

Permeability Heterogeneity Controls Fluid Migration and Microseismicity Evolution in The Geysers Geothermal Field, California

Corresponding Author: Professor Lei Li

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This study utilizes modern deep learning algorithms and relocation methods to obtain an updated catalogue of the seismicity observed in The Geysers (TG) in the past decade. Authors describe the spatial clustering and the long-term migration of seismicity in example clusters to argue that fracture networks illuminated by the focal mechanisms explain the vertical migration of seismicity. Some flow modeling is also done to highlight the effects of these vertical fracture networks on the time-dependent pore pressure migration in the reservoir. I find the updated catalogue of seismicity is very impressive and expect that this new catalogue surely has the potential to reveal spatial heterogeneity and temporal evolutions that were not seen in past catalogues. However, unfortunately, I do not feel that this new catalogue is utilized to its potential to reach any new findings in this manuscript.

TG has been studied extensively for many decades, and it is challenging to comprehensively acknowledge past works and findings from this area. The authors do a fantastic job covering the literature in this regard. However, perhaps because of this, the manuscript is dominated by past interpretations, and it is not easy to distinguish what new interpretations came out of this manuscript. In the results section, interpretations from past works are cited and listed but are not substantiated by or linked to the new dataset. Interpretations should not be supported by citations, but the results of this study.

Line 144: "The observed clustering is attributable to lateral heterogeneity in reservoir permeability and rock strength, with localized stress concentrations and pre-existing geologic structure". Where was any of this demonstrated?

Line 149-153: This mention about the dynamically evolving permeability in the reservoir is placed here referring to another study, but this is not at all linked to results and observations made in this study.

Line 167: "suggesting that long-term injection-extraction cycles have enhanced permeability of near-wellbore zones". First, the movie is not provided. Also there is no mechanical reasoning provided except that it is citing another study.

Figure 4: This is a very general compilation of phenomenon that happens in a geothermal system suggested by past studies, but many of these are not linked to what specifically was found in this study. It is a good figure for a textbook, but I'm not sure how it helps to highlight the findings of this study.

Some of the interpreted trends are also not clearly demonstrated or presented in the dataset and plots.

Line 136: "despite comparable fluid injection and steam production volumes in both sections" Figure S5 shows pretty clearly that injection and production was less in the SE half of TG.

Figure 2c, 2d: These I assume were generated by stacking the 10 years of data and it also represents the entire NW part of the reservoir. Given that cluster depths were variable, does this average trend really represent true depth migration? If such a high resolution catalogue was obtained, why not evaluate at a more granular scale?

Line 191: Cluster #16 does not look like its dominated by strike-slip and normal faulting according to figure S9

Line 204: "given low magnitudes, these most likely formed by connection of many fractures" why? Can't we have small individual slips along a continuous fault plane?

Figure 3c: The migration of very subtle in 3D distance and horizontal distance. Moreover the trend is non-existent in the depth distance plot which seems to be the most important for this study interpreting the suggested vertical fracture system.

Line 261-263: Authors claim the refined catalogue reveals pervasive fluid pathways

Line 278: "local stress exhibit evident heterogeneity and rotation", stress was not discussed in the results of this manuscript

at all.

The manuscript suffers from redundancy too because many interpretations are listed in the results section and then repeated in the implications section. The manuscript would be improved by clearly distinguishing what is suggested by past studies versus what is supported by the new results. The new catalogue improves the resolution of the dataset significantly, but the analyses and interpretations made in this study do not match the resolution of the dataset.

[Minor comments]

Line 176: "constrained by vertical confining stress" I do not know what this means.

Figure S10: a rose diagram to show distribution of dip does not feel right. Dip only varies from 0-90 whereas a rose diagram spans 0-360 degrees.

Reviewer #2

(Remarks to the Author)

The manuscript by Li et al. presents a thorough and well-executed analysis of microseismicity at The Geysers Geothermal Field in California. The authors compile an exceptionally large seismic catalog using a machine-learning detection approach and apply a Markov Chain framework to identify coherent seismicity clusters. The resulting dataset reveals a clear and systematic migration of seismicity to greater depths, which is plausibly interpreted as pressure propagation along fractures extending below the injection wells. Focal mechanism analyses of selected clusters are broadly consistent with the inferred regional stress state, and first-order hydraulic modeling shows that an orthotropic permeability structure can successfully reproduce the main features of the observed migration.

Overall, this is a high-quality and carefully conducted study that makes a valuable contribution to our understanding of injection-induced seismicity. The seismic catalog itself is particularly impressive, not only because of the large number of detected events, but also due to the robust clustering and the derivation of a substantial number of high-quality focal mechanisms. I believe the manuscript is well suited for publication in Nature Communications.

I have only a few minor comments and requests for clarification that, if addressed, would further strengthen an already strong manuscript:

- The authors describe the seismicity as predominantly propagating downward from the injection region. In the modeling, the injection interval is assumed to span 500 m; however, it would be helpful to clarify how this assumption compares with the typical length of the open or perforated sections of the wells at The Geysers. In Fig. 2B, some seismicity appears to occur at shallower depths, which may suggest limited upward migration as well. A brief discussion of this observation would improve the clarity of the interpretation.
- In the focal mechanism analysis, Cluster 16 displays relatively complex behavior, with events distributed broadly in the octant plot and a noticeable fraction exhibiting reverse faulting mechanisms. Additional discussion of the possible physical meaning of this variability—such as local stress heterogeneity or structural complexity—would be valuable.
- In Case B of the hydraulic model, permeability is assumed to be higher in the vertical direction than both horizontal directions near the injection wells. Given the presence of steeply dipping faults, one might expect large permeability also in one of the horizontal direction. A short discussion clarifying this assumption, or commenting on the potential role of anisotropy within the horizontal plane, would help contextualize the modeling choices.
- The hydraulic model is intentionally simple and effective at capturing the first-order observations. Nevertheless, a short qualitative discussion of other potentially relevant processes at The Geysers, such as thermal or poroelastic effects, would further strengthen the manuscript by placing the results in a broader physical context.

In summary, this manuscript presents an impressive dataset and a convincing analysis, and the minor points raised above are intended to further clarify and enhance an already solid contribution.

Reviewer #3

(Remarks to the Author)

This study focuses on the evolutionary controlling effects of permeability and heterogeneity on fluid migration and microseismic activity, and conducts an exhaustive investigation of The Geysers geothermal field in California, USA, filling the gaps in relevant research in this region. A deep learning-based location framework is adopted to detect and locate a large number of seismic events, which greatly enriches the seismic catalog and thus enables the characterization of highly detailed microseismicity. Meanwhile, the Markov Clustering Algorithm is innovatively applied to cluster seismic distributions into several groups. Combined with focal mechanism inversion and pore pressure simulation, a highly comprehensive and complete study on seismic activity and fluid migration in The Geysers geothermal field is formed. This manuscript is well written, with highly novel methodologies and findings of significant scientific value, and is worthy of publication in Nature Communications. The following are my comments on this paper.

- (1) In the process of numerical simulation of pore pressure, the injection rate in the simulation parameters only accounts for 1% of the actual total injection volume. Its rationality remains to be verified, and more justifications for the selection of this ratio need to be elaborated. It is necessary to prove the rationality of the 1% total injection volume parameter and examine whether there is a deviation between this parameter and the actual situation of pore pressure diffusion and microseismic evolution.
- (2) Do panels C and D in Figure 2 target a single seismic cluster, or are they a combination of multiple clusters? How to interpret the relationship between the diffusion coefficient D , seismic distribution and depth migration? This part lacks

sufficient analysis in the paper. It is necessary to further supplement the figure annotations and conduct a detailed analysis of the relationship between the diffusion coefficient and depth migration.

(3) For the focal mechanism analysis, only three representative clusters are used for illustration. Can these three representative clusters reflect the conditions of the entire TG region? The selection criteria need to be further explained, and it is necessary to clarify whether more other statistical analyses have been conducted.

(4) The double-couple focal mechanism model is adopted in the study. Whether there are components such as volumetric expansion induced by fluid pressure perturbations, which can provide more explanations for the fracturing mechanism and microseismic activity, remains to be explored.

(5) Elements such as the curves in Figure 3C need to be explained in the legend. It is necessary to specify how the shaded areas are calculated and what the curves represent.

Overall, it is an interesting paper, and thank the authors for the contributions.

Version 1:

Reviewer comments:

Reviewer #3

(Remarks to the Author)

The authors carefully revised the manuscript according to the review comments. I recommend the publication of the paper.

Reviewer #4

(Remarks to the Author)

This manuscript describes the results of a rigorous and multifaceted study of micro-seismicity in the Geysers geothermal field and infers its likely causes. The study is based on a re-examination of the original digital continuous waveform data to produce a new high-resolution homogeneous earthquake catalogue that is able to identify locations of previously undetermined (mostly small) earthquakes and improve others, and examine the resulting spatiotemporal trends in the seismicity, including clustering, and the degree to which this can be interpreted as pre-existing, deformation-induced or deformation-enhanced pathways for high permeability.

From the rebuttal, it is clear the authors have undertaken significant extra work since the original submission, notably in conducting full moment tensor inversion, stress inversion, and Thermo-Hydro-Mechanical coupling simulations that incorporate anisotropic permeability to investigate how permeability heterogeneity and anisotropy control fluid migration and micro-seismicity evolution. This has allowed the team to identify poro-elastic effects as more important than thermos-elastic ones, and that near well-bore fluid pressure alone plays a more important role than either. They have also run sensitivity tests for these simulations under different plausible permeability conditions, conditioned on prior knowledge of the field, to prove the results are robust with respect to this source of uncertainty.

The authors also conducted additional analyses at finer temporal (1-3 years) and spatial scales (specific micro-seismic clusters), which suggest that the inferred depth migration trend is better interpreted as a cumulative, time- and depth-averaged effect at the regional scale, rather than expected depth migration for short-term or local micro-seismicity. I would agree the isotropic diffusion curve, while a reasonable null hypothesis, does not describe the data so well, and that this is not surprising given the degree of permeability anisotropy and long-range triggering at short timescales observed.

I did not have access to the original manuscript, but I would say the revised manuscript identifies the key novel findings from the new catalogue and associated analyses in a proper context, drawing from the wider literature as prior information, and I thought the distinction between novel findings and previous knowledge was generally clear. The findings themselves, particularly with the extra work, are also a significant advance on the prior literature on induced seismicity in the field.

I have some specific comments in terms of presentation and interpretation the authors may like to consider in minor revision, summarised below and in the annotate text.

1. The writing style sometimes presents an inference as stated fact. For example, the abstract (lines 24-25) states 'Our observations reveal distinctive clustering patterns and fracture systems tightly correlated with injection operations.' It would be more accurate to state 'inferred fracture systems' here (notably from the clustering, the association with the wellbore, the presence of a tensile component in the focal mechanisms, and low seismic velocities in independent tomographic studies). I would have high confidence in the inference due to this corroboration, but it is not an observation. Similar examples are given in context in the annotated manuscript.

2. The microseismicity is interpreted with some justifiable confidence as causing preferential fluid pathways (lines 148-149 and elsewhere). However, the deformation also increases local porosity and bulk storage, independently confirmed by the volumetric component of the moment tensor for some events. Storage is important because it affects the relevant boundary conditions in the model. For example, in one example, only a small proportion of injected volume was produced at the production well, e.g. Figure 2 of Li, X., et al. (2018). Induced Seismicity at the UK "Hot Dry Rock" Test Site for Geothermal

Energy Production, *Geophysical Journal International*, ggy135. <https://doi.org/10.1093/gji/ggy135>). This implied the dominant effect was an increase in storage rather than the creation of an efficient permeability pathway between injector and producer. This study also shows stress aligned anisotropy in the diffusion cloud, with faster diffusion of seismicity in the vertical directions, although with a more even spread in the upward and downward directions consistent with the absence of a shallow barrier. At present the manuscript does not explicitly consider storage as such, but this must (or should be) be a feature of the model that could be addressed explicitly.

3. The text does not explicitly state whether or not the software used accounts for long-range poroelasticity in the model due to associated changes in effective stress throughout the medium, as in e.g. Segall (1989. Earthquakes triggered by fluid extraction, *Geology*, 17, 942–946). Long range triggering is also enabled by pre-existing near critical stress states in the far field (Maillot et al., 1999. Numerical simulation of seismicity due to fluid injection in a brittle poro-elastic medium, *Geophys. J. Int.* 139, 263-272), that are in turn consistent with long range triggering in the Geysers field from remote earthquakes (Hill D.P. et al. 1993. Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake, *Science*, 260, 1617–1623). In any case it would be helpful to clarify on first use of the term that the poroelastic component of the model does involve a full solution which incorporates both local and long-range triggering.

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Reviewer #1 (Remarks to the Author):

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TG has been studied extensively for many decades, and it is challenging to comprehensively acknowledge past works and findings from this area. The authors do a fantastic job covering the literature in this regard. However, perhaps because of this, the manuscript is dominated by past interpretations, and it is not easy to distinguish what new interpretations came out of this manuscript. In the results section, interpretations from past works are cited and listed but are not substantiated by or linked to the new dataset. Interpretations should not be supported by citations, but the results of this study.

Response: Thank you for your professional and thorough review. We have carefully considered all your comments and have revised the manuscript accordingly to better convey the main findings of the study and their potential significance.

As you said, TG geothermal field has been studied extensively for decades. The basis of our study is the construction of, to the best of our knowledge, the first decade-scale deep-learning-based microseismic catalog for this region. Using this enhanced catalogue, we applied an effective Markov clustering algorithm, which produced well-resolved clustering results in the resulting catalog. In the revised manuscript, we further conducted full moment tensor inversion, stress inversion, and THM coupling simulations that incorporate anisotropic permeability. From multiple perspectives, we investigate how permeability heterogeneity and anisotropy control fluid migration and microseismicity evolution. The refined catalog and the THM coupling simulation indicate that the TG microseismic clusters are mostly driven by near-borehole fluid pressure perturbations, and the poroelastic effects play a more significant role compared to thermal stress.

(1) Line 144: "The observed clustering is attributable to lateral heterogeneity in reservoir permeability and rock strength, with localized stress concentrations and pre-

existing geologic structure". Where was any of this demonstrated?

Response: The refined catalog and enhanced clustering show a reservoir-scale heterogeneous distribution of fluid pathways and fracture network, which is indicative of lateral heterogeneity in reservoir permeability. We supplemented stress inversions for three representative clusters and found temporal changes in the stress field, including stress rotations, reflecting stress perturbations from field operations (**Supplementary Fig. 13**).

We also revised the former pure diffusion modeling with more comprehensive THM coupling simulations under different permeability conditions. We added two additional fault configurations to assess first-order effects of geostructures on microseismic activity. The magnitude and footprint of the fluid pressure, vertical displacement, and temperature are demonstrated in **Supplementary Figs. S18 and S19**. More explanations have been added to emphasize the influence of heterogeneity, in both the main text and the Supplementary Material.

Besides, previous studies suggested the reservoir hosts fracture networks with varying orientations, segmented by Quaternary faults into multiple isolated compartments bounded by low-permeability fault zones. We believe that these factors jointly control the clustering pattern of microseismic events. We have revised the sentence as "The observed clustering of microseismicity could be attributable to lateral heterogeneity in reservoir permeability, localized stress concentrations, and pre-existing geologic structures" and added more explanations as **Supplementary Text 2**.

(2) Line 149-153: This mention about the dynamically evolving permeability in the reservoir is placed here referring to another study, but this is not at all linked to results and observations made in this study.

Response: Our intention was to emphasize that the clustering results presented here effectively delineate the existence and strong heterogeneity of fluid pathways in the current reservoir. In particular, compared with an originally low-permeability reservoir (**Supplementary Text 1**), the observed microseismic clusters, together with the source mechanism analysis of representative clusters and the pore-pressure simulation results, consistently indicate pronounced permeability heterogeneity and anisotropy associated with preferential fluid pathways. On this basis, we infer that long-term injection and production operations may have progressively enhanced this heterogeneity and anisotropy over decadal timescales. Although this inference is not established through a direct comparison with previous seismic datasets, it is supported by multiple observations. We have therefore revised the text as "Therefore, on decadal timescales, sustained injection and production operations may progressively increase the permeability heterogeneity and anisotropy of the originally low-permeability reservoir by promoting the development of preferential fluid pathways. Previous seismic

tomography studies have suggested changes in reservoir saturation condition and hydraulic structure, further supporting the presence of fluid pathways and their temporal evolution”.

(3) Line 167: "suggesting that long-term injection-extraction cycles have enhanced permeability of near-wellbore zones". First, the movie is not provided. Also there is no mechanical reasoning provided except that it is citing another study.

Response: The Movies can be downloaded via the Zenodo link and now we added corresponding instructions in the Data availability section and in the Supplementary file.

The permeability enhancement of near-wellbore zones is the cumulative result of long-term pore-pressure perturbation and thermal stressing around the injection/production wells. Injection increases pore pressure and reduces effective normal stress on critically stressed pre-existing fractures, promoting shear slip. The asperity self-propping can produce fracture dilation and enhance permeability. In addition, cold-water injection generates thermal contraction and stress redistribution in the surrounding rock, which can further promote shear slip, thermal cracking, and the creation of connected flow paths. These mechanisms have been identified by many geothermal projects and now we added these mechanical reasoning as “...enhanced the permeability of near-wellbore zones (e.g., shear zones) by pre-existing fractures opening/shearing, shear dilation, and thermal cracking”.

(4) Figure 4: This is a very general compilation of phenomenon that happens in a geothermal system suggested by past studies, but many of these are not linked to what specifically was found in this study. It is a good figure for a textbook, but I’ m not sure how it helps to highlight the findings of this study.

Response: The figure is intended to synthesize the specific findings of this study rather than to provide a generic conceptual summary of geothermal systems. Its main purpose is to highlight that our refined microseismic analysis reveals strong heterogeneity in reservoir permeability and a fluid diffusion (pore pressure) controlled microseismic response. In particular, the figure is designed to show resolved preferential fluid migration pathways and permeability heterogeneity/anisotropy at a fine scale. Such a fine scale analysis from extensive microseismic inversion is still relatively uncommon in geothermal studies. In addition, we used numerical simulations to verify the pore pressure diffusion patterns expected under different permeability heterogeneity/anisotropy scenarios. Results suggest that near-wellbore fluid pressure plays a more important role than poroelastic and thermal stress effects (smaller font sizes in the figure) in fluid migration and microseismicity evolution.

Some of the interpreted trends are also not clearly demonstrated or presented in the dataset and plots.

(5) Line 136: "despite comparable fluid injection and steam production volumes in both sections" Figure S5 shows pretty clearly that injection and production was less in the SE half of TG.

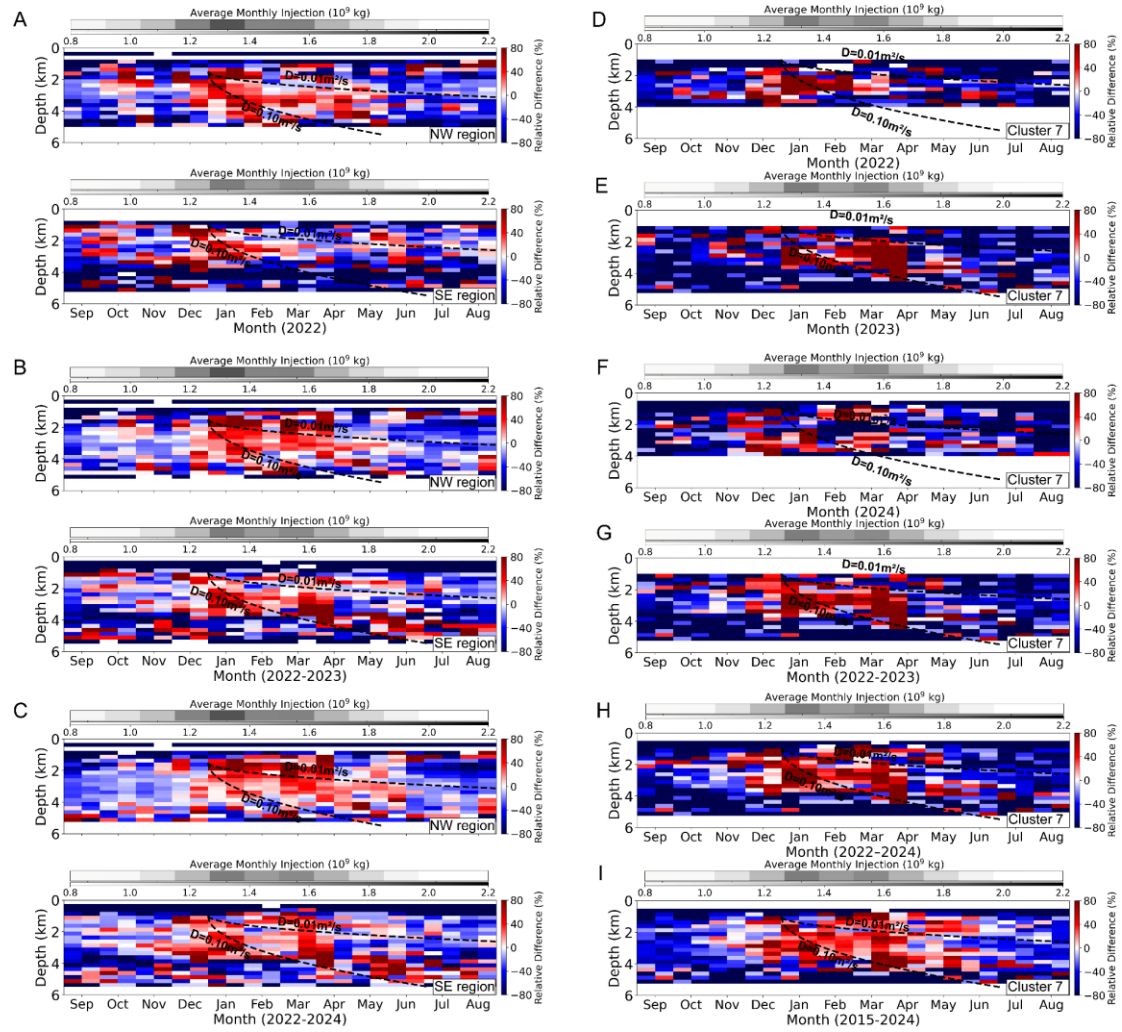
Response: Thank you for your careful observation. The differences are relatively small in magnitude, with the NW section exceeding the SE section by only 3.64% in injection volume and 0.78% in steam production. From a relative perspective, these differences are minor, especially compared with the much stronger contrast (~7:3) in seismicity between the two sections. Nevertheless, because the NW values are still systematically higher considering the total volume. We therefore revised the word from “comparable” to “slightly higher” in the text and figure caption.

(6) Figure 2c, 2d: These I assume were generated by stacking the 10 years of data and it also represents the entire NW part of the reservoir. Given that cluster depths were variable, does this average trend really represent true depth migration? If such a high resolution catalogue was obtained, why not evaluate at a more granular scale?

Response: We appreciate your questioning about the robustness of the depth migration hypothesis, as it prompted us to re-examine this observation at a finer scale. In the original manuscript, we interpreted the overall depth migration pattern of all clusters using the classical diffusion curves ($\sqrt{4\pi Dt}$), which yielded results basically consistent with previous studies. Following your suggestion, we conducted additional analyses at finer temporal (1-3 years) and spatial scales (specific microseismic clusters). These results suggest that the inferred depth migration trend is better interpreted as a cumulative, time- and depth-averaged effect at the regional scale, rather than expected depth migration for short-term or local microseismicity. Although the diffusion curve provides a reasonable first-order description of the long-term, regional-scale trend, it does not adequately capture the behavior of microseismicity over short periods or within single clusters (see below Supplementary Fig. 8).

This conclusion is consistent with the behavior of Cluster 7 in Figure 3C, where events occur rapidly across a broad depth range, suggesting rapid vertical fluid and pore pressure diffusion, rather than a delayed diffusion process. This is an important new finding of this study that long-term regional depth migration does not necessarily reflect short-term or local fluid/microseismicity migration behavior. Instead, prolonged injection and production may have established relatively stable flow pathways and permeability heterogeneity and anisotropy.

We have revised the manuscript accordingly to incorporate additional fine-scale analyses and discussion (Page 8 Lines 166-172).



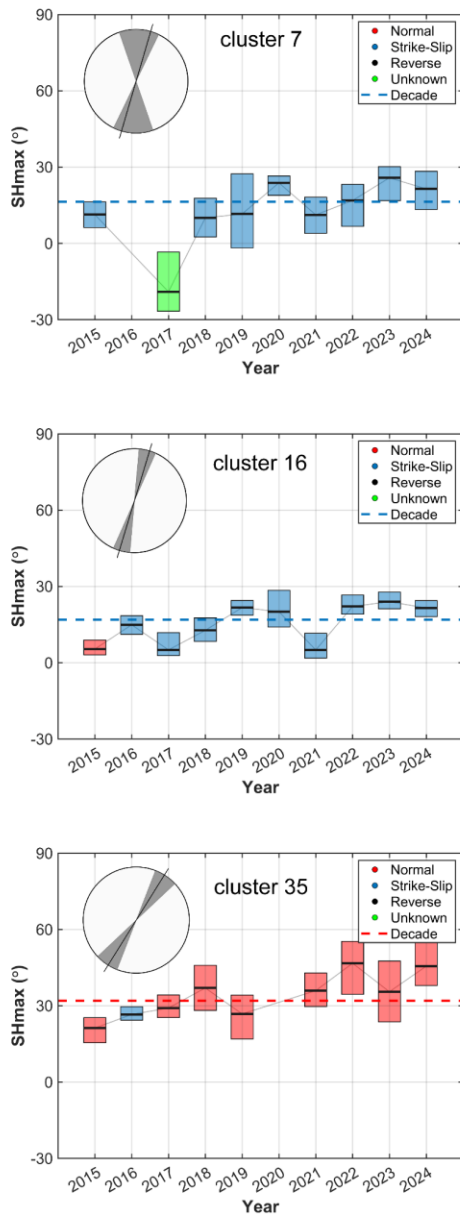
Supplementary Fig. 8 The percentage above or below the average number of clustered events in the NW (A)-(C), SE (A)-(C), and Cluster 7 (D-I) regions for each depth interval (0.25 km) is shown, where warm colors indicate more events and cool colors indicate fewer events. The thick dashed black lines correspond to the diffusion distance for diffusivities of 0.01 and 0.10 m^2/s , with the injection depth set at 1.5 km and 1.0 km for NW and SE region, respectively. As the observation period increases, the cumulative and averaging effects of microseismicity migration along the depth direction become more pronounced, whereas short-term (1-3 year) microseismic responses are less suitable for characterization using a diffusion curve.

(7) Line 191: Cluster #16 does not look like its dominated by strike-slip and normal faulting according to figure S9

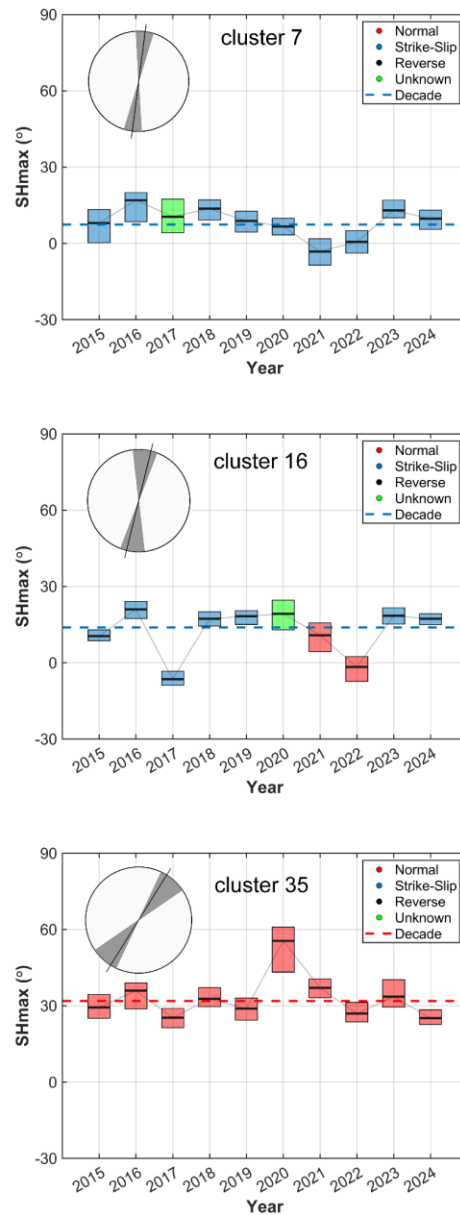
Response: We also noted that Cluster 16 exhibits relatively more complex source mechanisms and faulting regimes. One possible explanation is the stronger influence of field operations, i.e. intensive injection and production activities, in this area (Supplementary Fig. 5). To further investigate this issue, we supplemented the analysis with full moment tensor inversion and stress inversion. Compared with the double-

couple solutions, the full moment tensor results yield fewer low-angle reverse-faulting events. The stress inversion results indicate that Cluster 16 is predominantly characterized by a strike-slip stress regime. However, both the variation in SHmax orientation and the changes in stress regime are indeed more complex than in the other clusters (see below Supplementary Fig. 13). We therefore infer that local stress perturbations associated with field operations play a significant role in this cluster. We added more discussions as “Cluster 16 exhibits a more pronounced temporal rotation of the principal stress orientations, together with the relatively intense injection and production activity in this region, implies a stronger industrial perturbation of the local stress field.”.

A



B



Supplementary Fig. 13 Annual variations in the orientation of the SHmax for the three

clusters, using the results from SKHASH (A) and NaNDC (B). The boxplots illustrate the inversion uncertainty, while the gray shading within the circle in the upper-left corner represents the range of variation in the SHmax for each cluster over the past decade.

(8) Line 204: "given low magnitudes, these most likely formed by connection of many fractures" why? Can't we have small individual slips along a continuous fault plane?

Response: We do not exclude the possibility that some events reflect small slips on locally continuous fault segments. However, we consider it less likely that the entire cluster represents small slips on a single continuous fault plane. Seismicity extends over ~3 km vertically and ~1 km horizontally, implying a relatively large and persistent structure if interpreted as one fault. To our knowledge, existing structural studies of TG emphasize a complex reservoir-scale fault/fracture system and bounding fault zones.

In addition, previous analyses at The Geysers show that operations commonly reactivate pre-existing fractures with variable orientations, and our source mechanism inversion results also show shear-dominated events with non-negligible non-double-couple components (Fig. 3A and Supplementary Figs. 13 and 14), which is more consistent with slip and opening on multiple small fractures with different orientations and local stress conditions. Therefore, we interpret the observed cluster(s) as more likely representing a connected fracture system composed of multiple small-scale fractures/fault segments. We have revised the text by adding "small slips on locally continuous fault segments".

(9) Figure 3c: The migration of very subtle in 3D distance and horizontal distance. Moreover the trend is non-existent in the depth distance plot which seems to be the most important for this study interpreting the suggested vertical fracture system.

Response: The original Figure. 3C was not well presented and sufficiently explained (also noted by Reviewer 3). As you can see, the migration trends in all subplots are subtle, the occurrence of microseismic events shows a relatively flat temporal pattern rather than the delayed progression expected from a diffusion process. In other words, both near-field and far-field events, as well as shallow and deep events, appear rapidly following fluid injection and production, without an observable diffusion delay.

To make this comparison clearer, we have additionally plotted reference diffusion curves in the revised figure, assuming the estimated injection point as the source and taking the first day of each year as the start time. These curves are intended only as a reference framework for comparison, to better highlight the contrast between the expected diffusion-controlled migration and the observed microseismic spatiotemporal evolution. We have therefore revised both the figure annotation and the text to clarify

the spatiotemporal migration characteristics shown in this figure. This observation is consistent with our revised interpretation that the apparent long-term depth migration identified at the regional scale could not denote short-term or cluster-specific behavior.

(10) Line 261-263: Authors claim the refined catalogue reveals pervasive fluid pathways

Response: Our interpretation is based on several observations from the refined catalogue and subsequent source mechanism analysis. First, the enhanced clustering with refined catalogue exhibits clear spatial clustering, which can basically characterize the direct fluid diffusion domain and preferential pathways. Second, the detailed analysis of Cluster 7 further indicates a possible vertical pathway for fluid and pore pressure diffusion. In particular, source moment tensors show clear isotropic components, which denote fracture opening/closure and therefore provide more direct evidence for fluid migration. Third, we further note the existence of similar/repeated earthquakes (although these are not the primary focus of the present study). Their occurrence may reflect the repeated opening and slip of fractures along relatively stable conduits established during long-term injection and production. This provides additional, albeit indirect, evidence of persistent fluid pathways. To better explain the microseismic clusters and fluid pathways, we added more explanations as **Supplementary Text 2**.

(11) Line 278: “local stress exhibit evident heterogeneity and rotation” , stress was not discussed in the results of this manuscript at all.

Response: We have supplemented stress inversion analysis based on source mechanisms derived from two source models (double-couple source model and full moment tensor source model). The stress inversion results obtained from the two sets of source mechanism inputs are basically consistent (see above Supplementary Fig. 13). The new results show that the SHmax orientation varies from year to year, and that different clusters are governed by different stress regimes. In particular, Cluster 16 exhibits relatively stronger local stress variation than the other clusters. We infer that this behavior is partially associated with stronger operational influences (i.e. injection and production activity, see Supplementary Fig. 5) in this area. The corresponding stress inversion results, discussion (Pages 9-10), and methodological description (Pages 18-19) have now been added to the revised manuscript.

(12) The manuscript suffers from redundancy too because many interpretations are listed in the results section and then repeated in the implications section. The

manuscript would be improved by clearly distinguishing what is suggested by past studies versus what is supported by the new results. The new catalogue improves the resolution of the dataset significantly, but the analyses and interpretations made in this study do not match the resolution of the dataset.

Response: We have minimized the redundancy between the Results and Implications sections by removing repeated interpretive statements and emphasizing the key observations from the new catalogue and associated analyses. In the revised Implication section, we now emphasize the new results and understanding obtained from the high-resolution catalogue, including fluid migration characteristics at smaller spatiotemporal scales, local stress inversion, and novel THM simulations that incorporate anisotropic permeability.

[Minor comments]

(13) Line 176: "constrained by vertical confining stress" I do not know what this means.

Response: We agree that “vertical confining stresses” is potentially ambiguous. Our intent was to describe the vertical confinement/stress barriers that limit fracture growth in the vertical direction (fracture height) and thereby promote lateral fluid migration and microseismicity evolution. We have therefore revised the text to use a more precise expression “minimum horizontal stress contrasts between layers (referred to as stress barriers)”.

(14) Figure S10: a rose diagram to show distribution of dip does not feel right. Dip only varies from 0-90 whereas a rose diagram spans 0-360 degrees.

Response: We have revised the figures so that the dip distribution is shown only over the 0-90 degree range.

Reviewer #2 (Remarks to the Author):

The manuscript by Li et al. presents a thorough and well-executed analysis of microseismicity at The Geysers Geothermal Field in California. The authors compile an exceptionally large seismic catalog using a machine-learning detection approach and apply a Markov Chain framework to identify coherent seismicity clusters. The resulting dataset reveals a clear and systematic migration of seismicity to greater depths, which is plausibly interpreted as pressure propagation along fractures extending below the injection wells. Focal mechanism analyses of selected clusters are broadly consistent with the inferred regional stress state, and first-order hydraulic modeling shows that an orthotropic permeability structure can successfully reproduce the main features of the observed migration.

Overall, this is a high-quality and carefully conducted study that makes a valuable contribution to our understanding of injection-induced seismicity. The seismic catalog itself is particularly impressive, not only because of the large number of detected events, but also due to the robust clustering and the derivation of a substantial number of high-quality focal mechanisms. I believe the manuscript is well suited for publication in Nature Communications.

Response: We sincerely thank you for this positive and encouraging assessment of our work. We are pleased that you recognize the quality of the seismic catalog, including the large number of detected events, the robust clustering analysis, and the substantial set of high-quality focal mechanisms. Following your comments, we have further strengthened the manuscript by conducting additional moment tensor inversion (MTI) and THM coupling simulations. We have also included results from an alternative clustering approach (i.e. DBSCAN) and additional stress analyses to address other reviewers' concerns, further highlighting new insights into the roles of permeability heterogeneity and anisotropy in controlling fluid flow and microseismic activity. We believe that these new analyses provide further support for our interpretations and enhance the overall quality and impact of the study.

I have only a few minor comments and requests for clarification that, if addressed, would further strengthen an already strong manuscript:

(1)- The authors describe the seismicity as predominantly propagating downward from the injection region. In the modeling, the injection interval is assumed to span 500 m; however, it would be helpful to clarify how this assumption compares with the typical length of the open or perforated sections of the wells at The Geysers. In Fig. 2B, some seismicity appears to occur at shallower depths, which may suggest limited upward migration as well. A brief discussion of this observation would improve the clarity of the interpretation.

Response: The 500 m injection interval in the modeling is set based on previous studies

and the reported injection-depth distributions at The Geysers. Previous studies show that injection depths for the 49 highest-volume injection wells fall within relatively confined depth ranges (Gritto et al., 2014; Johnson et al., 2016): in the NW, more than 95% of injection depths are between 0.9 and 1.5 km, and in the SE, more than 90% are between 0 and 0.9 km. Therefore, we believe that the 500 m injection interval adopted in our model is a reasonable assumption. We have added this explanation to the new **Supplementary Text 3** to clarify the parameter choice.

The occurrence of shallower events (Figs. 2B-2D and Fig. 3C) suggests that upward fluid migration through near-wellbore pathways. We infer that these pathways were generated by long-term injection-extraction cycles and have enhanced the permeability of near-wellbore zones (e.g., shear zones), by pre-existing fractures opening/shearing, shear dilation, and thermal cracking. It is clear that seismicity is more developed at greater depths, especially from the perspective of long-term observations. This asymmetry is mainly controlled by at least two factors. First, fracture connectivity and permeability are strongly heterogeneous, so pressure diffusion can be different at different depths. Second, the preferential downward propagation of fluid pressure is likely governed by the low permeability of the caprock. As indicated by the geological map of Garcia et al. (2016), most injection wells penetrated the caprock, thereby restricting upward pressure diffusion. We have added a brief discussion in the text as “Stronger microseismic activity at depth than at shallow reservoirs might be attributed to the combined influence of limited stimulation and low permeability of the caprock.”.

Gritto, R., D. Dreger, O. Heidbach, and L. Hutchings. Towards the understanding of induced seismicity in enhanced geothermal systems. 210 (2014).

Johnson, C. W., Totten, E. J. & Bürgmann, R. Depth migration of seasonally induced seismicity at The Geysers geothermal field. Geophysical Research Letters 43, 6196 – 6204 (2016).

Garcia, J. et al. The Northwest Geysers EGS Demonstration Project, California – Part 1: Characterization and reservoir response to injection. Geothermics 63, 97–119 (2016).

(2)- In the focal mechanism analysis, Cluster 16 displays relatively complex behavior, with events distributed broadly in the octant plot and a noticeable fraction exhibiting reverse faulting mechanisms. Additional discussion of the possible physical meaning of this variability—such as local stress heterogeneity or structural complexity—would be valuable.

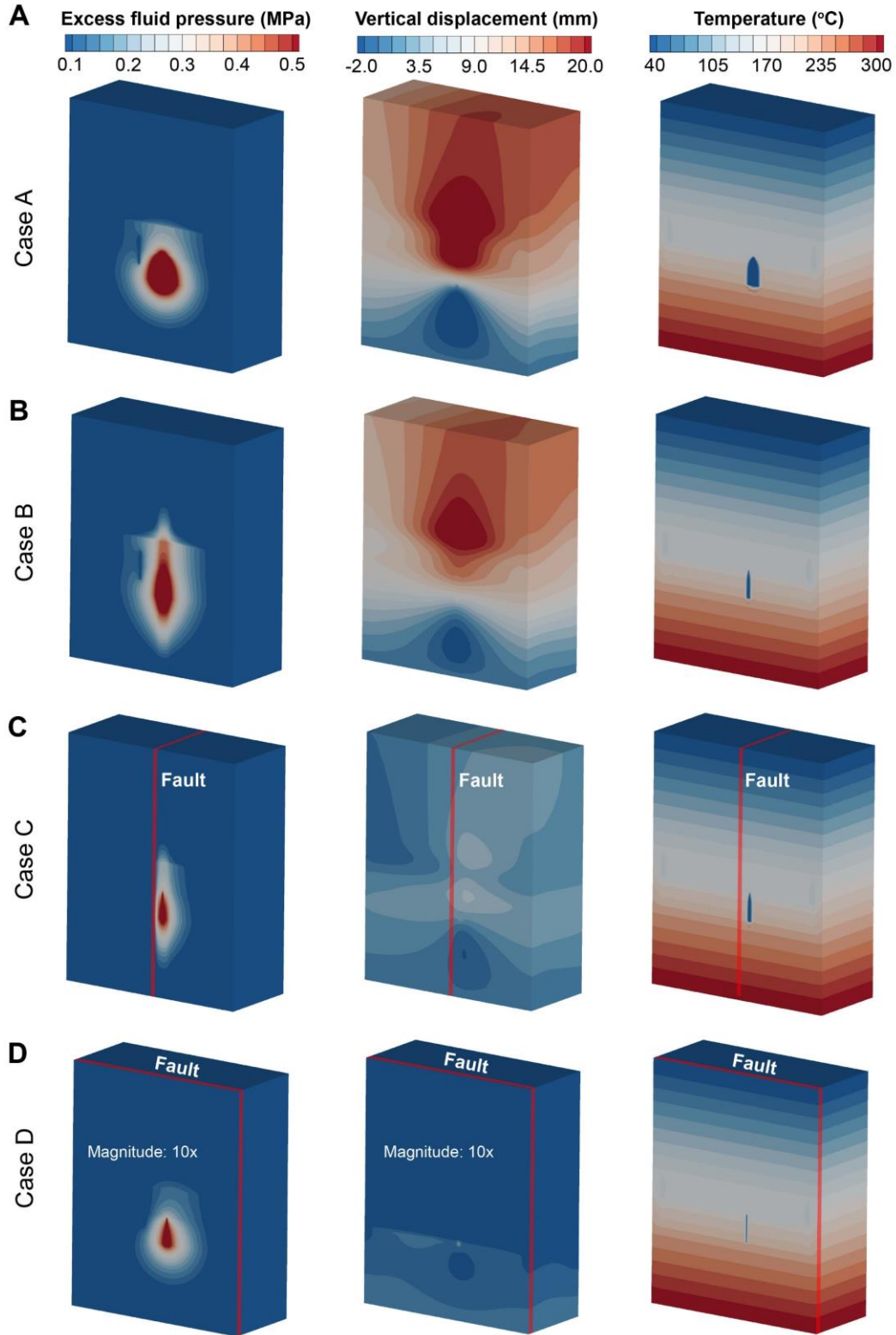
Response: We also noted that Cluster 16 exhibits relatively more complex source mechanisms and faulting regimes. One possible explanation is the stronger influence of field operations, i.e. intensive injection and production activities, in this area (Supplementary Fig. 5). To further investigate this issue, we supplemented the analysis

with full moment tensor inversion and stress inversion. Compared with the double-couple solutions, the full moment tensor results yield fewer low-angle reverse-faulting events.

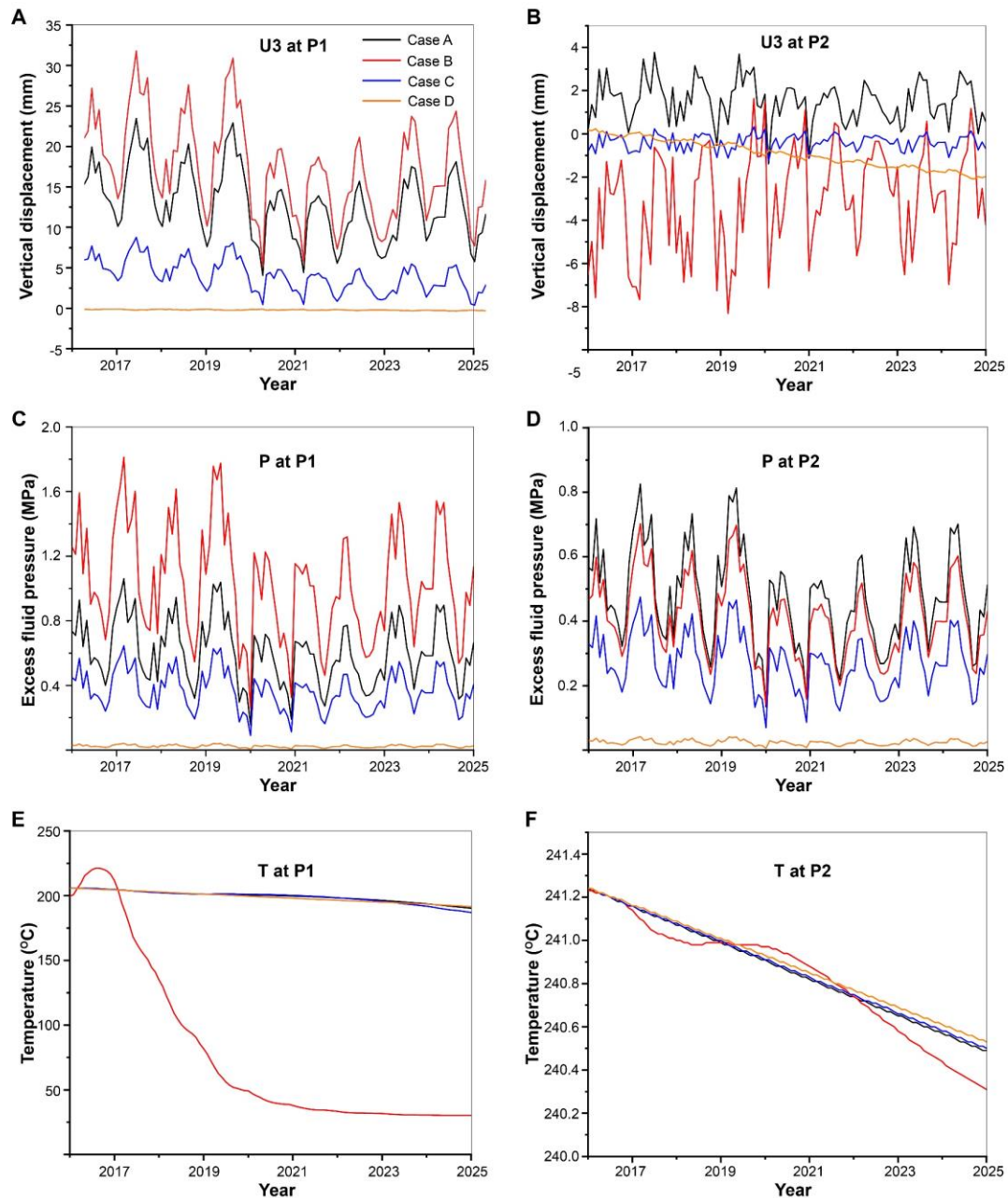
The stress inversion results indicate that Cluster 16 is predominantly characterized by a strike-slip stress regime. However, both the variation in SHmax orientation and the changes in stress regime are indeed more complex than in the other clusters (Supplementary Fig. 13). We therefore infer that local stress perturbations associated with field operations play a significant role in this cluster. This complexity may reflect the combined effects of local stress heterogeneity, structural complexity, and operational influences. We added more discussions as “Cluster 16 exhibits a more pronounced temporal rotation of the principal stress orientations, together with the relatively intense injection and production activity in this region, implies a stronger industrial perturbation of the local stress field.”.

(3)- In Case B of the hydraulic model, permeability is assumed to be higher in the vertical direction than both horizontal directions near the injection wells. Given the presence of steeply dipping faults, one might expect large permeability also in one of the horizontal direction. A short discussion clarifying this assumption, or commenting on the potential role of anisotropy within the horizontal plane, would help contextualize the modeling choices.

Response: We greatly appreciate this constructive comment. We extend the previous fluid pressure modeling to the THM coupling simulations, considering displacement and temperature fields as well. In addition to the original two different permeability configurations, we add two cases with a high-permeability fault that is situated either parallel or normal to the injector-producer plane (see **Supplementary Figs. S18 and 19** below). The fault highlights enhanced permeability in one of the horizontal directions. We also rewrote the THM coupling simulations part in both the main text and the Supplementary Material. Please refer to the revised sections “Pore pressure largely controls microseismicity evolution” (Page 11) and “Thermo-hydro-mechanical coupling simulations” (Page 21).



Supplementary Fig. 18 Snapshots of excess fluid pressure, vertical displacement, and temperature of cases A-D at the end of 2024. In (D), the magnitudes of excess fluid pressure and vertical displacement are multiplied by a factor of 10 to enhance visual clarity.



Supplementary Fig. 19 Histories of vertical displacement (U3), fluid pressure (P), and temperature (T) at two monitoring points, P1 and P2 (Fig. 3), in cases A-D.

(4)- The hydraulic model is intentionally simple and effective at capturing the first-order observations. Nevertheless, a short qualitative discussion of other potentially relevant processes at The Geysers, such as thermal or poroelastic effects, would further strengthen the manuscript by placing the results in a broader physical context.

Response: Thank you for this suggestion. We have supplemented THM simulations to better understand the influence of the poroelastic effect and thermal stress (see **Supplementary Figs. S18 and 19** above). The overall conclusion is that the poroelastic effect plays a more important role in determining the ground deformation compared to

the thermal stress. Please refer to the revised sections “Pore pressure largely controls microseismicity evolution” (Page 11) and “Thermo-hydro-mechanical coupling simulations” (Page 21).

In summary, this manuscript presents an impressive dataset and a convincing analysis, and the minor points raised above are intended to further clarify and enhance an already solid contribution.

Response: Thank you again for your careful and constructive comments. We have carefully addressed these minor points and revised the manuscript accordingly to further improve its clarity and overall quality.

Reviewer #3 (Remarks to the Author):

This study focuses on the evolutionary controlling effects of permeability and heterogeneity on fluid migration and microseismic activity, and conducts an exhaustive investigation of The Geysers geothermal field in California, USA, filling the gaps in relevant research in this region. A deep learning-based location framework is adopted to detect and locate a large number of seismic events, which greatly enriches the seismic catalog and thus enables the characterization of highly detailed microseismicity. Meanwhile, the Markov Clustering Algorithm is innovatively applied to cluster seismic distributions into several groups. Combined with focal mechanism inversion and pore pressure simulation, a highly comprehensive and complete study on seismic activity and fluid migration in The Geysers geothermal field is formed. This manuscript is well written, with highly novel methodologies and findings of significant scientific value, and is worthy of publication in Nature Communications. The following are my comments on this paper.

Response: We appreciate your professional evaluation of our manuscript and the recognition of the novelty and scientific value of the study. We have carefully considered all your comments and revised the manuscript accordingly. In particular, we have supplemented the study with moment tensor inversion (MTI) and stress inversion, along with corresponding analyses. We have also included results from an alternative clustering approach (i.e. DBSCAN) and new THM numerical simulations, to address other reviewers' concerns, further highlighting new insights into the roles of permeability heterogeneity and anisotropy in controlling fluid flow and microseismic activity. We believe that these additions further strengthen the manuscript and improve its overall completeness.

(1) In the process of numerical simulation of pore pressure, the injection rate in the simulation parameters only accounts for 1% of the actual total injection volume. Its rationality remains to be verified, and more justifications for the selection of this ratio need to be elaborated. It is necessary to prove the rationality of the 1% total injection volume parameter and examine whether there is a deviation between this parameter and the actual situation of pore pressure diffusion and microseismic evolution.

Response: We chose 1% of the total injection rate because there are roughly 100 wells in the TG geothermal field. In the revised manuscript, we use 2%, which leads to 5-30 L/s injection rate and is comparable to the 25 L/s of the P-32 injection well reported by Rutqvist et al. (2016). In addition, we replace the former fluid pressure modeling with THM coupling simulations to highlight the influence of the poroelastic effect and thermal stress. The magnitude and footprint of fluid pressure perturbation in the isotropic permeability case (Fig. 3D) and the level of ground deformation are comparable to those reported by Rutqvist et al. (2016) and Liu et al. (2021), respectively. To better address this concern, we have added a clearer explanation of the parameter

selection in **Supplementary Text 3**.

Rutqvist, J. et al. The Northwest Geysers EGS Demonstration Project, California – Part 2: Modeling and interpretation. Geothermics 63, 120 – 138 (2016).

Liu, J. et al. A Strain-Model Based InSAR Time Series Method and Its Application to The Geysers Geothermal Field, California. Journal of Geophysical Research: Solid Earth 126, e2021JB021939 (2021).

(2) Do panels C and D in Figure 2 target a single seismic cluster, or are they a combination of multiple clusters? How to interpret the relationship between the diffusion coefficient D , seismic distribution and depth migration? This part lacks sufficient analysis in the paper. It is necessary to further supplement the figure annotations and conduct a detailed analysis of the relationship between the diffusion coefficient and depth migration.

Response: Thank you for this constructive comment. Figures 2C and 2D are based on the combined seismicity from all clusters across the study region, rather than on a single cluster. We examined the overall depth migration behavior of the full catalog using the classical diffusion-curve formulation ($\sqrt{4\pi Dt}$), and fitted the temporal migration of microseismicity using different values of diffusivity D (e.g., 0.01 and 0.10 m²/s). This yielded results broadly consistent with previous studies.

However, the enhanced microseismic catalog enables us to further investigate depth migration at shorter timescales and for individual clusters (also pointed out in Comment (6) from Reviewer 1). The supplemented analyses show that the previously inferred deep fluid migration pattern is more likely to represent a cumulative, time- and depth-averaged effect, rather than a process that can be directly applied to short-term evolution or to individual event clusters. In other words, although the diffusion curve provides a reasonable first-order description of the long-term, regional-scale trend, it does not adequately capture the behavior of microseismicity over short periods or within single clusters (see Supplementary Fig. 8). This interpretation is also consistent with the behavior shown in Fig. 3C for Cluster 7, where events occur rapidly over a broad depth range. Such a pattern implies relatively rapid vertical fluid migration and pore pressure diffusion, implying a large effective vertical diffusivity and permeability, and therefore does not exhibit a clear delayed downward migration that shown at the regional scale (Figures 2C and 2D).

Accordingly, we have revised the manuscript to clarify that Fig. 2C and 2D describe the integrated behavior of multiple clusters over the entire region, added more detailed discussion of how the diffusivity should be interpreted in relation to seismic distribution and apparent depth migration (Page 8 Lines 166-172).

(3) For the focal mechanism analysis, only three representative clusters are used for illustration. Can these three representative clusters reflect the conditions of the entire TG region? The selection criteria need to be further explained, and it is necessary to clarify whether more other statistical analyses have been conducted.

Response: The three clusters used for focal mechanism analysis were selected after careful consideration of their representativeness, including their locations within TG, event numbers, and their relationships with other nearby clusters. Among them, Cluster 7 is in the central-southeastern region, where well density is relatively high and the events are distributed more scattered in the horizontal direction. By contrast, Clusters 16 and 35 exhibit more evident spatial clustering, and Cluster 16 is distinguished by higher fluid injection and steam production volumes in its surrounding area (see Fig. S5), indicating a representative operation environment. Revised descriptions and explanations read as follows.

“We investigated three clusters (Cluster IDs are 7, 16, and 35) to analyze and interpret their source mechanisms. These clusters are chosen as representative members from the full microseismicity cluster catalog after careful evaluation of their spatial locations, event populations, associations with nearby clusters, local well density, and operation characteristics (Supplementary Fig. 5). They are distributed across different regions of TG and are intended to represent three potentially distinct types of microseismic response.”

(4) The double-couple focal mechanism model is adopted in the study. Whether there are components such as volumetric expansion induced by fluid pressure perturbations, which can provide more explanations for the fracturing mechanism and microseismic activity, remains to be explored.

Response: Thank you for this insightful comment. Yes, previous studies and our discussion have indicated the presence of non-DC components associated with field operation. Following your suggestion, we conducted moment tensor inversion (and also stress inversion) for the three clusters to better characterize microseismic activity and the associated fracturing mechanisms.

The inversion results based on the two source models are basically consistent (Supplementary Figs. 10-13). However, the full moment tensor inversion further reveals pronounced non-DC components in all three clusters (Supplementary Fig. 14). In particular, the ISO component provides more direct evidence for fracture opening and closure associated with fluid migration. We revised the corresponding texts (Pages 9-10) and added methodological descriptions (Pages 18-19).

(5) Elements such as the curves in Figure 3C need to be explained in the legend. It is necessary to specify how the shaded areas are calculated and what the curves represent.

Response: Thank you for the reminder. The gray solid line in Figure 3C represents the average value calculated every 30 days, and the shaded area denotes the data range defined by the average value $\pm$ a specified interval, which contains more than 85% of the events. Besides, we added diffusion curves in this figure to better compare large diffusivities indicated by relatively flat seismicity trends with a normal diffusivity $0.10 \text{ m}^2/\text{s}$. We have added a more explicit description to the figure caption as “Temporal variation in 3D Euclidean distance, horizontal, and depth of seismicity relative to the assumed injection point (520.70 km, 4293.61 km, 2.00 km) during the past three years (2022-2024). The gray solid line indicates the 30-day average of the data. The shaded area represents the range defined by the mean $\pm$ a specified interval, which contains more than 85% of the events. The dashed gray lines correspond to the diffusion distance for a diffusivity of $0.10 \text{ m}^2/\text{s}$.”.

Overall, it is an interesting paper, and thank the authors for the contribution

Response: Thank you very much for your helpful comments.

Responses to Editors and Reviewers

Comments from the AE

Thank you again for submitting your manuscript "Permeability Heterogeneity Controls Fluid Migration and Microseismicity Evolution in The Geysers Geothermal Field, California" to Nature Communications. We have now received reports from 2 reviewers and, based on their comments, we have decided to invite a revision of your work. Your revision should address all the points raised by our reviewers (see their reports below).

When resubmitting, you must provide a point-by-point response to the reviewers' comments. Please show all changes in the manuscript text file with track changes or colour highlighting. If you are unable to address specific reviewer requests or find any points invalid, please explain why in the point-by-point response.

Dear Editor,

Thank you again for handling our manuscript and for providing valuable comments from 2 reviewers. We have carefully considered all comments and have made corresponding revisions to the manuscript to better convey the ideas and interpret the results. We also conducted additional simulations of storage effects (increased porosity) and find that the porosity has minor effects on fluid pressure compared to the large permeability in The Geysers.

All revisions in the main text are marked in **red**. Please find our point-by-point response below. We hope that these revisions adequately address your concerns.

Besides the machine learning checklist, data and code availability section requirements, we also noted the colours selection reminders for readers with colour vision deficiency. We checked all figures and identified three figures that might potentially cause difficulties in visual discrimination. However, none of them relies solely on a red-green colour scheme, and any possible confusion between red and green would not affect the interpretation of the results (e.g., depth can also be interpreted with the aid of the corresponding depth-profile plots, and the outward propagation of pore pressure from the vicinity of the wellbore is a well-established and intuitive physical behaviour).

Lei Li

on behalf of all co-authors

Reviewer #3 (Remarks to the Author):

The authors carefully revised the manuscript according to the review comments. I recommend the publication of the paper.

Response: Thank you for your review and positive feedback.

Reviewer #4 (Remarks to the Author):

This manuscript describes the results of a rigorous and multifaceted study of micro-seismicity in the Geysers geothermal field and infers its likely causes. The study is based on a re-examination of the original digital continuous waveform data to produce a new high-resolution homogeneous earthquake catalogue that is able to identify locations of previously undetermined (mostly small) earthquakes and improve others, and examine the resulting spatiotemporal trends in the seismicity, including clustering, and the degree to which this can be interpreted as pre-existing, deformation-induced or deformation-enhanced pathways for high permeability.

From the rebuttal, it is clear the authors have undertaken significant extra work since the original submission, notably in conducting full moment tensor inversion, stress inversion, and Thermo-Hydro-Mechanical coupling simulations that incorporate anisotropic permeability to investigate how permeability heterogeneity and anisotropy control fluid migration and micro-seismicity evolution. This has allowed the team to identify poro-elastic effects as more important than thermos-elastic ones, and that near well-bore fluid pressure alone plays a more important role than either. They have also run sensitivity tests for these simulations under different plausible permeability conditions, conditioned on prior knowledge of the field, to prove the results are robust with respect to this source of uncertainty.

Response: Thank you very much for your positive assessment of our work and for recognizing the efforts we made in the first round of revision. We carried out a substantial revision of the manuscript to address concerns from all the three reviewers. In particular, Reviewer 1 raised some critical and constructive comments, which prompted us to re-examine several important aspects of the study. We truly appreciate these thoughtful reviews, as they have helped us improve the quality and presentation of the manuscript.

The authors also conducted additional analyses at finer temporal (1-3 years) and spatial scales (specific micro-seismic clusters), which suggest that the inferred depth migration trend is better interpreted as a cumulative, time- and depth-averaged effect at the regional scale, rather than expected depth migration for short-term or local micro-seismicity. I would agree the isotropic diffusion curve, while a reasonable null hypothesis, does not describe the data so well, and that this is not surprising given the degree of permeability anisotropy and long-range triggering at short timescales observed.

Response: Thank you for your careful observation (as also noted in Line 171 in the annotated manuscript file). The assumption of isotropic fluid diffusion within a uniform medium cannot adequately characterize the inferred permeability anisotropy observed at smaller temporal and spatial scales in our study. This discrepancy also provides

further support for the robustness of the inferred anisotropic characteristics. We have added further clarification in the revised manuscript (Line 173).

“Neither short-term behavior of microseismicity across the entire field (e.g., 1-3 years) nor the evolution of individual microseismic clusters can be well described by such a diffusion curve (Supplementary Fig. 8). **This discrepancy further demonstrates that the isotropic diffusion curve cannot adequately characterize fluid migration in an anisotropic permeability field at smaller temporal and spatial scales.**”

I did not have access to the original manuscript, but I would say the revised manuscript identifies the key novel findings from the new catalogue and associated analyses in a proper context, drawing from the wider literature as prior information, and I thought the distinction between novel findings and previous knowledge was generally clear. The findings themselves, particularly with the extra work, are also a significant advance on the prior literature on induced seismicity in the field.

Response: We sincerely appreciate your kind and positive feedback regarding the first-round revision. We also thank you for your additional comments which further improve the completeness of the manuscript.

I have some specific comments in terms of presentation and interpretation the authors may like to consider in minor revision, summarised below and in the annotated text.

(1) The writing style sometimes presents an inference as stated fact. For example, the abstract (lines 24-25) states ‘Our observations reveal distinctive clustering patterns and fracture systems tightly correlated with injection operations.’ It would be more accurate to state ‘inferred fracture systems’ here (notably from the clustering, the association with the wellbore, the presence of a tensile component in the focal mechanisms, and low seismic velocities in independent tomographic studies). I would have high confidence in the inference due to this corroboration, but it is not an observation. Similar examples are given in context in the annotated manuscript.

Response: Thank you very much for your careful reviews on the wording and expressions throughout the manuscript. We agree that adding ‘inferred’ would be more accurate expressions and have made revisions in the manuscript. We also carefully reviewed all the 17 comments in the annotated manuscript. In addition to those addressed elsewhere in our responses, two comments are addressed separately below.

Line 103: are these likely to be tensile (e.g. joints), or are they more likely to be part of a damage zone around faults?

Response: We think they are more likely to be damage zones (shear zones) around the wellbores and faults, though there are also some tensile fractures involved (indicated by isotropic components). We have discussed this in Line 177 and previous studies also indicate the shear zone could play an important role in enhancing reservoir permeability.

Line 220: More precisely a direct indicator of local increase in storage (as you mention next), consistent with an increase in permeability.

Response: We agree that the isotropic component is a direct indicator of volumetric deformation, which is responsible for local increase of permeability and porosity. Positive isotropic components of moment tensor solutions reflect volumetric expansion associated with fracture opening and dilatancy, which may indicate the creation of additional pore space and enhanced permeability.

We made revisions in Line 220 as follows.

“Specifically, the isotropic component can serve as an indicator of fluid migration associated with volumetric deformation, increased fracture porosity, and enhanced permeability...”

(2) The microseismicity is interpreted with some justifiable confidence as causing preferential fluid pathways (lines 148-149 and elsewhere). However, the deformation also increases local porosity and bulk storage, independently confirmed by the volumetric component of the moment tensor for some events. Storage is important because it affects the relevant boundary conditions in the model. For example, in one example, only a small proportion of injected volume was produced at the production well, e.g. Figure 2 of Li, X., et al. (2018. Induced Seismicity at the UK “Hot Dry Rock” Test Site for Geothermal Energy Production, *Geophysical Journal International*, ggy135. <https://doi.org/10.1093/gji/ggy135>). This implied the dominant effect was an increase in storage rather than the creation of an efficient permeability pathway between injector and producer. This study also shows stress aligned anisotropy in the diffusion cloud, with faster diffusion of seismicity in the vertical directions, although with a more even spread in the upward and downward directions consistent with the absence of a shallow barrier. At present the manuscript does not explicitly consider storage as such, but this must (or should be) be a feature of the model that could be addressed explicitly.

Response: Thank you for your constructive comment. As discussed in Ben-Zion and Ampuero (2009) (Ben-Zion, Y. & Ampuero, J.-P. Seismic radiation from regions

sustaining material damage. Geophysical Journal International 178, 1351–1356), damage-related sources in low-porosity rock can produce significant isotropic components. Therefore, isotropic components may be indicative of increased fracture porosity (and we made revision in Line 220).

We agree that storage may also play a role in fluid diffusion. We carefully read Li, X. et al. (2018) and we are glad to see that the authors also used an orthotropic diffusion tensor (Eq. 29) (we added the citation in Line 175). We did not consider the storage coefficient in our original mass conservation equation. To respond your comment, we modify the mass conservation equation and introduce the change in porosity by a factor of κ

$$\begin{cases} \nabla \cdot [\mathbf{D} \nabla \mathbf{u} - \beta_v K_s (T - T_0) \mathbf{I} - \alpha p \mathbf{I}] + \mathbf{f} = \mathbf{0} & \text{(R1-1)} \\ \kappa \phi \left(\beta_p \frac{\partial p}{\partial t} - \beta_T \frac{\partial T}{\partial t} \right) - \nabla \cdot \left[\frac{\rho_f \mathbf{k}}{\mu_f \rho_0} (\nabla p - \rho_f \mathbf{g}) \right] + \delta(\mathbf{x} - \mathbf{x}_0) \frac{\rho_f q_{fs}}{\rho_0} + \frac{\alpha \rho_f}{\rho_0} \frac{\partial}{\partial t} (\nabla \cdot \mathbf{u}) = \mathbf{0} & \text{(R1-2).} \\ (\rho C)_m \frac{\partial T}{\partial t} - \kappa \phi \beta_p T \frac{\partial p}{\partial t} - \beta_v K_s T \frac{\partial}{\partial t} (\nabla \cdot \mathbf{u}) - \rho_f C_f \mathbf{v}_f (T - T_0) + \nabla \cdot (\lambda_m \nabla T) + \delta(\mathbf{x} - \mathbf{x}_1) q_{hs} = \mathbf{0} & \text{(R1-3)} \end{cases}$$

In Equation R1, we can group the parameters $S = \kappa \phi \beta_p$, where S (Pa⁻¹) is the storativity.

Rewriting the mass conservation (R1-2), we can get

$$\mathbf{D} = \frac{\mathbf{k}}{S \mu_f}, \quad \text{(R2)}$$

the same as Eq. 24 of Li et al. (2018). Porosity increase and permeability increase generally occur simultaneously. In Figure 3E, we introduced a field variable

$$\omega = \begin{cases} 0.01d & (d \leq 100) \\ 1.0 & (d > 100) \end{cases} \quad \text{(S1)}$$

and used $\mathbf{k} = (1 - \omega) \mathbf{k}_1 + \omega \mathbf{k}_0$ where $\text{diag}(\mathbf{k}_0) = [k, k, k]$ and $\text{diag}(\mathbf{k}_1) = [10k, 10k, 100k]$ to linearly modulate the permeability according to the distance d away from the injection well.

To consider the influence of κ , we conducted an additional set of simulations with $\phi = \omega \phi_0 + 10(1 - \omega) \phi_0$ to consider a ten-fold increase in porosity near the injection well.

However, the simulation shows almost no difference in the fluid pressure field compared to the case without porosity change. The reason is that the permeability at Geysers is high, as evidenced by decades of fluid injection and extraction, and we use

a large time step (1 month) in simulations. Both make the influence of the $\dot{p}$ term in Equation R1-2 minor. In other words, the influence of storage, if any, would occur on a much smaller time scale.

Regarding the limited fluid extraction compared to injection reported by Li et al. (2018), we would like to comment that the flow rate at the production well is related to the well-head pressure and formation permeability, especially the latter. According to Equation R2, D is on the order of $10^2 \text{ m}^2/\text{s}$ in the Graywacke layer at The Geysers, much higher than the $0.12 \text{ m}^2/\text{s}$ (may be less if considering the aseismic slip) suggested by Fig. 8 of Li et al. (2018). We therefore think that, at The Geysers, the effect of storage is less than that of permeability. We also want to kindly remind you that the steam production volume is relatively steady in The Geysers and is larger than fluid injection (as shown in Fig. 1C).

Nevertheless, you mentioned a good point, and we should include the porosity change in our model. In the Methods section, we add the following after Equation (2) (Line 529):

“Within a radius of 100 m from the injection well, the orthotropic permeability gradually transitions to the far-field isotropic value. We further investigate the effects of porosity increases accompanying permeability enhancement on fluid pressure. Two scenarios are examined: (1) constant porosity, and (2) $\phi = \omega\phi_0 + 10(1-\omega)\phi_0$. The latter reflects a ten-fold increase in porosity near the borehole and similarly decays with the distance away from the injection well. However, simulation results show that the two porosity cases produce no appreciable difference in fluid pressure. This is because the permeability at TG is relatively high, and we use a large time step (1 month) in the THM coupling model, both of which render the porosity effect minor. In other words, any porosity-related influence would manifest only at much shorter time scales, which is out of the scope of this study.”

(3) The text does not explicitly state whether or not the software used accounts for long-range poroelasticity in the model due to associated changes in effective stress throughout the medium, as in e.g. Segall (1989. Earthquakes triggered by fluid extraction, *Geology*, 17, 942–946). Long range triggering is also enabled by pre-existing near critical stress states in the far field (Maillot et al., 1999. Numerical simulation of seismicity due to fluid injection in a brittle poro-elastic medium, *Geophys. J. Int.* 139, 263–272), that are in turn consistent with long range triggering in the Geysers field from remote earthquakes (Hill D.P. et al. 1993. Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake, *Science*, 260, 1617–1623). In any case it would be helpful to clarify on first use of the term that the poroelastic component of the model does involve a full solution which incorporates both local and long-range triggering.

Response: We greatly thank you for the insightful suggestion. Our THM coupling model is strictly two-way coupled in the poroelastic framework, so the long-range stress perturbation is considered. In Equation R1-1, the fluid pressure is fully coupled to the rock displacement by the $\alpha p \mathbf{I}$ term, no matter how far away from the injection well. In Equation R1-2, any rock deformation can in turn influence the fluid pressure distribution by the volumetric strain rate term $\nabla \cdot \dot{\mathbf{u}}$. You might not have access to our original manuscript, but the fluid pressure field changed after we switched from the pure diffusion model to a THM coupling model. We now clarify this in the main text when the coupling model is first introduced (Line 244):

“To investigate the thermo-hydro-mechanical (THM) coupling effects, particularly the fluid pressure perturbations controlled by permeability variation, we performed 3D THM simulations using the geological model proposed in previous studies^{27,48}. **Two-way coupling is fully considered in our model under the framework of poroelasticity, and both local and long-range stress perturbations can be captured.** The model comprises four rock units: Gaprock, Graywacke, Hornfels, and Felsite (Supplementary Fig. S17). ...”

We also elaborate more in the Methods section (Line 511):

“... The material properties are summarized in Supplementary Table S2.

Fluid pressure is commonly considered to reduce effective normal stress, primarily exerting a localized influence on fault stability. However, a growing body of evidence suggests that poroelastic stress may lead to long-range perturbations and trigger remote earthquakes (Segall, 1989; Segall & Lu, 2015; Goebel & Brodsky, 2018). In our model, two-way coupling is implemented in Equation (2) under the framework of poroelasticity. The terms $\alpha p \mathbf{I}$ and $\nabla \cdot \dot{\mathbf{u}}$ (dot means time derivative) can capture both local and long-range stress perturbations.

We considered four models with different permeability configurations. ...”

References:

Segall, P. (1989). Earthquakes triggered by fluid extraction. *Geology*, 17, 942.

Segall, P., & Lu, S. (2015). Injection-induced seismicity: Poroelastic and earthquake nucleation effects. *Journal of Geophysical Research: Solid Earth*, 120(7), 5082-5103.

Goebel, T. H., & Brodsky, E. E. (2018). The spatial footprint of injection wells in a global compilation of induced earthquake sequences. *Science*, 361(6405), 899-904.