based on inventories from Bavaria, Saxony, and the Czech Republic (updated Figure 1).

Deputy Editor #1

Joe Aslin

Your manuscript titled "Revived Earthquake Swarms: The Role of Magma in NW Bohemia/Vogtland" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We sincerely thank Deputy Editor Dr. Joe Aslin for the constructive editorial guidance. We have addressed each of the editorial points in detail below:

In particular, please ensure that the revised manuscript meets the following editorial thresholds:

* Present a robust and compelling case that the 2024 seismic swarm in the Bohemia/Vogtland region was caused by ascension of magmatic fluids and that this can be demonstrated by the dense-array seismic observations.

We have strengthened the argument that the 2024 swarm was triggered by ascending magmatic fluids by integrating high-resolution seismic observations with fluid intrusion models. Over 8,000 events, revealing clear spatiotemporal patterns consistent with predicted fluid migration from models. In particular, we now show that the seismicity evolved from a bidirectional growth phase (high buoyancy, very low viscosity, small volume of fluids) to a radial growth phase (denser melt/brine intrusion, but significant smaller than mafic melts, larger volume, still very small viscosity). These patterns are supported by our modeling. We also added new supplementary figures showing phase diagrams of CO_2 and water, and Vp/Vs variations that further support the fluid-driven nature of the swarm.

* Ensure that your conclusions are fully supported by the data and results and fairly account for alternative explanations.

Our conclusions are firmly grounded in a robust dataset of over 8,000 well-located seismic events recorded by a dense seismic array, which reveals distinctive spatiotemporal patterns consistent with magmatic fluid ascent. The two-phase evolution of the 2024 Klingenthal-Kraslice swarm—from an initial vertical, bidirectional growth phase with high overpressure and buoyancy (indicative of CO_2-rich fluids) to a subsequent radial expansion phase with decreased fluid density difference and overpressure, but larger volume (suggesting melt or brine influx)—is quantitatively supported by our hydrofracture model. This model successfully reproduces key observed features, including the ascent from below, the seismic cloud geometry, and the change to larger shear cracks all with the same mechanism during the second phase of the swarm, thereby linking seismicity patterns directly to fluid properties and fracture mechanics. Derived fluid densities and fluid viscosities agree well with those for postulated magmatic fluids in the region.

We have carefully considered alternative explanations, such as purely tectonic stress changes or fluid migration unrelated to magmatic activity. However, these alternatives do not adequately account for the complex temporal evolution and fluid property changes inferred from our data. For example, tectonic models alone cannot explain the rapid shift from vertical to radial seismicity growth. Thus, while alternative mechanisms cannot be completely ruled out, the comprehensive integration of seismic, modeling, strongly supports the interpretation that mantle-derived magmatic fluids interacting with crustal fault zones triggered the 2024 swarm. This conclusion is fully supported by our data and provides the most consistent explanation of the observed phenomena. Additionally, we identify and discuss plausible type of fluids and their state/geochemical signature that could explain our observations.

* Describe your methods in detail to the extent that your work is fully reproducible. Please note that we allow up to 5,000 words in the main text plus unlimited space in the methods section.

In response to the editorial suggestion, we have significantly expanded the description of our methodology in the main text to ensure full transparency and reproducibility. We provide detailed explanations (or references to published work) of the underlying assumptions, governing equations, and parameter choices for our hydro-fracture model, including the physical basis for fluid overpressure, viscosity, density contrasts, and fracture propagation mechanics.

To maintain clarity and reader accessibility, we carefully balanced the level of detail in the main text while respecting the 5,000-word limit. Extensive additional information—such as derivations and supplementary figures illustrating model inputs and outputs—is provided in the dedicated methods section and supplementary materials. This allows readers to fully reproduce our results and facilitates future research based on our approach.

We believe these methodological expansions thoroughly address both editorial and reviewer comments and significantly enhance the reproducibility and robustness of our work.

Reviewer #1

Revived Earthquake Swarms: The Role of Magma in NW Bohemia/Vogtland

Dear editors, dear authors,

Please find below my comments on the ms by Büyükakpinar et al., submitted for publication in Communications Earth & Environment. This article presents a nice, comprehensive and detailed study of a seismic swarm occurring in 2024 in Bohemia/Vogtland area. This area show regular swarm activity, studied in pioneering articles on swarms. Therefore, this area is a perfect place to gain insights on swarm processes. This study includes detection and localization through novel IA algorithm, focal mechanisms and analysis of the migration patterns. It then compares the data with mechanical models to build a comprehensive story about the swarm processes. Overall, this study use up-to-date methods and concepts and it is clear and well-written.

However, I find that the model they develop is overly complex (involving several phases of injection, with different types of fluids and pressure levels) and it is poorly supported by the observations. It sounds correct and interesting, but the link between the data and the models does not allow to exclude other potential mechanisms. In particular, the presence of a magmatic dike propagation seems to be an a priori in this analysis, but not justified by data or references. Therefore, the interpretation goes beyond what can be proven/shown, leading to very strong and not fully justified statements (eg: role of magma in the title). At least, some discussion about alternative possibilities for the swarm processes, and why they can be discarded, may help convincing the reader on the validity of the interpretations.

I therefore suggest major revisions for this article. Please find below my detailed comments, in addition to major comments stated above.

We sincerely thank Reviewer #1 comments on our manuscript. In the revised manuscript, we carefully revisited our model. Rather than the magmatic component, we reshape our hypothesis consistent with observed dynamics. We characterize and constrain the physical properties of the fluids needed to explain observations, as e.g. fluid density, viscosity, or overall volume, and discuss which type of magmatic fluids fit the observations. Additionally, alternative models, —such as CO_2-triggered fault behavior, tectonic loading—are now discussed in more detail in a dedicated section of the “The role of magmatic fluids in driving swarms - discussion”, with the relevant references. We revised and improved the title, abstract, and conclusions accordingly. We added a clear summary of the analytical assumptions and physical parameters used to define the two phases of intrusion.

Detailed comments

General comments: please add line numbers to help the review process.

Line numbers have been added.

P2: "Our findings provide key insights for understanding fluid-driven deformation in geodynamically active regions worldwide.", or similar statement in the conclusion (p11). It is not straightforward as it stands, especially given the very complex you suggest at this end. please precise (other locations?, what insights?Etc.)

We rephrased and improved both the abstract and introduction (main). The last sentence of the abstract now states: "Our results emphasize the pivotal role of fluid overpressure and fault zone weakening in controlling swarm dynamics" (lines 26-27), and the last sentence of the introduction (main) is: "These findings are compared with alternative models and shed light on the crucial role of CO_2-rich magmatic fluids in the formation of recurrent earthquake swarms." (lines 58-59).

P2: "As this is the first time a swarm has evolved in undisturbed rock" is not clear, please reformulate.

Thank you for the comment. We found historical records from 1897, 1904, and 1920 that describe swarms near Klingenthal. One of these events, which occurred in 1897, was similar to the 2024 swarm. These records have been included and reformulated in the introduction, and a supplementary figure (Fig. S4) has been added. The sentence in question has been replaced (lines 46–52).

Fig 1: for what Neunhofer, Webnet and oseek stand for? How to you define the red area in c (all the seismicity in the KK square?)?

We have added the following clarifications to the Figure 1 caption:

- *Neunhöfer*: Earthquake catalog compiled by Horst Neunhöfer, documenting a weak swarm near Klingenthal between 1962–1997.
- *WEBNET*: It refers to the Czech regional seismic network operated by the Czech Academy of Sciences.
- *Qseek*: The high-resolution catalog for 2023–2024 obtained through machine learning (ML).

The red area in Fig. 1c corresponds to all seismic events within the black box delineated in Fig. 1A, which has been added to the caption. This area was defined by applying a ±2.5 km buffer around the 2023–2024 core swarm zone to account for uncertainties and to enable direct comparison with earlier seismicity, including the 1994 events.

P4: a few lines (in the main text, appendixes or supp) on the seismic stations (numbers, geometry, types of sensors, etc) may be useful.

A supplementary figure (Figure S1) and summary table of station locations, the network, and station codes has been added to the supplementary materials (Table S1). It is referenced in the main text.

P4: “unprecendented spatial resolution”: Could you comment in the method section on the resolution of the location? How does it compare to relative double-difference location?

The Qseek method, developed in our group, was recently published in Seismica (Isken et al., 2025, cited). In that paper, extensive tests and comparisons with other methods were performed, to assess resolution and other features. As for every location method, resolution, uncertainty, and other measures, depend on the station coverage and quality, the velocity model and other factors. We refer to the Qseek paper in the method section. A comparison to double difference location is not directly provided in the Qseek paper in 2025. However, the Qseek concept is based on a waveform attribute stacking approach. Precursor methods of this concept have been applied in the Vogtland region specifically and have been compared with conventional master event and double difference methods (Grigoli et al., 2016). According to the aforementioned study, stacking waveform attributes for earthquake swarms in the Vogtland region yields results comparable to those of the double difference method. We now explain this in more detail in the method section (Lines 542-547) and refer to Grigoli et al. (2016).

P4: “Conventionnal approaches … through the crust”. I do not get the aim of this sentence, please reformulate.

Thank you for pointing this out. We removed the sentence because it did not fit into the revised version.

P4-P5 “fracture developpment”, “hydro-shearing”, etc are already interpretations, not justified so far. Same in P6: “hydroshearing is prominent … larger hydrofracturing components”, but following your interpretation, stress drops are just showing higher pressure in the 1st phase than in the second one (even though variations of stress drop can be related to other interpretations, such as the differences in depth).

We deleted the “interpretation of hydro-shearing” and “fracture development” in this paragraph, as it will be discussed later. Accordingly corrected in a later paragraph of the text. We discussed the possible effects of earthquake depths on stress drop variations, and conclude that this cannot explain the observations, locations, including depth, have small uncertainties, because of the many stations in close distance. The borehole array GX.TIS00 is almost above the epicentre. The depth variation of events compared in Figure S3 is 0.25 km. A simple simulation of the effect of this depth variation on the corner frequency must be very small. We therefore think that the variation in corner frequency is related to a source and not a path effect. The text from has been improved.

Fig. S2: I am a bit confused, more details on this analysis may be needed. If you stack waveforms having different fc, you do not get a waveform that follows a Brune-type model (ie having a single corner frequency). Moreover, you can compare only events with same magnitude, so how do you select the events? Finally, as Phase 1 are deeper than Phase 2 events, differences in attenuation may lead to differences in spectrum.

Thank you to point out what was unclear. We can only compare events from Phase I and Phase II have the same spectral plateaus, meaning the same magnitudes. Because magnitudes during Phase I were in general small, the number of usable events with good quality and similar locations and depths are limited. We selected as subset the larger events from Phase I, and search for events of the same size (plateau) and at similar depth (similar S-P time) from Phase II for comparison. We checked the waveforms of selected traces individually, but present the stack of waveforms, which is similar (Figure S3a and b). Therefore, we are pretty sure that our events had similar locations and similar radiation patterns. The comparison of (stacked) spectra then tells us whether there are systematic differences in the rupture type or mode between Phase I and II, which is the case. We also compared spectra without stacking and come to the same conclusions, only that the spectra are not so smooth. We know this approach can have some risk for bias if the events are not carefully selected, but for the scope of our study find it sufficient. The caption description was improved.

P5: such low value of Vp/Vs are highly uncommon, and should be discussed more extensively. What mechanical models may explain such values, corresponding to null or negative Poisson's ratio?

The temporal reduction of Vp/Vs values during earthquake swarms and during dike intrusions has been observed before, even below sqrt(2) (see given references). Vp/Vs ratios below sqrt(2) can be associated to a medium that expands in all directions if loaded by tension in one direction. For instance, if the pore space is saturated by volatiles or gas, the Vp/Vs ratio becomes small. If the pore space is pressurized and would expand during the passage of a P wave, an overall response would occur similar to a substitute medium with negative Poisson ratio. If the pore space is filled by water or CO_2 brine, the reduction of Vp under constant Vs is not as dramatic, only if the fluid would vaporize during the early violent phase of a swarm. We can only speculate what could lead to such a behavior. For instance, CO_2 at the temperature in 10 km depth is in a supercritical state and cannot be vaporized if pressure would drop. Water could vaporize, but only if the pressure would drop dramatically during a short time. Rubin (1993) describes the mechanics how magma dikes grow at large depth in an undrained host rock. He emphasized the role of the tip cavities, that generate extensional forces and dike-parallel shear cracks if the viscous melt cannot flow quickly into the crack tip. The tip suction forces lead to influx of volatiles from the host rock and may lead to vaporization in the tip and rock volume, that experiences sudden extension. Even if geological evidence for this process is discussed in Rubin (1993), beside the theoretical and numerical simulations, we cannot estimate how effective the process might be. It would be fully in line with our model assumption, and could be a mechanism, to explain the massive hydrofracturing and intense brecciation that is documented in fenitization processes in the aurora of carbonatitic intrusions. A study we found from 1979 shows that such fracture zones have very low P wave velocities (Vartiainen and Paarme, 1979) – which is now also cited.

Other explanations might consider the effects of anisotropy from a predominant orienation of fractures and cracks (e.g. wing cracks), which may influence the Vp/Vs ratio estimated with Wadati diagrams. It is now mentioned , but more discussion is out of the scope of this article. While the smallest values of Vp/Vs in the beginning may therefore be taken with care, the general pattern and trends are robust and reproducible in several swarms. We improved the discussion in the main text, and also added supporting plots to the supplementary material.

P6: Bilateral (non radial) migration may be explained by several processes. In particular, control from the fault structure, such as intersection of faults lead to 1D migration. Moreover, considering the first points of the swarms, migration is dominantly downward. So, even if I fully agree with the model you propose, a bit more justification and discussion on alternative processes may be useful.

Thank you for the comments. It is correct that intersection of faults, or fault structure, can possibly explain 1D migration. We mention this now in the text. An important observation in our case is a change of the migration mode with time. While it is bidirectional in the first Phase I, it becomes radial during a later Phase II. The change in growth mode is difficult to explain by the intersection of faults alone. We moved the bidirectional and radial models paragraph into the main text, justify the arguments better and include alternative models in the discussion.

P6: You mention several times hydro-fracturing. However, a pressure of 6MPa seems quite small to generate hydro-fracturing at this depth. If estimation of the stress level exist in this area, comparing it with the inferred overpressure through a simple failure criterion may help.

Thank you for the comment. Maybe there was a misunderstanding, as we refer to overpressure, not injection pressure. Additionally, we recognized that the brief mentioning of tensional strength and failure criterions should be included, additionally to the references of Yuan et al, 2020 and Barros et al., 2021, which were given so far. Tensile strength of intact crustal rocks varies between 2-40 MPa (e.g. Pollard and Fletcher). Tensile strength of a pre-existing fault is expected even smaller. If overpressure against the normal stress on the fault would exceed the tensile strength, the rock will open as tensile fracture. However, the opening of tensile faults is controlled by the stress intensity factor Kc and the fracture toughness of the rock. Kc is determined by the overpressure and the length of the fracture (and elastic modules). If fractures have a length of few tens of meters or more, the overpressure to drive a tensile crack can actually be even smaller than the tensile strength. In our paper we talk about overpressure at the injection point, defining the pressure larger than the least principle stress. In contrary, for stimulation experiments, often the pressure at the well head is reported, For instance, if fluid would be injected in 3 km depth and the horizontal stress at this depth is 84 MPa, the injection pressure for water at the surface to reach 6 MPa overpressure at depth would be 60 MPa. For instance, as described in Rintamäki et al. (2025, BSSA) for the Otanmiei EGS injection, the least horizontal stress at 6 km depth was 110 MPa, the pore pressure was hydrostatic at 59 MPa, and the injection pressure to create hydrofractures was about 50 MPa. Adding the 50 MPa to the pore pressure leads to about 110 MPa, showing that the granite rocks fractured with only very little or none overpressure against Sh at 6 km depth. We now defined the term "overpressure" better and added an explanation in the text.

P8: In your model, you have a relation between v and r. Are you observing it with this data? The existence of an aseismic slip makes that migration may strongly differ from a purely diffusive law (see e.g. paper from Danré et al, 2022, 2024).

Thank you for the reference. Aseismic slip in combination with a fluid injection / intrusion is indeed a process that may explain growth of peak stresses and thus of seismicity clouds. The growth of the seismic cloud may differ from a purely diffusive law – we agree and give references. We agree that the radial growth during phase II, which we assume to occur under smaller overpressure and to involve the triggering of shear cracks from change in Coulomb stress, may involve aseismic shear dislocation. We mention this now in the text. We also do not interpret diffusivity in this case. We also improved the discussion on this aspects, and include alternative model.

P8: no back-front… Please add references, as there are several papers discussing about the existence of back-front during or after the injection stops.

We added references in the modeling part, which is now moved to the main text.

P8: The discussion of the two fluid batches with different types of fluids contents sounds like overinterpretation given the evidences from the data. I fully agree that dike propagation, as you propose is a possibility. However, based on your observations, could you discard that this seismicity pattern may be induced by water or CO2 with differences between both phases explained by eg a fault structural control?

We improved the discussions and also added alternative models. Structural control cannot explain the specific patterns we observe. As in any scientific discussion, our goal is to juxtapose possible explanations. We added now phase diagrams and estimates of densities for both, CO_2 and H_2O, for a depth of 10 km. These show clearly that CO_2 and H_2O have very similar properties and are therefore difficult to distinguish from the pattern of the seismic cloud alone. The clear change of the growth pattern between Phases I and II cannot be explained by the effect of H_2O different to CO_2. A fluid with different properties is needed (e.g. higher density). We have added the arguments for the proposed and alternative models to the discussion, to make a fair assessment for readers possible.

We agree with the reviewer that the model cannot be evidenced by seismicity data alone. We clarify this better in the manuscript. However, we point to the approach that the model is plausible. High flux of magma-released CO_2 is clearly observed in the Eger region, including He-isotope ratios in springs and surface mofettes that indicate carbonate-rich melts (as fluid inclusions in Xenoliths, references now added). Carbon-rich melt exsolves CO_2 and H_2O during ascent and may interaction with host rock, additionally creating fluids that are able to increase pore pressures and even hydrofracturing. Such secondary influx of melt or melt brine into micro fractures of the rock is documented in several geological and petrological studies on exposed carbonatitic rocks and rare earth element complexes which formed in the upper crust. We added references and improved the discussion. Thanks to the reviewers' comments and suggestions, the discussion is now very balanced and our observations and findings are well linked to the proposed models.

Fig. 4: something very hard to understand in this 3D view, as part of it is cut N-35°, while another part is cut E-W.

Thank you for the comment. We simplified the figure even more, and now the 3D view is easy to understand.

P9: The assumption of having the seismic cloud of the same size as the ascending fluid batch is odd, especially for phase 2 where you consider having fluid diffusion on the fault. The assumption of having the same structure size for both batches may seem geologically meaningful (especially since the pressure is lower for the second batch), leading to a same density for both batches. Please better justify your assumptions, and evaluate how it make change your interpretation.

Thank you for the suggestion. We improved our argumentation to justify the assumption. Note that this assumption is not critical for the overall interpretation. On the other hand, we were surprisingly impressed that the estimates fit very well to realistic fluid values, despite the model is simplifying.

P10: with your model, a overpressure of 6MPa and a density of 1200 kg/m3 produces bilateral migration because of buoyancy-induced pressure gradients, hence hydro- fracturing. How to make this observation consistent with EGS stimulation, where pressure is higher and fluid density lower (water), but migration is globally radial? Is it a matter of viscosity?

Thank you for the good question, which is not easy to answer. One aspect can be quickly clarified. EGS stimulations ususally do not aim to generate hydrofractures in a classical sense, therefore the realized overpressure is small (or even negative, see our comments above). This is very different to our “natural injections”. In our case, we assume 6 MPa and about 3 MPa overpressure in the very beginning of Phase I and II, respectively. This pressure exceeds the fault normal stress, and is therefore comparable to a high pressure injection ususally not realised in field experiments.

But even if we discuss hydro-shearing for EGS stimulation, and not isolated (sealed) hydrofractures, one may wonder why EGS seismicity often not clearly indicates predominantly updip growth (note that some cases indicate the trigegring of later earthquakes in updip direction, e.g. Rintamäki et al., 2025). We can only speculate on the reason, as (apparent) buoyancy forces should be present also for EGS low pressure stimulations. One reason could be that hydroshearing does not really change the permeability structure, very different to true hydrofractures. On other words, the speed of pore pressure diffusion depends on the pre-existing premeability structure, and is not controlled by the triggered shear cracks.

As the fault is not opening during shear cracks, adhesion forces will become more important compared to buoyancy. Both may explain why seismic clouds in low pressure EGS stimulations do not systematically grow upwards and in some cases even downward (e.g., Wong Chang and Yoon, 2022, Scientific Reports, where it is suggested that the migration pattern is controlled by the fault permeability).

Reviewer #2 (Remarks to the Author):

Thank you for your insightful study into the potential role of magma in NW Bohemia/Vogtland earthquake swarms. Your study could be an important contribution to the debate about which role fluids, and more specific magma, might play in the process of swarm earthquake activity. At the present stage the manuscript would benefit from moderate to major revisions, as I will express below, More detailed comments you will find in the annotated manuscript.

At first, you should make more clear what it means that a volume of "undisturbed rock" got activated during the studied 2024 earthquake swarm. As it can be seen from you figures, the area was active over the last decades and most probably the last century. Therefore, I would assume, that an existing fault zone got reactivated. What would be different, if actually an existing fault zone gets reactivated instead of fracking an undisturbed volume of rock? What is the general fault inventory of the study area?

The statement regarding "undisturbed rock" has been clarified. We found literature from 1889, 1904, and 1920 that describes historical swarms at Klingenthal. The activity in 1897 appears similar to our observations in 2024. This information has been added to the introduction, and the text has been revised. We reconstructed the radiation patterns of the strongest events in the 1897 sequence and observed striking similarities to the 2024 swarm. These findings are discussed in the main text, and supporting material is provided in the supplementary section (Fig. S4). The faults have been plotted in the revised Figure 1.

Many aspects mentioned in the manuscript are not yet fully documented, e.g., the double-difference Wadati plots. Also, uncertainties are not yet presented and discussed.

We have added a section to the Methods for the double-difference Wadati methods and added supplementary figures (Figures S6-S9). Uncertainties are displayed in Figure 2c.

Can you provide more information on the physical state of relevant fluids at mid-crustal levels, e.g., CO_2, water or more realistic brines, magma. What about host rock density variations throughout the studied crustal section? Could a change from lithostatic to hydrostatic pressure regime have an influence on the fluid/seismic activity? When/where CO_2 dissolves from fluids/brines?

Which parameters beside the density of the fluid can have a strong influence on the studied dynamics?

We added a phase diagram for CO2 and H2O to the supplement, where beside the state under a typical P-T-depth path the density, P wave velocity and viscosity is plotted. H2O and CO2 are the most important magmatic volatiles at 10 km depth, and the phase diagrams for pure material can be regarded as end member models. Anyway, as can be concluded, H2O and CO2 are very similar in the state, except that CO2 is in a supercritial state while H2O is not. This is now mentioned and briefly discussed. The change from a closed system (undrained, lithostatic) to an open system (hydrostatic) would change a lot, as overpressure cannot be realised. But this is not expected close to the brittle ductile transition, and is possibly occurring at much shallower depth. It could explain that in Vogtland / NW Bohemia earthquake swarms shallower than 8 km are rarely observed, if at all. We do not further discuss this, as it is not in the scope of our study because the Klingenthal swarm was deeper.

To me it is not yet clear at all, why you stack waveforms, and especially amplitude spectra (Fig. S2). Having similar magnitudes, that could in principle make sense for P and S waves individually, but not for P and S waves combined.

The earthquakes analyzed in our study are of relatively small magnitude (typically below ML 2), resulting in low signal-to-noise ratios (SNR), especially at higher frequencies. To enhance the SNR and obtain a stable average spectral shape, we chose to stack waveforms and amplitude spectra across several events. We acknowledge that stacking P and S waves together is a simplification; however, for the magnitude range we are dealing with, we found that separating P and S wave spectra did not significantly alter the qualitative shape or interpretation of the average source spectra. Therefore, we decided to keep this part as in Supplementary Figure S3. Nevertheless, we fully agree that a more detailed spectral analysis — separating phases and accounting for site and path effects — would provide deeper insights, and we consider this an important and separate work for future studies in this region.

The conclusions do not yet fit to the title. I would expect a more general discussion and conclusion about the potential role of magma in the earthquake swarm generation in NW Bohemia/Vogtland region. Until now, it is a bit too much focused on the 2024 swarm. Furthermore, it would be benefitial for the impact of your study, if you could provide also a more global perspective at the end.

We improved the title and added a full paragraph on alternative models, discussed on a broader scale. We think our study can demonstrate relevance on a global scale, The discussion has been improved to point this out. We close discussion with a more global perspective.

The manuscript text and especially the figures need some more elaboration. Some figures are very difficult to read (e.g., due to small font sizes, used color scales). You should also check the references. In my opionion, some relevant ones are missing.

Thank you for your valuable feedback on our manuscript. We carefully considered your comments and made several improvements in the revised version.

Specifically, we have elaborated further on the manuscript text and revised the figures to enhance clarity and readability. Adjustments were made to font sizes and color scales to ensure they are more accessible. Additionally, we revisited the references section and included several relevant works that were previously missing to strengthen the manuscript.

Please give reference to all station/data providers, including the institutes from Czech Republic. Are there dois available that could be referenced to?

Added. Please see the Data Availability Section.

In summary, your manuscript has a high potential to become an important reference in the debate on the role of magma/fluids in the generation of earthquake swarms, but it has to be improved in many aspects before. I hope my comments and questions will help you to improve your manuscript and the impact of the study.

We greatly value your detailed comments and questions. They have provided us with clear guidance on how to refine and improve our work. In the revised version, we addressed the points you raised in order to enhance the quality and impact of the study.

With best regards, Wolfram Geissler

Additional technical comment: the layout of the manuscript file was not great for review.

The attachment provided by Reviewer 2 regarding minor issues was considered during the revision process. We used the journal's Overleaf template, but we have now added line numbers to facilitate the review process.

Reviewer #3 (Remarks to the Author):

In this paper, the authors analyze the structural symmetry of an energetic swarm that occurred in the Vogtland after a long period of quiescence. This is an important region for studying and learning about swarms and the authors observe that this is a unique swarm in that for this region it was the first time that a swarm evolved in undisturbed rock. The authors conclude that the swarm resulted from hydro-fracturing and hydro-shearing from two different ascending magmatic fluids with differing buoyancies.

The analysis of the observations is very nice, and I have no comments on the data analysis. There is a complete analysis of the magnitude time history, locations, and source properties. The relation to Vp/Vs is solid and draws out nice attributes of the sequence. However, the link between observations and conclusions is weak. I attribute this to the short format of this paper and too much of a reliance on referring to other papers.

Thank you for your detailed review and positive feedback on our analysis of the observations, particularly regarding the magnitude time history, locations, source properties, and the relation to

Vp/Vs. To address suggestions, we have revised the manuscript to provide a more explicit and cohesive discussion of how our observations directly support the proposed conclusions. As suggested, we moved the paragraphs on our model into the main part, to improve readability. Specifically, we have expanded the sections where we interpret the data in the context of hydro-fracturing and hydro-shearing processes, as well as the involvement of two distinct magmatic fluids. We also improved the discussion on alternative models.

I recommend rejecting this paper and encourage the authors to develop this as a long format paper that has a detailed motivation of the proposed models. so that the observations can more clearly be compared. I understand that some of this information is in the Methods section, but in this short format, the paper is too disjoint to follow the arguments.

We have extensively improved the manuscript, paying close attention to enhancing the flow and coherence of our arguments. Specifically, we have extended the model Methodology (Hydro-fracture model for bidirectional and radial growth) section and moved the paragraph in to the main text to ensure that the motivation behind the models that were suggested and how they apply to observations are elaborated in greater detail. We believe these revisions&modifications have addressed the Reviewer's concerns within the journal's word limits. We hope this revised version better shows the strength and relevance of our research.

If this paper is to be accepted, I strongly recommend that the section Hydro-fracture model for bilateral and radial growth in Methods be moved to the body of the paper or at least the discussion around Figure 5. This is not really a Method and in my opinion that discussion would be better used as an introduction to the models for structuring the discussion surrounding Figure 3 and the conclusions in the paper. I am also confused by Figure 4, specifically, I do not understand what the gray shading is representing; also the offset in the horizontal layer does not correlate with the fault—there appear to be multiple offsets. It is not clear what my takeaway from this cartoon should be.

Thank you for your valuable suggestions regarding the organization and clarity of the manuscript.

We appreciate your recommendation to move the section *"Hydro-fracture model for bidirectional and radial growth"* from the Methods section to the main body of the paper, specifically in the discussion around Figure 5. Following your advice, we have repositioned this section to better integrate it into the core narrative. It now serves as an introduction to the models and provides a structured framework for discussing Figure 3 and our conclusions. We agree that this placement improves the coherence and flow of the manuscript.

Thank you again for your insightful feedback, which has helped us improve the clarity and structure of our work. We hope these revisions address your concerns effectively.

We thank the Reviewers again for their valuable feedback. The manuscript has undergone substantial revisions to address all comments comprehensively. We believe these changes have significantly improved the quality and clarity of our study. We look forward to your further feedback.

Sincerely,

Pinar Buyukakpinar and co-authors

Response to the Editor:

Your manuscript titled "Modelling of earthquake swarms indicates magmatic fluids in the Upper Crust Beneath the Eger Rift" has now been seen again by 3 reviewers, and we include their comments at the end of this message. They remain interested in your work, but some important points are retained. We also remain 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.

In particular please ensure that you adapt the interpretations and conclusions to match the level of support available, as questioned and highlighted by Reviewer #1.

We thank the Editor and all three Reviewers for their constructive feedback, which has improved our manuscript. We have addressed all points raised, as detailed below. The changes are highlighted in the annotated text, and our responses are indicated in italic and blue. Please note that all line numbers referenced in our responses correspond to the revised version of the manuscript.

Following the Editor's remarks—particularly those emphasizing Reviewer #1's concern—we carefully revised the manuscript by expanding and clarifying the discussion of alternative models that have been proposed for the Vogtland region. We emphasize that while our preferred interpretation is supported by the available evidence, we do not rule out other possible processes that may contribute to the observed swarm activity. This point has now been explicitly stated and further elaborated in the revised manuscript (see below and lines 269-286).

To date, a number of alternative models have been proposed for the Vogtland region. Purely tectonic models based on the interaction of fault networks [e.g., 39, 40] have now been ruled out, as modern geodetic data show only minor tectonic deformations, difficult to explain repeating swarms. Proposals that the swarms are triggered by exogenous environmental factors can also be ruled out [41]. Most proposals assume transients of CO_2 flow, sometimes linked to so-called valve mechanisms in fault zones [e.g., 42]. Decades of extensive measurements in Vogtland region mofettes show that flow transients can be triggered by different mechanisms and are therefore difficult to interpret [e.g. 43]. A possible problem with the flow-controlled valve model is that already small volumes of CO2 are sufficient to build up the excess pressure to reopen sealed fault patches, making it difficult to explain month-long swarms alone. However, detailed analyses show that the swarm patterns result from a combination of fluid intrusion and earthquake interactions driven by co- and postseismic stress transfer, which can explain their duration [44–46]. Similarly, CO_2 alone, which is light and tends to move upwards, cannot explain the incremental growth of the NK swarms in about 9 km depth horizontally over the length of more than 20 km since 1985, if not an unbroken sealed layer is assumed at approximately 7 km depth. **Although we cannot rule out that previously suggested processes, such as CO_2 driven pore-pressure diffusion in combination with earthquake-induced stress changes and rheological boundaries or fault complexity, might also explain the observations, our suggested model provides a straightforward and comprehensive explanation for the observed rapid bidirectional and radial migration phases and VP /VS changes.**

Response to Reviewers

Reviewer #1 (Remarks to the Author):

Dear editors and authors,

Please find my comments on the revised version of the manuscript by Büyükakpinar et al., submitted for publication in Communications Earth & Environment, below. The revisions made by the authors are helpful, as the manuscript is now easier to follow, particularly with regard to the link between the data and the model. However, I am still convinced that the model they proposed (nice and meaningful) is one possibility, among other ones. More specifically, 'fluid diffusion' alone within a pre-existing complex fault network may be consistent with the data results. The data cannot rule out this possibility, given that the main argument lies in the migration pattern of the seismicity. Such complex migration patterns are observed in other contexts worldwide (Japan, California, Greece, etc.) without the need for hydrofracturing or magmatic processes. As I asked in my initial review, these points should be emphasized more in the discussion to avoid readers directly interpreting 1D migration with back-front as hydrofracturing or magmatic fluid processes. I am not fully qualified to judge the scientific quality of the discussion on magmas, but it seems also to go too far given the results of the data.

We appreciate the reviewer's careful reading and critical comments. In our revised version, we already emphasized that the model proposed is plausible, but alternative explanations might be possible. We recognize that our discussion was possibly not complete enough, still. Therefore, in the revised manuscript, we have further clarified and expanded this part of the discussion (see lines 269–286; also see our response to *the Editor above). As described in the text and discussion, an interesting observations for the Klingenthal swam is that changes in the migration patterns occur. This is not very often observed and provides new constraints to elucidate and test the underlying processes.*

Lines (282-286): Although we cannot rule out that previously suggested processes, such as CO_2 driven pore-pressure diffusion in combination with earthquake-induced stress changes and rheological boundaries or fault complexity, might also explain the observations, our suggested model provides a straightforward and comprehensive explanation for the observed rapid bidirectional and radial migration phases and Vp/Vs changes.

Finally, I have a few minor concerns about the results and the clarity of some points. Taking these points into account, I still believe that the manuscript is worth publishing, but I apologize for asking again for some major revisions.

Thank you for the careful reading. We considered the minor comments point by point, see below:

Detailed comments

- title: "indicates" might sounds quite strong. Maybe change it by "suggests" (or "is consistent with")

We have changed "indicates" to "suggests" as recommended.

- l20: there is no proof of a reawakening, as the last swarm in this area was one century ago, without strong constraints on its location. 'activation' seems more suitable.

We have replaced "reawakening" with "activation" following the reviewer's suggestion.

- L100-107: Please refers to the figures in supplementary materials. Maybe you could give more details on the uncertainties to show how robust are these results as fits in Fig. S7b and S8b are not so convincing.

We have added references to Supplementary Figures (now S4 to S5). Additional details on how the uncertainties were estimated have been included in the Methods.

- In Fig. S3: Could you plot a Brune spectrum estimation and the noise level on each station? As you should work with event with same moment, Fig S3c and d should not be normalized.

We have added noise levels for each station to the Supplementary. Figures S8c and S8d (in the revised version now) have been corrected and are no longer normalized, as they correspond to events with the same moment. Since we are focusing on relative changes of the source spectrum (not necessarily Brune's model), the Brune spectrum is beyond the scope of our study and will be analyzed separately in another study.

- L116-117: This sounds as over-interpretation: from one EGS results where most (if not all) the seismicity is due to shearing events, I do not see how you can conclude that phase I is dominantly opening. Do you have evidences of tensile motions in the CMT?

We have clarified this part in the revised manuscript (Lines 118–121) as follows:
While high pore pressure, as exhibited in Phase I, can be associated with a greater contribution of distributed fluid flow and co-seismic volume expansion, which leads to slower rupture velocities, we attribute the higher corner frequencies to the higher rupture velocities associated with dominantly shear motion during Phase II.

ỗ L118-165: they might be some redudancies with the following sub-sections. Please check.

We have removed four sentences at the end of this section to remove redundancies with the subsequent sub-sections.

ỗ L129 and through the text: I was confused in the first set of review by what you call overpressure, sorry for that. It is now defined l199, which is late in the text. Maybe it could be better to speak about effective normal stress of -6MPa, to avoid amibiguity as overpressure commonly designed the pressure above the hydrostatic pressure, and not above the normal stress.

The term "negative effective normal stress" can be misleading for some readers, as we feel. Therefore, we want to keep the term "overpressure" and define it now earlier on line 132-133 (formerly 129).

ỗ L245: density of 1020 kg/m3 is here directly associated with CO2, which is possible according to S5 (not mentioned here). How do you discard water, which seems also possible? Moreover, l251-523 seems to suggest that water may be a better candidate.

Both possibilities were already mentioned. We have improved further the discussion to better present both possibilities: "A fluid density of 1020 kg/m³ could be explained by free CO_2 or by water near the critical point."

ỗ Fig. 5: I still do not get why you consider the batch feeding Phase II has a lateral size of R1. In this case, there is no fluid diffusion on the fault, hence eq 3 and its discussion has nomeaning. Why are you not considering an injection with radius r1, in consequence of phase I?

The discussion distinguishes what arrives from below (natural, buoyancy-driven batch of fluid, ascending towards the fault) and how fluid pressure diffuses when it intrudes into the fault. If the phase II batch would have the same dimension as the phase I batch before intrusion, it would have the same fluid density, the same overpressure at its tip and the same volume. The seismicity patterns that develops during the intrusion would be similar, having the same overall duration, intensity and magnitudes, mostly unidirectional growth, clear backfront, etc. However, we observe a clear change between phase I and II indicating that: overpressure was smaller, duration is longer (larger volume), growth pattern not preferentially up-down but radial (smaller buoyancy), no clear backfront. All this can be explained if the fluid in batch II has a larger density, larger volume, and larger lateral size, as it is predicted from the simple crack models. The fact that the second batch starts to intrude from the already broken portion on the fault is expected, because any fluid would first search its path using the already open segments on the fault. ***We further improve the text on line 259-261****.*

ⵃ L249-253: Thank you for the explanation about the very low Vp/Vs. If I understand correctly, it means that vaporisation occurs dynamically when P-waves is passing, hence with a fluid very close from the transition gas/liquid?

The fluid-rock-fault interactions at the brittle ductile transition are possibly complex and only poorly understood. We speculate on a possible scenario that could explain the observed temporary small Vp/Vs ratios. The processes are definitely dynamic. One option to reduce pressure for short time to vaporize fluids could be the passage of seismic waves, as you mention. However, we suggest (and cite) a process that is slower and related to the intrusion and growth of fluid filled cracks, where tip cavities and tensional suction forces can occur on distributed fractures (Rubin, 1993). The candidate *fluid component to vaporize is water.*

ঁ L257-265: The pressure and the density you use are inferred from a propagating crack (mode I), while you show that seismicity is dominantly shearing with a diffusive fluid (Thiem equation). Are the inferred values are still valid?

Here is a misunderstanding, as we describe something else in the manuscript. The overpressure and fluid density is derived from the assumption that a buoyancy-driven crack arrives from below. The solutions for these types of cracks are self-similar, and knowing the lateral extend is sufficient to estimate the density (equation after line 143-146). This can be related to the vertical length and thus to the overpressure at the tip (equation in line 143, estimated pressures in lines 151-154).
Using these values, it was very interesting for us to see that the evolution of the seismicity can be explained using hydrofracture models (figs 4c and d), for both phases I and II. We see this as a confirmation that the suggested model and process is realistic.

ঁ L267-268: I can understand that geodesy rule out a pure tectonic forcing. However, the
presence of a complex fault network is an additional difficulty to the processes at play. And complex fault network may lead to complex migration pattern (in particular 1D, bidirectional or unidirectionnal). As mentioned in first review, I think it can be good to discuss a bit more that complex fault networks may also lead to complex migrating patterns. At least, please stress that the model you proposed is one possible interpretation, but that data results cannot fully ruled out other possible models.

We have added a discussion in the manuscript acknowledging that our proposed model represents one possible interpretation and that the available data cannot fully rule out *alternative models. We also refer to our detailed reply to the editor above.*

Reviewer #2 (Remarks to the Author):

Dear authors,

thank you very much for your detailed response to the reviews and all the revisions made to the manuscript. In my opinion, the manuscript got very much improved. I would agree with reviewer 3 that the format of the selected journal is very challenging to present your study. Some disadvantages of this format remain after the revisions, e.g., I find it not perfect to have the figures illustrating parts of the methods then only in the supplementary material, and there these figures are presented without much context. Maybe it could be possible to place a few figures also in the methods section?

We sincerely thank Wolfram Geissler for his very positive evaluation and constructive suggestions, which have helped us to further improve the manuscript. After evaluation, ***we moved Fig. S5, which shows phase diagrams of H_2O and CO_2, to the end of the method section (Now Fig. 6)****, and added some descriptive text. The phase diagrams are indeed important for the understanding of the discussion of possible models. While the data plotted in the phase diagrams are not our own, the way we plot and compare is not widely available and very specific to the discussion we have. Thank you for the suggestion.*

I very much appreciate that you included a comparison to the 1897 earthquake that occurred in the same area as the 2024 earthquake swarm.

Thank you for the supporting statement. It is indeed very interesting.

I have only some minor additional comments and suggestions. You will find them in the annotated manuscript.

We thank the reviewer for the detailed annotations and suggestions provided in the annotated manuscript. We have carefully reviewed all comments and have incorporated them into the revised manuscript.

The most relevant to me I will list below:
Which definition of the local Magnitude ML do you use? How this definition compares to standard regionally applied ML formulas?

*Regarding the local magnitude definition, **we have now specified in the Methods section**: 'The local magnitude was calculated using the formula from Horálek et al. (2000).*

When you calculate the changes in the Vp/Vs ratios in the swarm volume, do you assume point sources for the individual events? How do you derive/define the uncertainties of the regional and source volume Vp/Vs ratios?

***We clarified that point sources were assumed** for individual events (method section) and explained how uncertainties were derived for both regional and source volume Vp/Vs ratios (line 421-422).*

Which peridotitic melts are you thinking of, basalts/nephelinites, or just more general?

Volcanic rock sampled in the Vogtland and Eger region indicates that nephelinitic magmas of small viscosity occasionally reached the surface (Mrlina et al., 2007;

Hrubcova et al., 2023; both now cited). ***Therefore, we agree and specified that we mean by peridotitic melts basalts/nephelinites (line 301).*** *Thank you for the suggestion.*

In some paragraphs, and also in parts of the Supplementary Materials, you should provide also references. Overall, the reference list looks very comprehensive.

We carefully reviewed the text and Supplementary Material to ensure that all statements are properly supported by references.

With best regards, Wolfram Geissler

Reviewer #3 (Remarks to the Author):

Review of revision for "Revived Earthquake Swarms: The Role of Magma in NW Bohemia/Vogtland" by P. Bükükakpinar and others
The re-organization of this paper and addition of a supplement directly responds to my past review. My additional comments below are editorial. The new paper is clearer with a consistent argument. I now recommend publishing.

Dear Reviewer,
We are very grateful for your positive review and positive recommendation for publication. Thank you for highlighting the improvements in clarity and consistency that we made to the revised manuscript.

One editorial comment that should be addressed. Lines 166 to 178 cite Figure 3 but refer to Figure 4. I recommend swapping Figure 3 and 4 so that the observations come first. Lines 179 to 189 also cite Figure 3, if you reorder figures as suggested these should be updated to Figure 4. Lines 220 to 231 would then reference figure 3 and Line 258.

Thank you for the suggestion. ***We corrected the typo on line 166 and cite there Figure 4.*** *We were also very positive to follow the suggestion of changing the order of the figures. When looking in detail, however, we found some problems in realizing it. Fig. 2 introduces the observations, including the visualization of the two different swarm phases and their migration (by color). Current Fig. 3 introduces the suggested model for the growth of the seismicity cloud. Then, Fig. 4 shows how the model predictions fit the observed growth. If we would change the order of figures 3 and 4, some readers may get confused. Therefore, after long discussion, we decided to keep the figure order as it was.*

I note a few other minor editorial comments below for the authors to consider (line numbers correspond to track changes version):

Line 106: suggest changing to “progressively extends bidirectionally”

Line 112: suggest changing to “down-dip directions along the fault”

Line 122: suggest Reykjanes Peninsula, Iceland”

All suggested changes (Line 92: "progressively extends bidirectionally"; Line 97: "down-dip directions along the fault"; Line 106: "Reykjanes Peninsula, Iceland") have been implemented.

On behalf of the co-authors,

Pinar Buyukakpinar

Dear Dr. Aslin,

We sincerely thank you and the reviewer for the valuable final comments and for giving us the opportunity to revise our manuscript. We have addressed the remaining minor suggestions as detailed in the response document. We are delighted that our manuscript has been accepted for publication in Communications Earth & Environment.

Sincerely,

Pınar Büyükakpınar on behalf of all co-authors

Reviewer #1 (Remarks to the Author):

Dear authors,

Thank you for the detailled responses on my comments. In my previous comments, I can just regret that the noise level has been added in an extra figure and not directly in fig. S8, and that a schematic Brune model (plateau + f^-2) was not added in this fig. These are still suggestions, up to the authors to follow them or not, but it may help to convince the readers on the change of the corner frequency. Exept this minor suggestion, I think the ms is now clear enough, giving strong and balanced results, and in good shape for being published. I therefore recommand publications for this article.

Response to Reviewer #1:

We sincerely thank the reviewer for the constructive suggestions and the positive assessment of our revised manuscript.

Regarding the presentation of the noise level, we decided to keep the noise figure separate in the Supplementary Material. Since the spectra are shown in different physical units, merging them could lead to confusion.

To improve the clarity of Fig. S8, instead of including a schematic Brune model (plateau + f^{-2}), we added a schematic source spectrum that extends to the high-frequency f^{-3} fall-off, providing a more generalized reference for comparison.

We greatly appreciate the reviewer's careful reading and helpful remarks, and we are grateful that our manuscript has now been accepted for publication in Communications Earth & Environment.