

Supplementary Information for

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

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Supplementary Text 1 Geological background

The Geysers (TG) geothermal field is located in the Mayacamas Mountains of northern California, about 110 km north of San Francisco (Fig. 1A). The field covers approximately 120 km² and is adjacent to the southwest edge of the Quaternary Clear Lake volcanic field. TG field exhibits an elongated northwest-southeast (NW-SE) orientation and is bounded by two major right-lateral faults (the Collayomi Fault and Mercuryville Fault), which act as structural boundaries for the geothermal reservoir. There are several known high-angle faults oriented dominantly NW-SE and NE-SW within and surrounding the reservoir. Cobb Mountain and Geysers Peak are situated in the middle region of the Collayomi Fault to the northeast and the Mercuryville Fault to the southwest of the field.

The regional tectonic stress regime at TG is governed by the San Andreas fault system and is predominantly strike-slip faulting, with a transtensional component. The maximum horizontal stress (SHmax) is oriented roughly north-northeast (e.g., ~N30°E), consistent with the broader stress field of the northern California transform plate boundary ^{1,2}. TG geothermal system is hosted within the Franciscan Complex formed during late Mesozoic-Cenozoic subduction, comprising graywacke, metagraywacke, greenstone, and serpentinite, which provides a low-permeability and fractured medium for steam storage and circulation ³.

Supplementary Text 2 Microseismic clustering and fluid pathways

The Markov clustering algorithm applied to the relocated catalog yields a clear clustering results and improved spatial resolution compared to the classical DBSCAN algorithm⁴ (the neighborhood radius $\epsilon = 0.5$ km and the minimum number of points required to form a dense region MinPts = 100) (compare Fig. 2A and Supplementary Fig. 20). At both the decadal and annual scales, it recovers more reasonable numbers of clusters and more reasonable spatial delineations, alleviating the omission of small clusters and the artificial merging of adjacent clusters over broad areas (compare Fig. 2 and Supplementary Movies 2 with Supplementary Fig. 20).

On this basis, the enhanced clustering helps reveal a high-resolution reservoir-scale heterogeneous distribution of microseismicity, fluid pathways, and fracture networks, highlighting the lateral heterogeneity in reservoir permeability. Previous studies have also suggested that the reservoir contains fracture networks with varying orientations and is segmented by Quaternary faults into multiple isolated compartments bounded by low-permeability fault zones⁵. This interpretation is further supported by stress inversions for three representative clusters, which indicate temporal changes in the stress field, including stress rotations, reflecting stress perturbations associated with field operations. We therefore infer that permeability heterogeneity, geological structures, and operation-induced stress perturbations jointly control the clustering pattern of microseismic events.

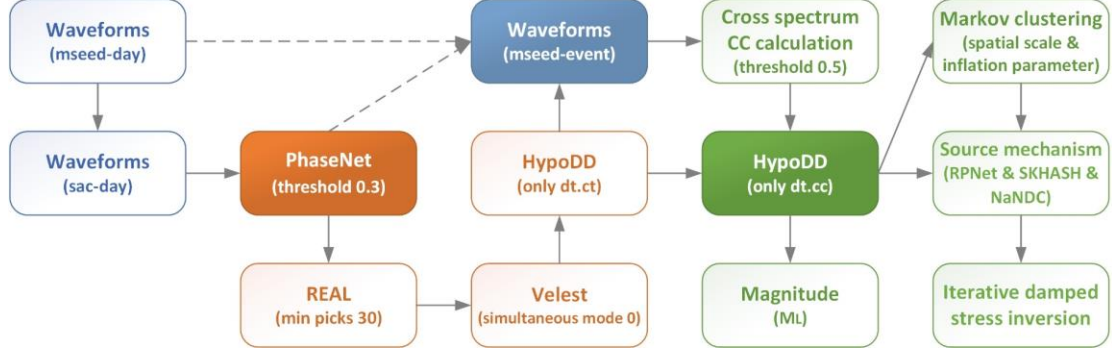
Microseismic clusters broadly delineate the direct fluid diffusion domain and preferential migration pathways. The detailed analysis of Cluster 7 indicates a possible vertical pathway for fluid and pore pressure diffusion. In particular, isotropic components from moment tensor inversion indicate fracture opening and closure, and thus provide more direct evidence for fluid migration. We also observed the occurrence of similar/repeated earthquakes, which may reflect repeated fracture opening and slip along relatively stable conduits developed during long-term injection and production.

Supplementary Text 3 Simulation parameter selection

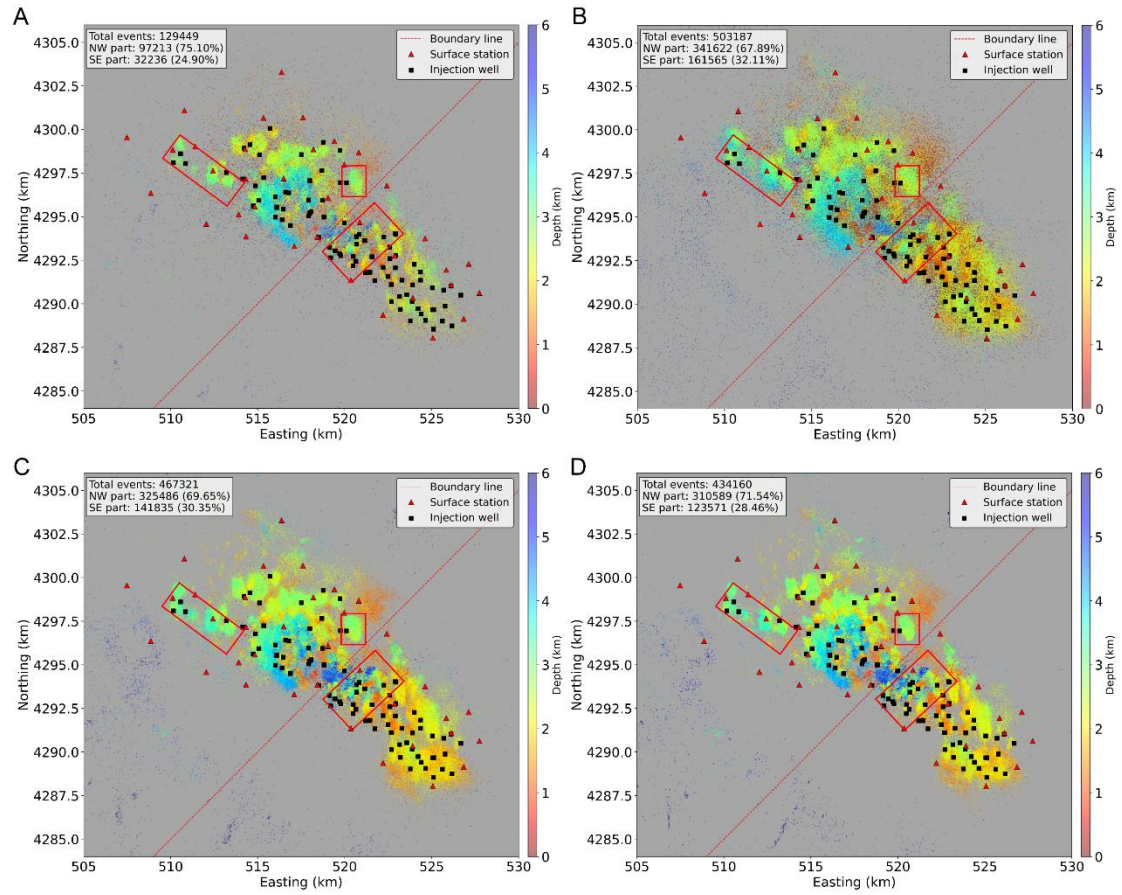
The injection and production intervals were set as 500 m, and the producer was located 250 m higher than the injector. Following Rutqvist et al. (2016)⁶, fluid is injected along the lowermost 500 m of the injection well (highlighted in blue in Supplementary Fig. S17). The injection interval is also basically consistent with reported injection-depth distributions at TG. For the 49 highest-volume injection wells, more than 95% of the injection depths in the NW section are between 0.9 and 1.5 km, and more than 90% in the SE are between 0 and 0.9 km^{7,8}.

The injection rate was set at 5-30 L/s, which is approximately 2% of the total TG injection rate, referring to the 25 L/s (400 gpm) adopted by Rutqvist et al. (2016)⁶. A higher injection rate would produce a larger pore-pressure increase/variation, though it would not affect the main conclusion of the simulations, which are intended to qualitatively illustrate how different permeability conditions control pore-pressure evolution. At the producer, the excess fluid pressure along the lowermost 500 m (highlighted in red in Supplementary Fig. S17) was prescribed to zero. Excess fluid pressure on the injector-producer plane was calculated, while the rest of the boundaries were set to zero excess fluid pressure.

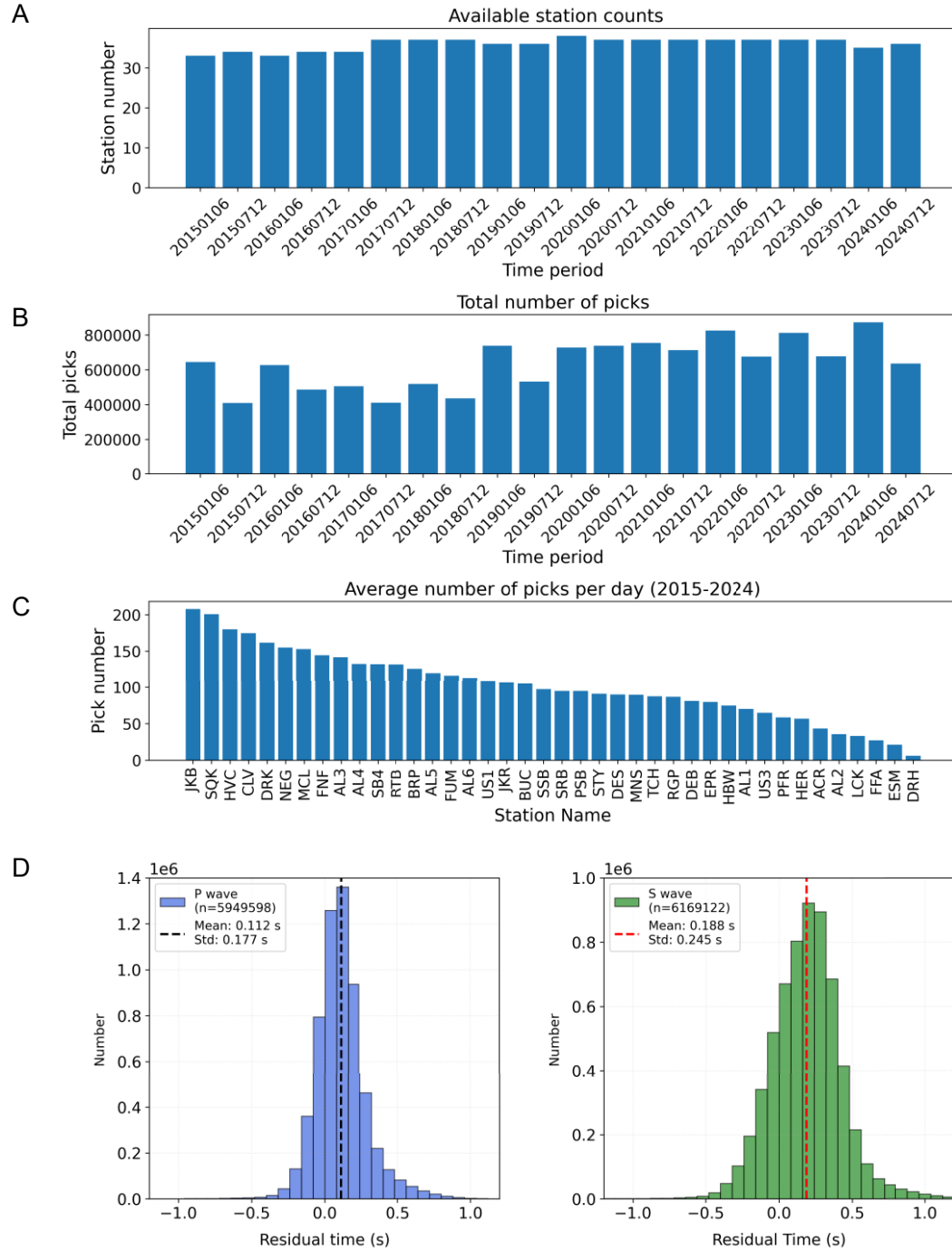
For the displacement boundary condition, the bottom was fixed, but the lateral boundaries were only allowed to deform vertically. The top surface was set as a free surface. For temperature, we considered a thermal gradient of 0.07 °C/m, which lead to approximately 230 °C bottom-hole temperature. Once the injection started, the temperature within the injection interval was fixed at 30 °C. The temperatures at the boundaries were maintained at the far-field values.



Supplementary Fig. 1 Workflow for developing enhanced microseismic catalog and source parameter inversion. Microseismic events located by Velest within the same half year (e.g., from 1 January to 30 June) are then relocated as a whole. For spatial clustering, microseismic events from the same year (e.g., from 1 January to 31 December) are clustered separately, and then merged based on the distance of their central positions. To better retrieve first-motion polarity for focal mechanism estimation, we employ a deep learning model RPNNet to predict the P-wave polarity with phase picking results from PhaseNet as inputs. Both DC-constrained focal mechanisms and full moment tensor source mechanisms, as well as local principal stress rotations are estimated for three representative clusters.

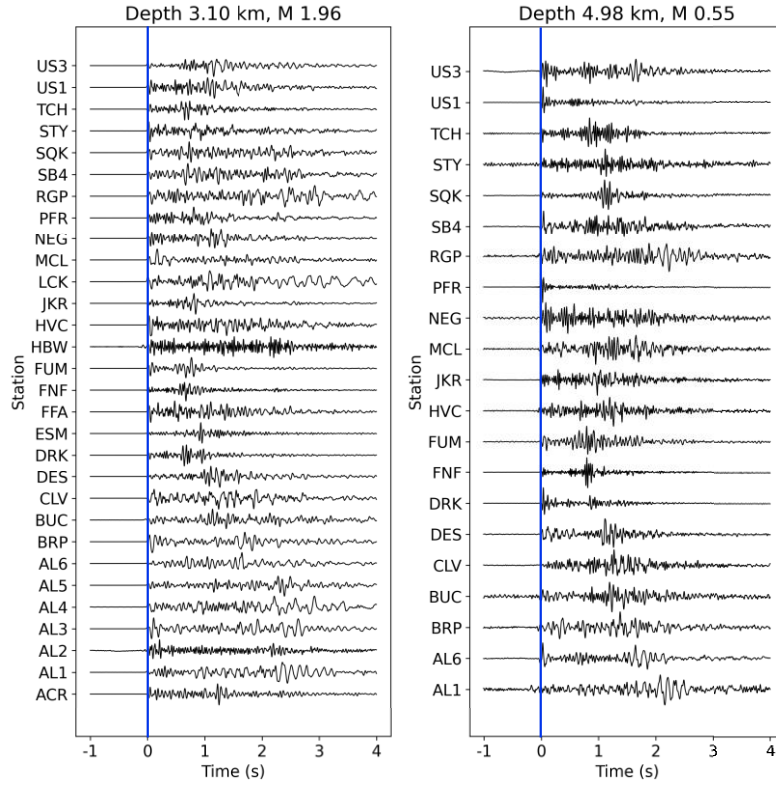


Supplementary Fig. 2 Microseismic catalogs from (A) NCEDC real time hypoDD, (B) LOCFLOW-based Velest, (C) LOCFLOW-based hypoDD (catalog-based differential traveltime), and (D) LOCFLOW-based hypoDD (waveform cross correlation-based differential traveltime). These catalogs share similar spatial patterns but LOCFLOW-based hypoDD catalogs show enhanced event clustering and more potential fine-scale structures (e.g., in red boxes). We selected one representative event cluster from each of the three red boxes for detailed investigations.

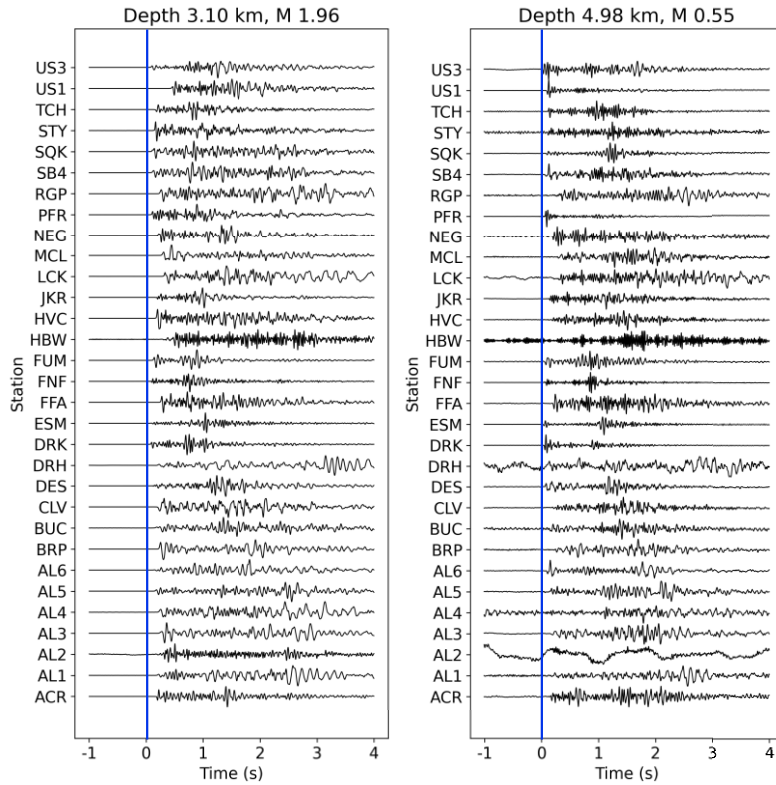


Supplementary Fig. 3 Quality control of stations and phase picks. (A) Available station counts every half year, ranging from 33 to 38. (B) Total number of picks every half year. The phase pick numbers for the first five years (2015-2019) are smaller than the second five years (2020-2024), which corresponds to event-rate variations in Fig. 1C. (C) Average number of picks per day for all stations during the past decade. (D) Histograms of P-wave and S-wave traveltime residuals between theoretical traveltimes and PhaseNet picks for all events and all stations. Positive mean values indicate lower theoretical traveltimes, indicating the adopted velocities are higher than real (effective) velocities and/or estimated depths are shallower.

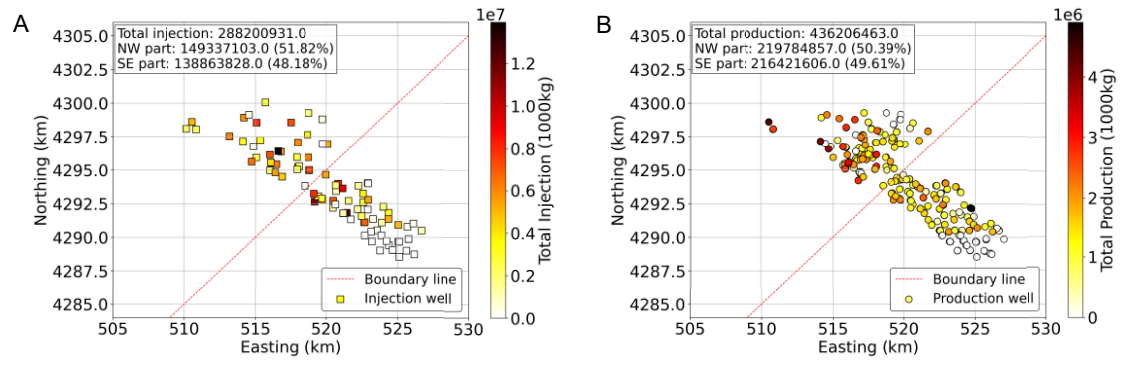
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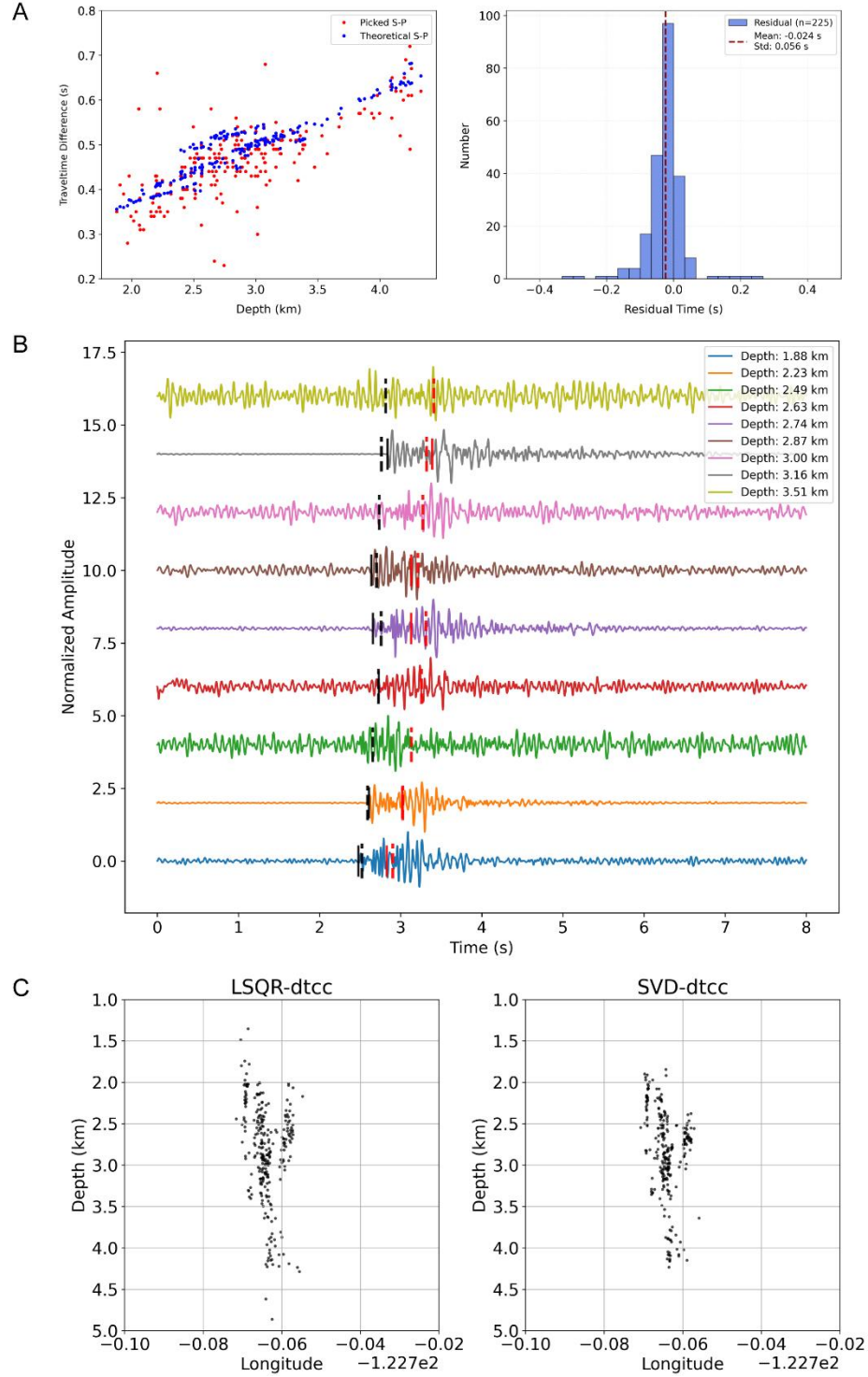
B



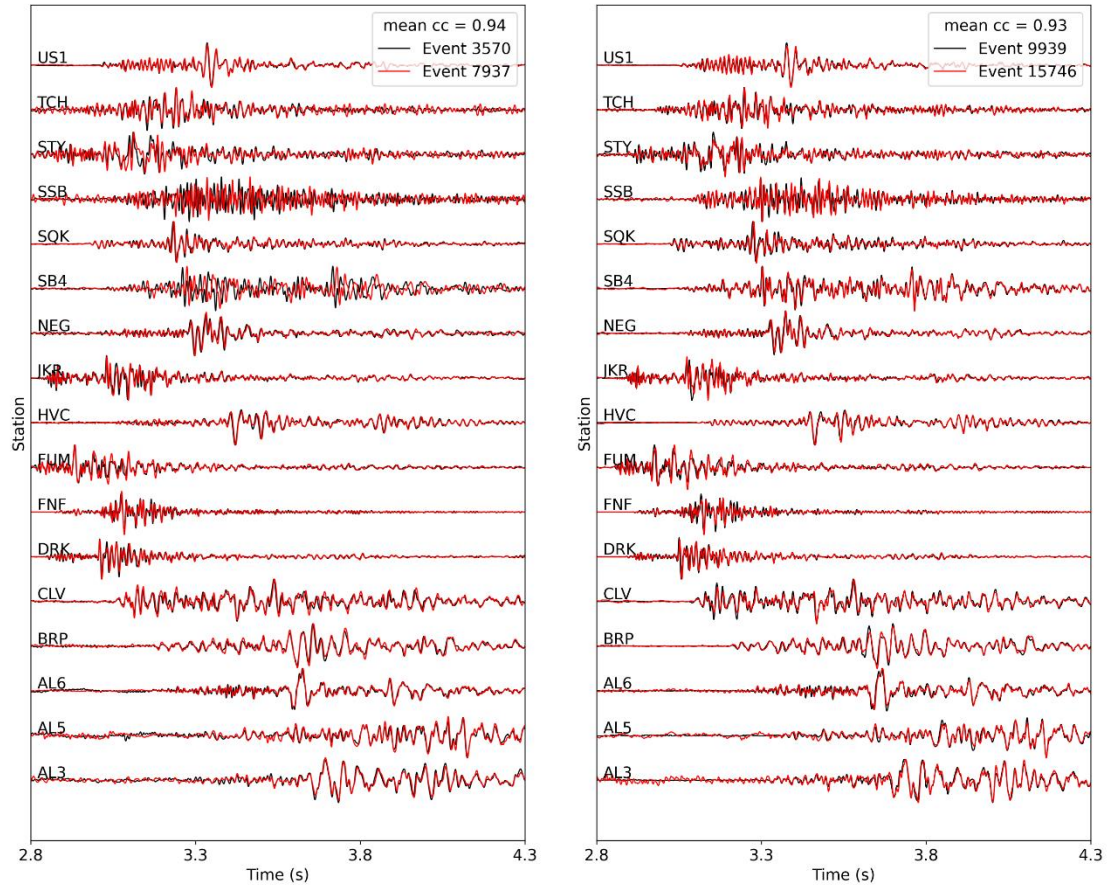
Supplementary Fig. 4 Waveform alignment based on P-wave arrival time for two sample events. (A) Waveforms are aligned based on picked arrival times of P-wave. (B) Waveforms are aligned based on theoretical traveltimes of P-wave and the estimated origin times.



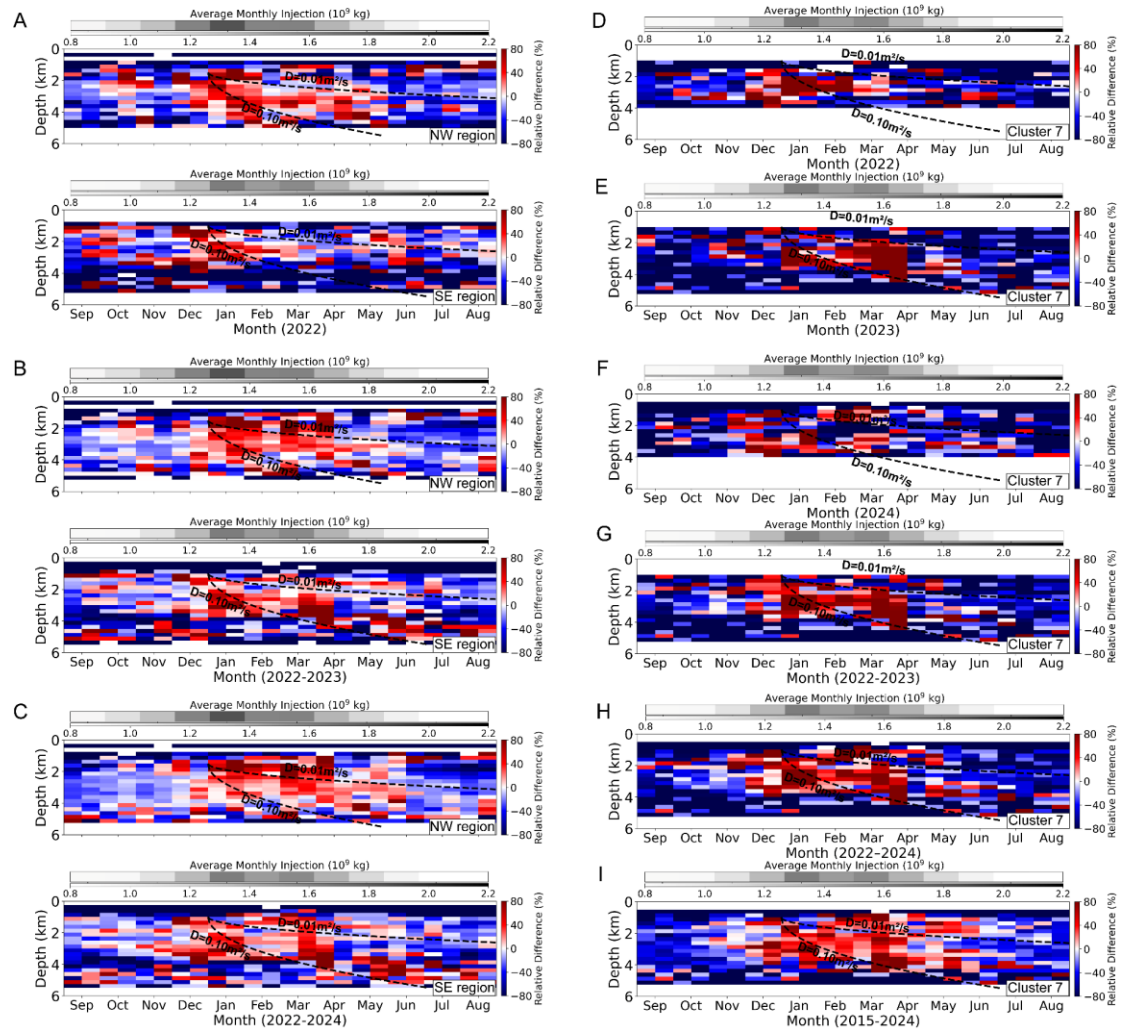
Supplementary Fig. 5 Total injection and production volume for all related wells in The Geysers during the past decade. The distributions of both injection and production volumes are heterogeneous, and the NW section exhibits slightly higher fluid injection (3.64 %) and steam production (0.78 %) volumes than the SE section.



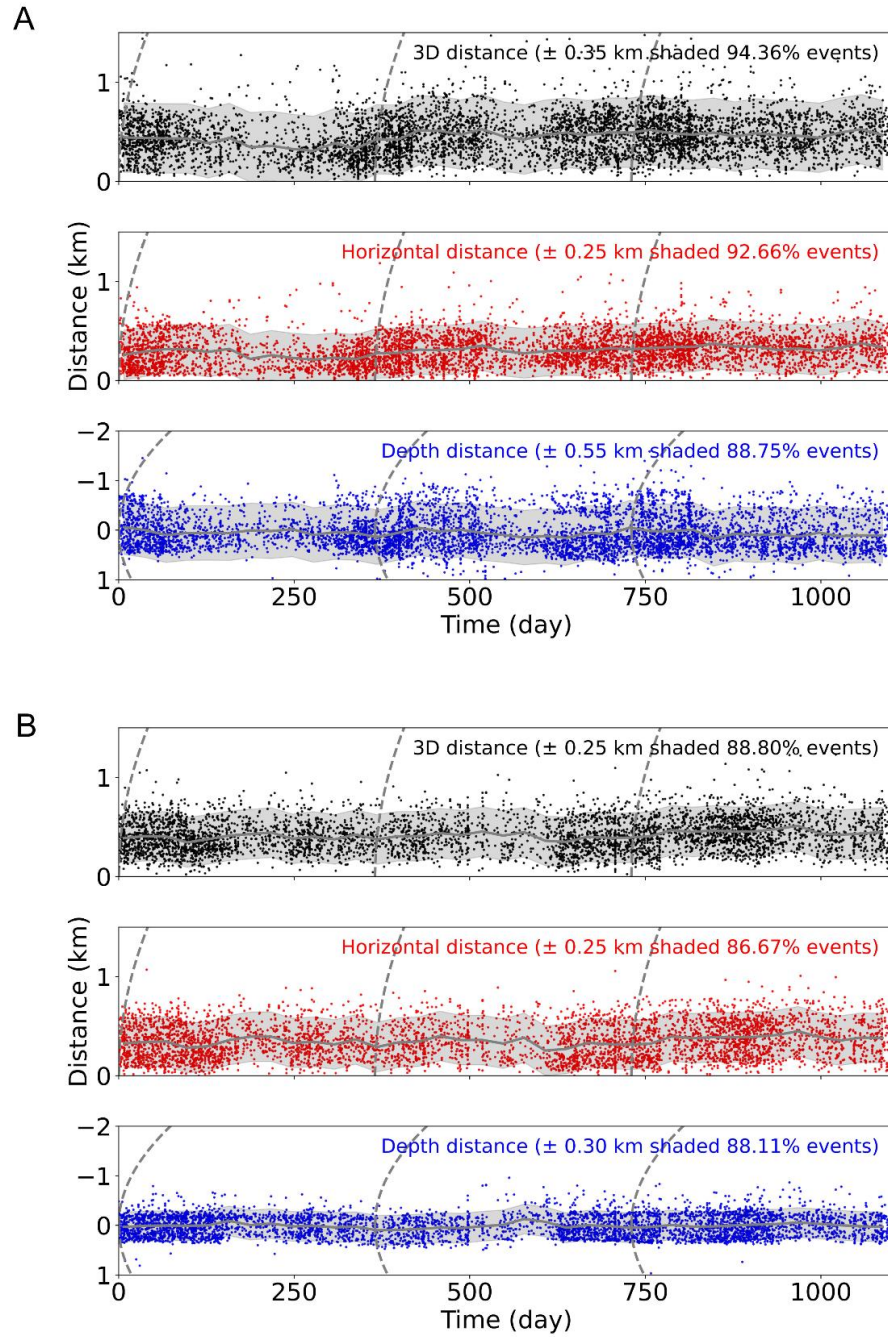
Supplementary Fig. 6 Quality control of the depth range for a specific event cluster in 2023. (A) Both picked and theoretical differential traveltime between S- and P-waves for the station BG.FUM show a consistent trend along depth, and the residual between the differential traveltimes is small. (B) Sample waveforms from the station BG.FUM for random events with increasing depths showing increasing traveltimes. (C) Both LSQR and SVD solvers in hypoDD relocation yield consistent depth distributions.



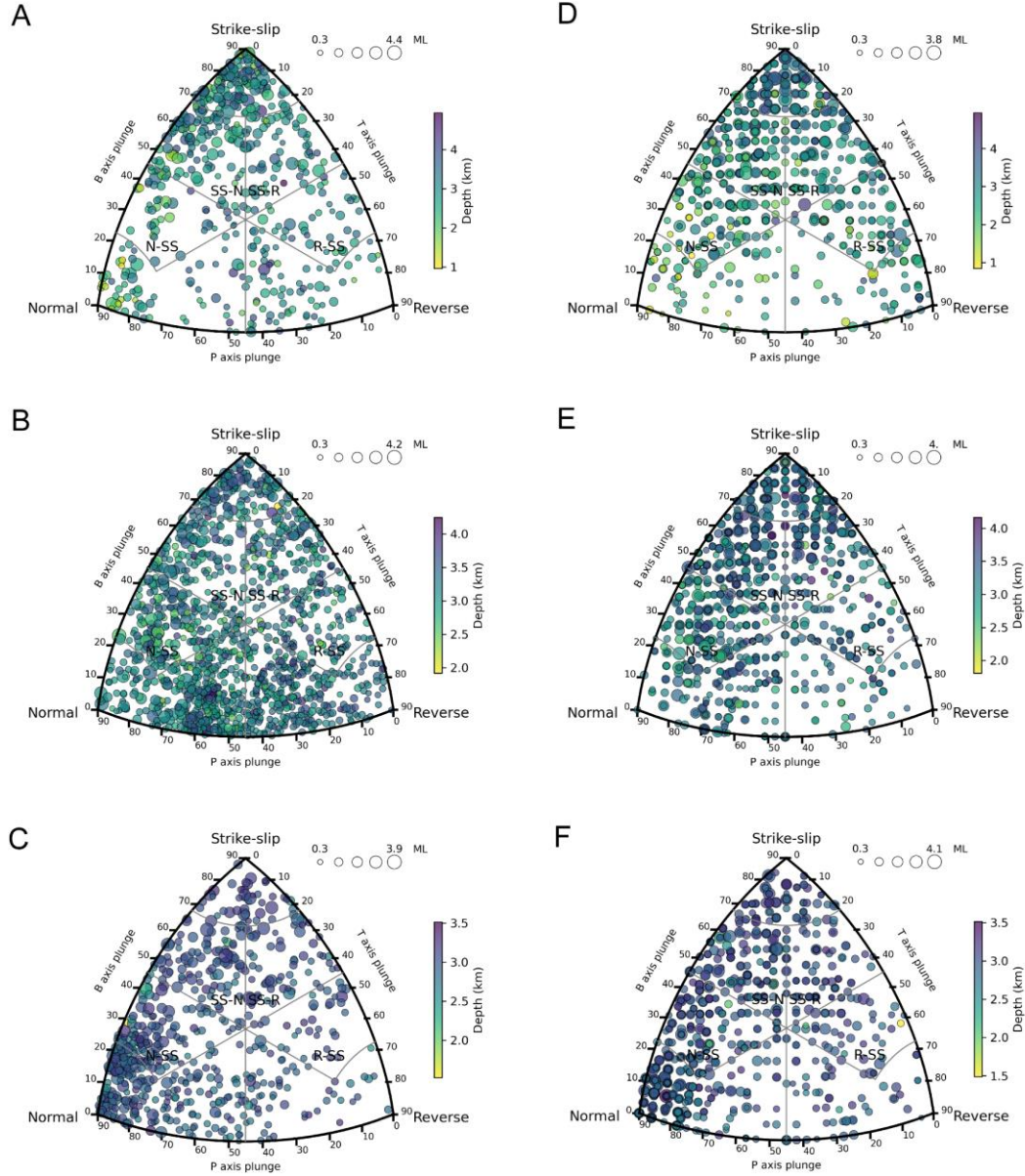
Supplementary Fig. 7 A group of four similar/repeated earthquakes detected in the second half of 2024.



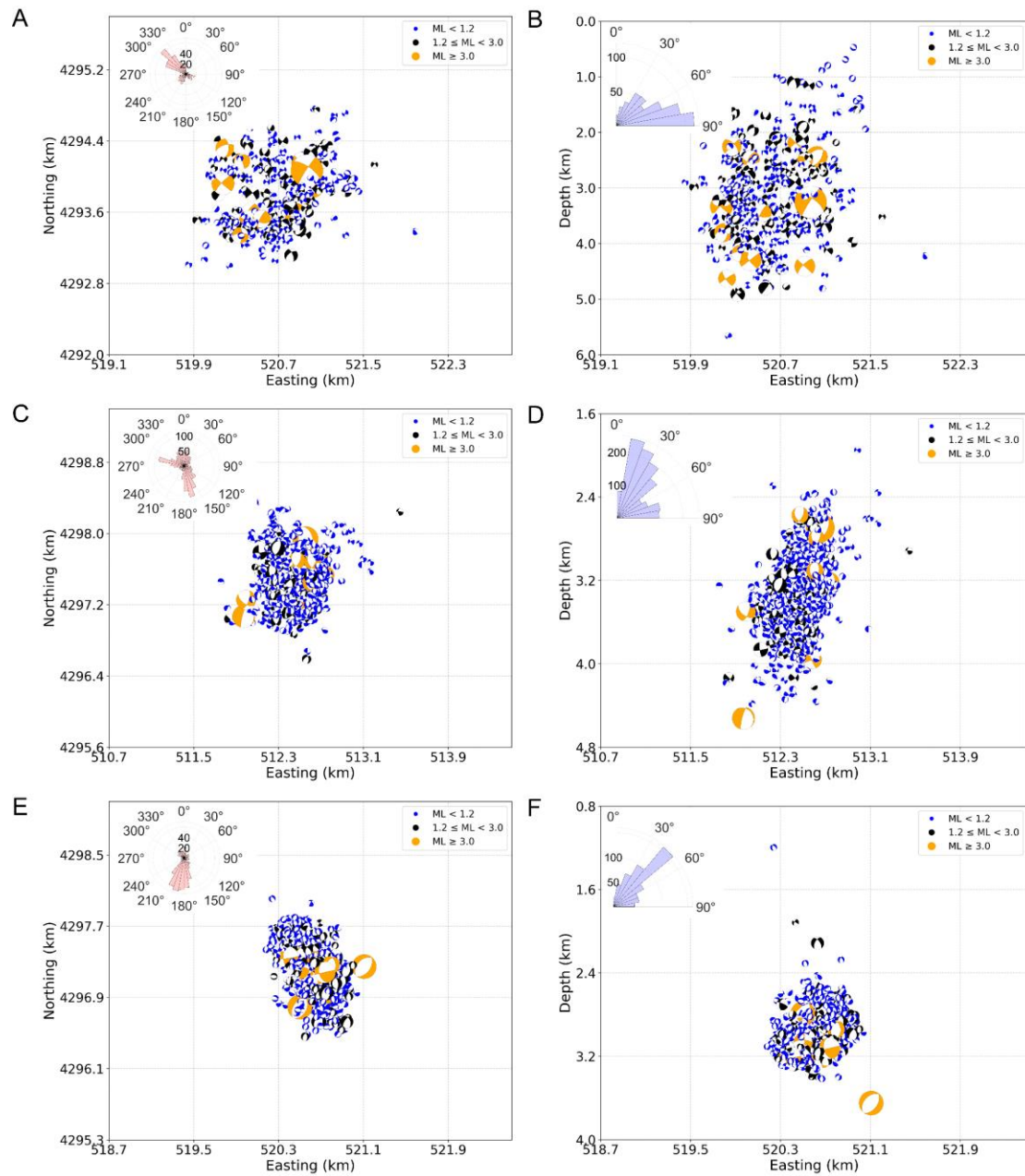
Supplementary Fig. 8 The percentage above or below the average number of clustered events in the NW (A)-(C), SE (A)-(C), and Cluster 7 (D-I) regions for each depth interval (0.25 km) is shown, where warm colors indicate more events and cool colors indicate fewer events. The thick dashed black lines correspond 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.



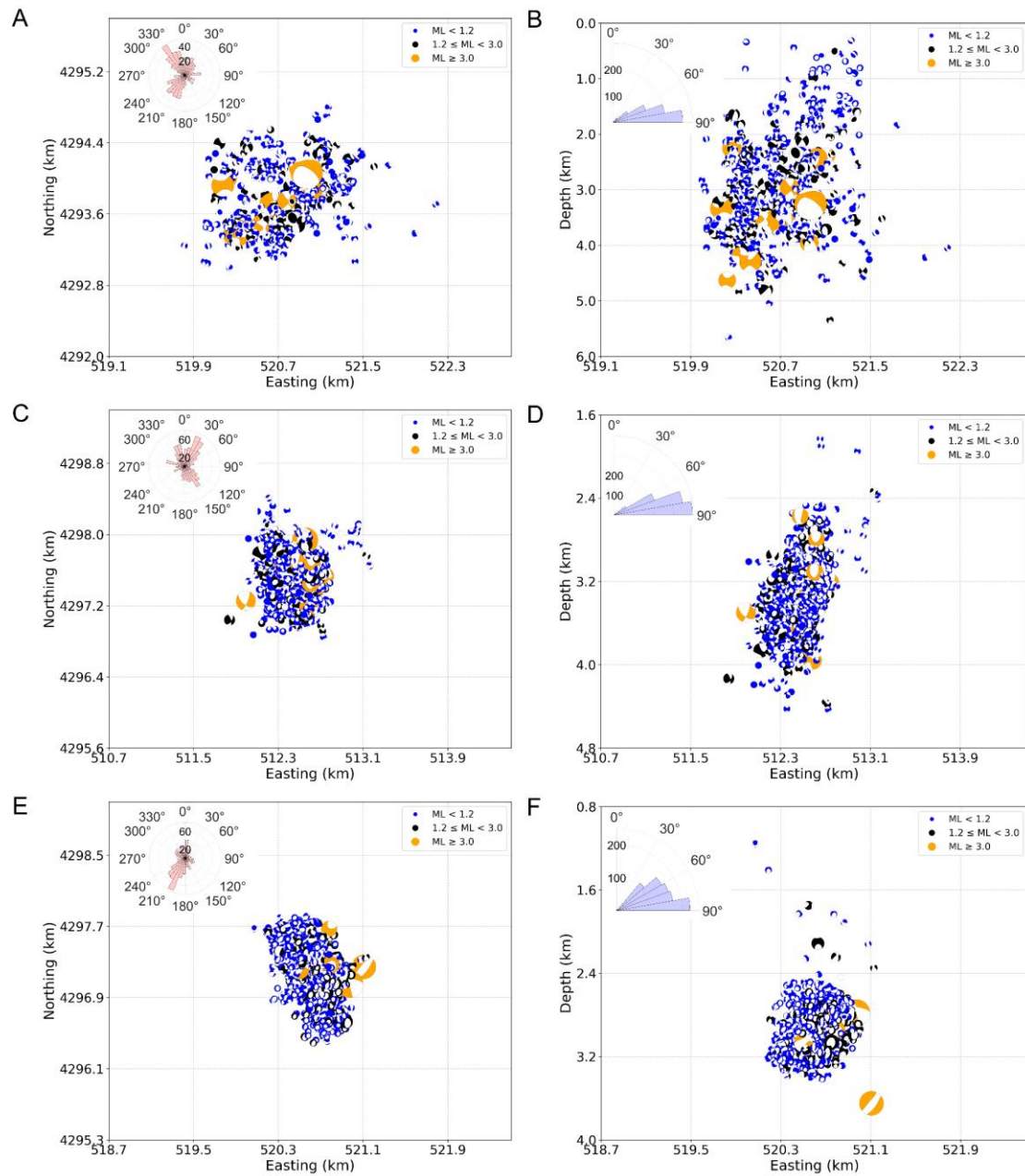
Supplementary Fig. 9 Spatial evolution of microseismic events for Cluster 16 (A) and Cluster 35 (B). The assumed locations of injection points are (512.42 km, 4297.52 km, 3.17 km) and (520.54 km, 4297.16 km, 2.87 km), respectively. The dashed gray lines correspond to the diffusion distance for a diffusivity of $0.10 \text{ m}^2/\text{s}$, starting from the first day of each year. Compared with the large depth range of Cluster 7, the two clusters here exhibit smaller depth ranges. As for Cluster 7, both clusters here also show steady evolution of distance indicating fast fluid/pressure migration along both horizontal and depth directions.



Supplementary Fig. 10 Spherical octant plots with high-quality fault plane solutions for Cluster 7 (A, D), Cluster 16 (B, E), and Cluster 35 (C, F). Left and right columns represent the results from SKHASH and NaNDC, respectively. Each corner denotes one major faulting class (strike-slip, normal, or reverse faulting), and intermediate areas show mixed faulting modes.

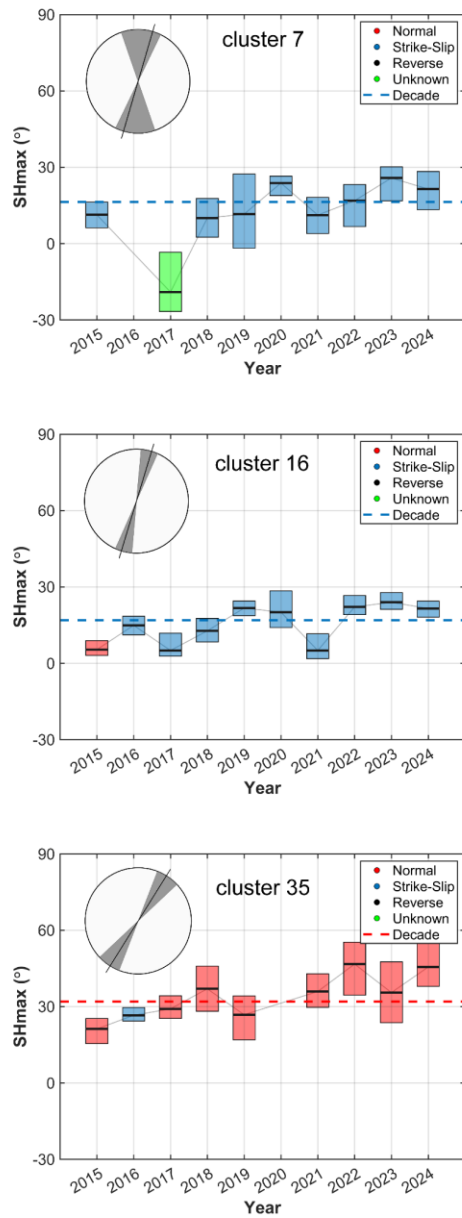


Supplementary Fig. 11 Double-couple focal mechanisms and Rose diagrams of the strike and dip angles by SKHASH for the three event clusters.

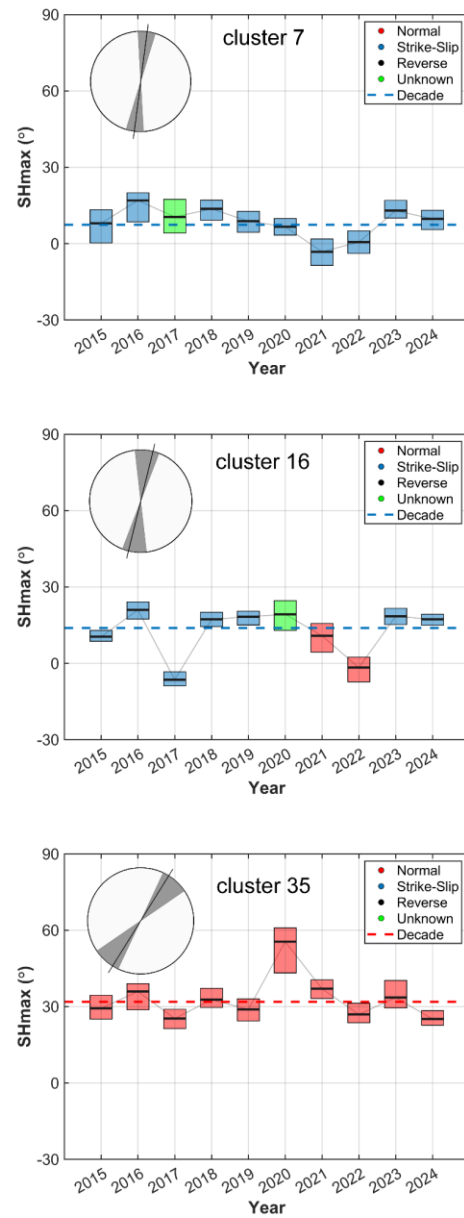


Supplementary Fig. 12 Full moment tensor source mechanisms and Rose diagrams of the strike and dip angles by NaNDC for the three event clusters.

A

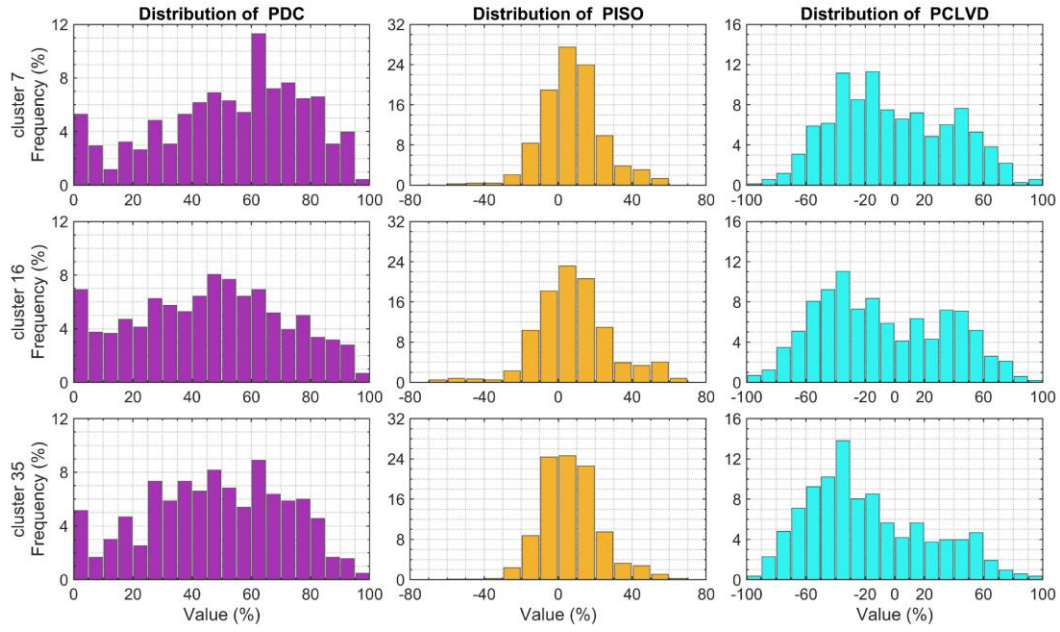


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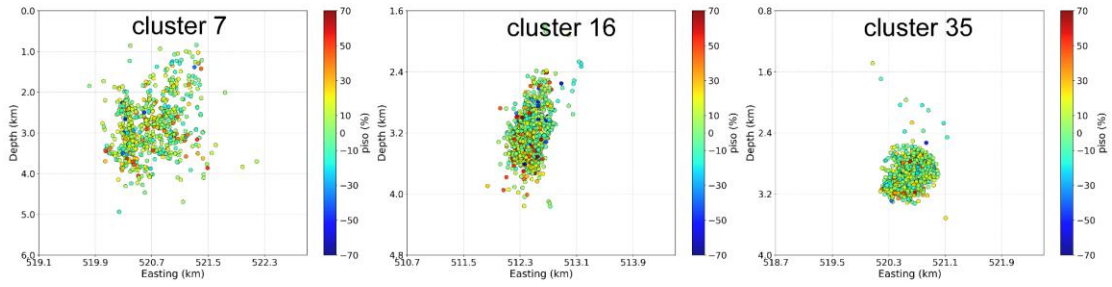


Supplementary Fig. 13 Annual variations in the orientation of the SHmax for the three clusters, using the results from SKHASH (A) and NaNDC (B). The boxplots illustrate the inversion uncertainty, while the gray shading within the circle in the upper-left corner represents the range of variation in the SHmax for each cluster over the past decade.

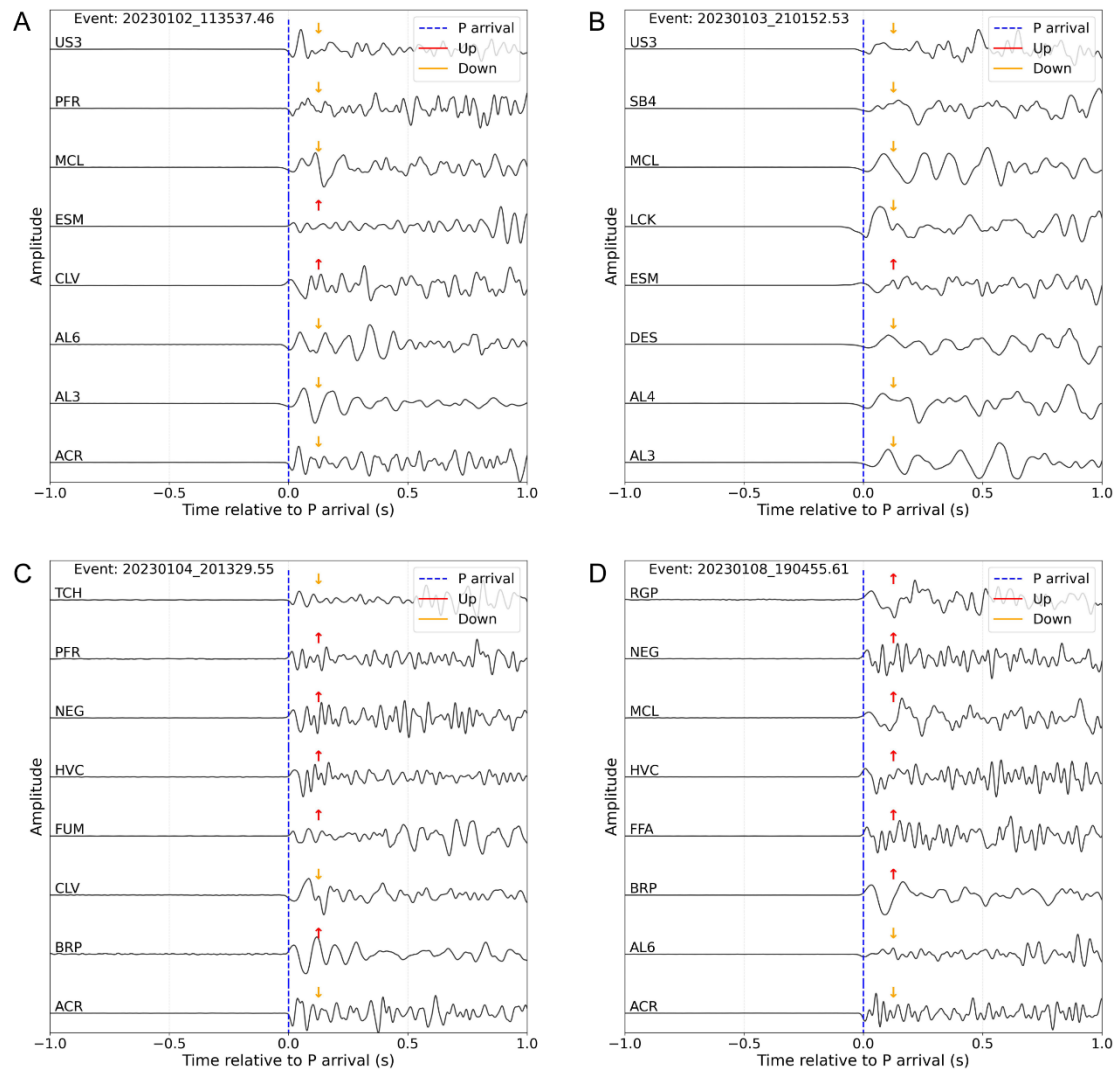
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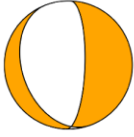
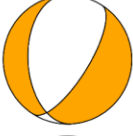
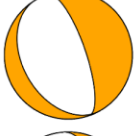
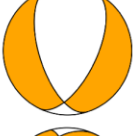
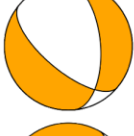
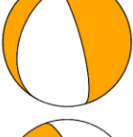
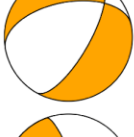
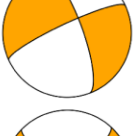
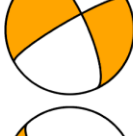
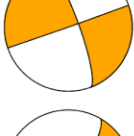
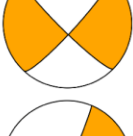
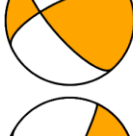
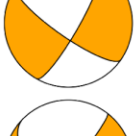
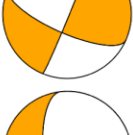
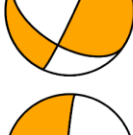
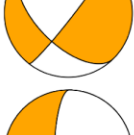
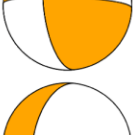
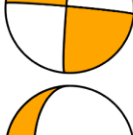
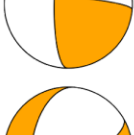
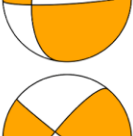
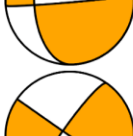
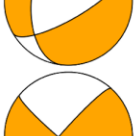
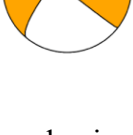
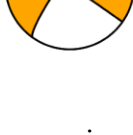
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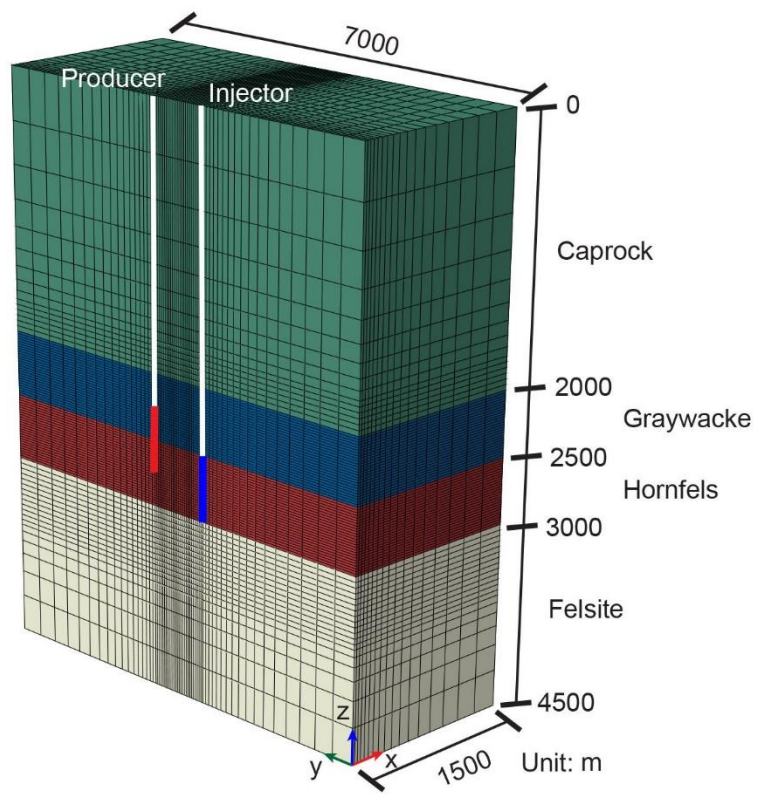
Supplementary Fig. 14 Proportions of the DC, ISO, and CLVD components in the moment tensors of microseismic events for different clusters (A), together with the ISO proportions for all events (B). Pronounced non-DC components are observed in all clusters, and significant positive and negative ISO components occur across events from different depth intervals, suggesting fracture opening and closure induced by fluid migration.



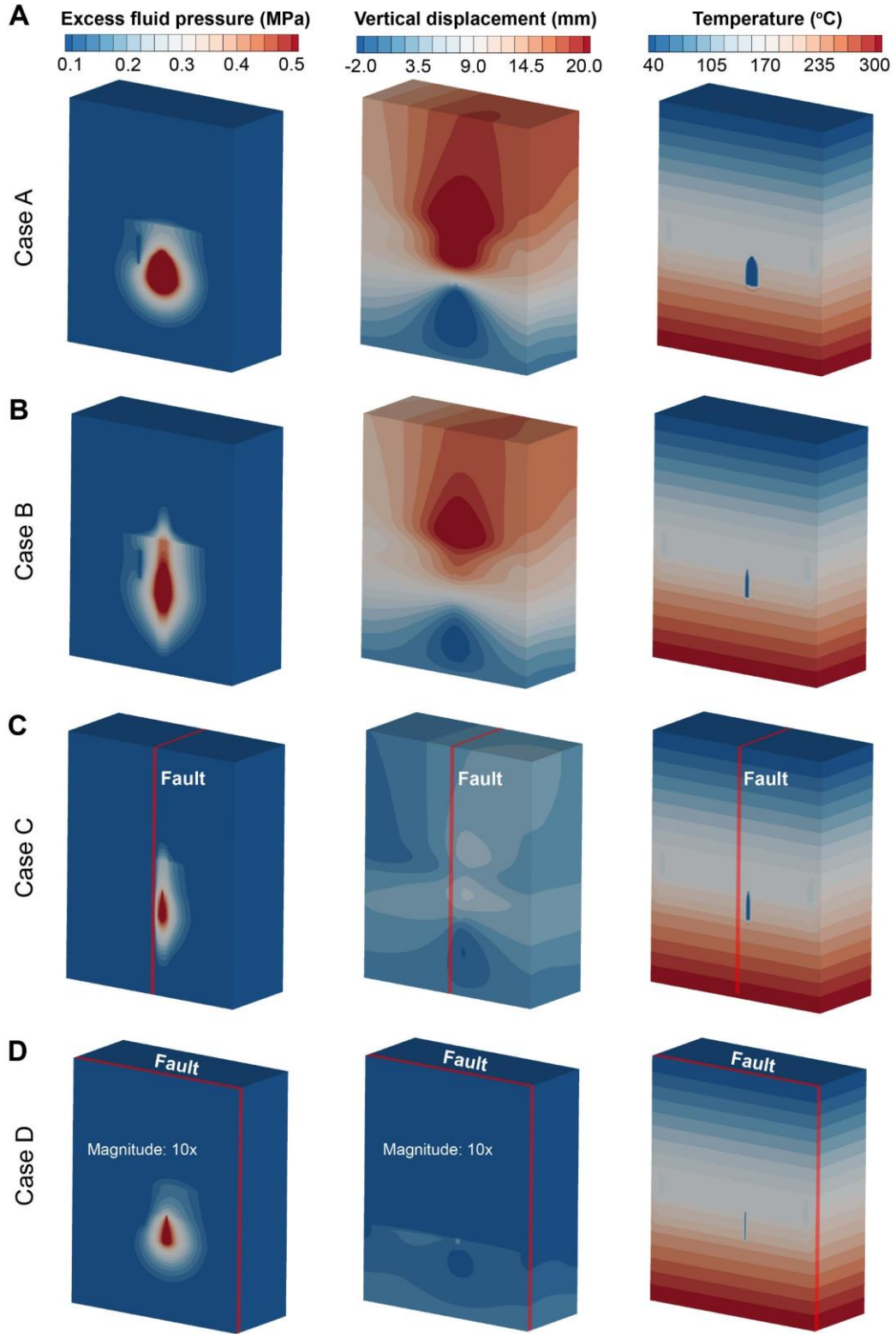
Supplementary Fig. 15 Illustration of the first-motion polarity prediction from RPNet for four sample events.

Origin Time	Magnitude	SKHASH	NaNDC	Magnitude	NCSS
20150310 00:40:09.18	ML 4.02			Mw 3.43	
20160115 13:05:24.65	ML 4.11			Mw 3.42	
20160408 12:58:31.00	ML 4.17			Mw 3.77	
20190604 01:44:21.20	ML 4.24			Mw 3.88	
20200227 23:27:29.86	ML 4.02			Mw 3.68	
20200325 11:57:37.92	ML 4.21			Mw 4.06	
20220430 18:17:56.84	ML 4.07			ML 3.32	
20230302 21:16:50.45	ML 4.27			Mw 3.59	
20230825 14:14:45.64	ML 4.25			Mw 3.96	
20240608 19:34:29.07	ML 4.55			Mw 4.48	

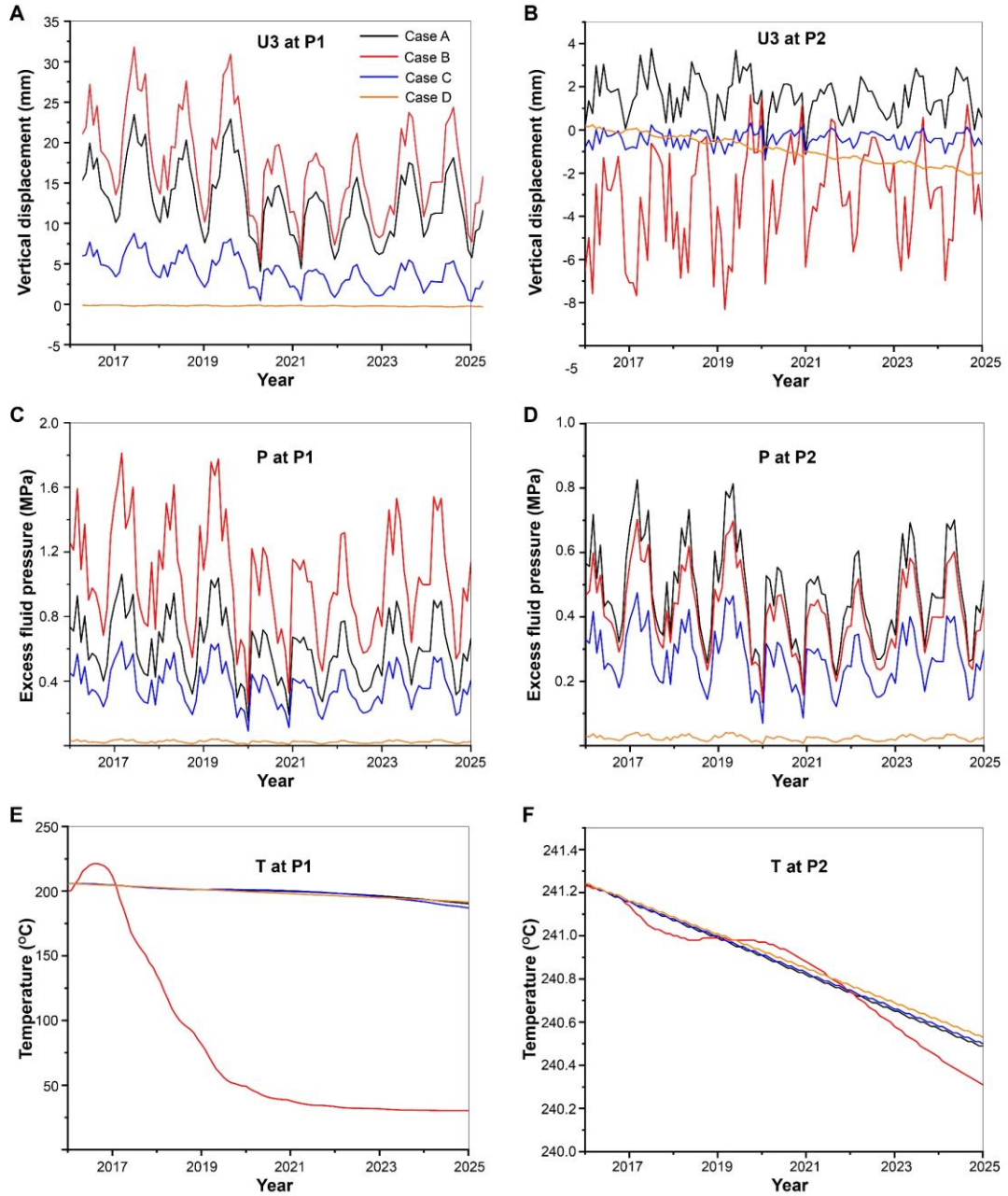
Supplementary Fig. 16 Source mechanism comparison between SKHASH, NaNDC, and the NCSS (Northern California Seismic System) results. Detailed focal mechanisms are listed in Supplementary Table 1.



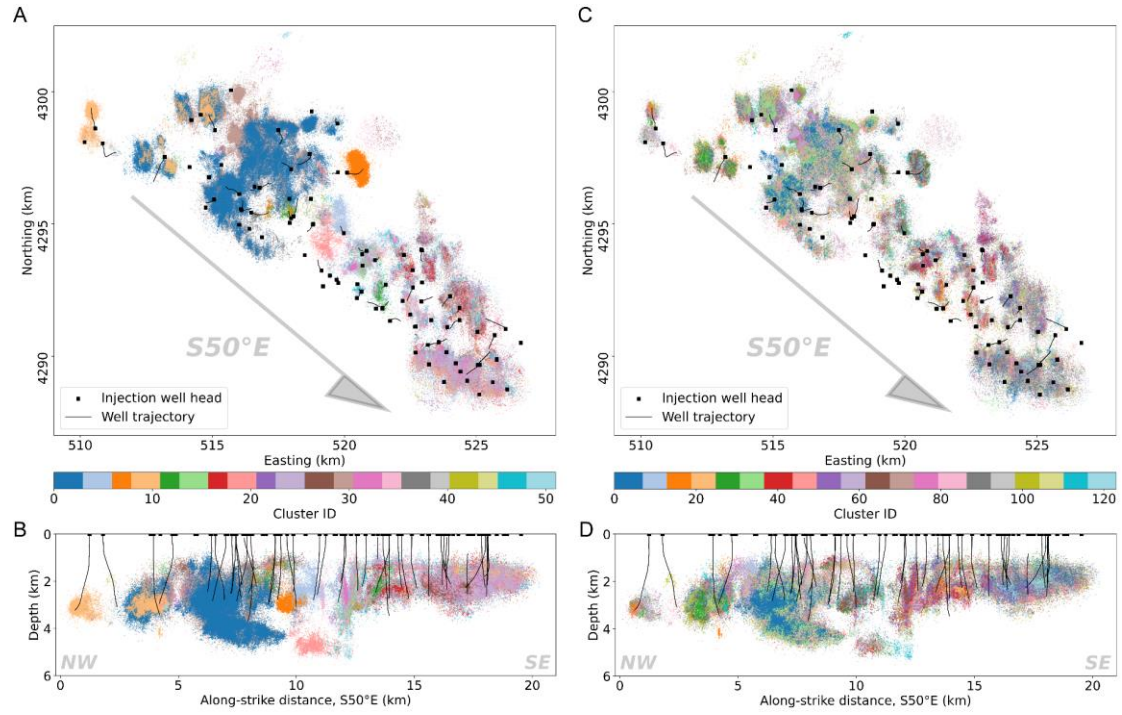
Supplementary Fig. 17 Schematic and mesh of the 3D geological model.



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. Case A: isotropic permeability within each layer. Case B: orthotropic permeability in which the vertical component is two orders of magnitude higher. Case C: the fault is perpendicular to the injector-producer plane, reflecting enhanced permeability in both the x and z directions. Case D: a fault is situated in the injector-producer plane, reflecting enhanced permeability in both the y and z directions.



Supplementary Table 1 Source parameters of the ten selected ML 4 events in Fig. 1 and Supplementary Fig. 16.

Origin time	This study			NCSS	
	Magnitude	SKHASH (strike/dip/rake)	NaNDC (strike/dip/rake)	Magnitude	Focal mechanism (strike/dips/rake)
20150310 00:40:09.18	ML 4.02	315/6/-124	140/13/-139	Mw 3.43	160/25/-110
20160115 13:05:24.65	ML 4.11	177/35/-120	175/30/-90	Mw 3.42	150/25/-100
20160408 12:58:31.00	ML 4.17	163/50/-121	139/52/-158	Mw 3.77	130/55/-120
20190604 01:44:21.20	ML 4.24	207/26/-51	215/26/-70	Mw 3.88	259/41/-49
20200227 23:27:29.86	ML 4.02	340/68/-166	335/66/-167	Mw 3.68	340/75/180
20200325 11:57:37.92	ML 4.21	135/80/-168	139/64/146	Mw 4.06	125/71/-164
20220430 18:17:56.84	ML 4.07	114/63/-176	122/40/-171	ML 3.32	135/45/-170
20230302 21:16:50.45	ML 4.27	174/56/166	185/85/177	Mw 3.59	181/70/169
20230825 14:14:45.64	ML 4.25	188/41/-166	178/40/-176	Mw 3.96	186/38/-137
20240608 19:34:29.07	ML 4.55	128/87/161	215/78/0	Mw 4.48	130/80/170

Supplementary Table 2 Material properties of rock units (Rutqvist et al., 2016)

Material properties		Caprock	Graywacke	Hornfels	Felsite
Physical	Solid density ρ_s (kg/m ³)	2700	2700	2700	2700
	Fluid density ρ_f (kg/m ³)	1000	1000	1000	1000
	Porosity (%)	0.01	1.5	1.0	1.0
Mechanical	Elastic modulus E (GPa)	5.0	5.0	5.0	5.0
	Poisson's ratio	0.25	0.25	0.25	0.25
	Fluid compressibility β_p (Pa ⁻¹)	4.5×10^{-10}	4.5×10^{-10}	4.5×10^{-10}	4.5×10^{-10}
Hydraulic	Intrinsic permeability k (m ²)	1.0×10^{-17}	5.0×10^{-13}	2.0×10^{-13}	1.0×10^{-14}
	Fluid dynamic viscosity μ_f (Pa · s)	0.001	0.001	0.001	0.001
Thermal	Solid specific heat C_s (kJ/(kg°C))	1.0	1.0	1.0	1.0
	Solid heat conductivity λ_s (W/(m°C))	3.2	3.2	3.2	3.2
	Solid thermal expansion coefficient β_v (°C ⁻¹)	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}
	Fluid specific heat C_f (kJ/(kg°C))	4.18	4.18	4.18	4.18
	Fluid heat conductivity λ_f (W/(m°C))	0.6	0.6	0.6	0.6
	Fluid thermal expansion coefficient β_T (°C ⁻¹)	3.0×10^{-4}	3.0×10^{-4}	3.0×10^{-4}	3.0×10^{-4}

References

1. Martínez-Garzón, P., Bohnhoff, M., Kwiatak, G. & Dresen, G. Stress tensor changes related to fluid injection at The Geysers geothermal field, California. *Geophysical Research Letters* **40**, 2596–2601 (2013).
2. Boyle, K. & Zoback, M. The Stress State of the Northwest Geysers, California Geothermal Field, and Implications for Fault-Controlled Fluid Flow. *Bulletin of the Seismological Society of America* **104**, 2303–2312 (2014).
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