

Development of a Combined Detection and Relocation Workflow (TM2DD) to
Characterize Escalating Hydraulic Fracturing Induced Seismicity in the Karnes
Trough Fault Zone of the Eagle Ford Shale Play, Texas

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Key Points:

1. We address the increasing magnitude and frequency of earthquakes in the Eagle Ford Shale Play by developing a combined Template Matching to Double Difference relocation workflow.
2. The enhanced, relocated catalog reveals the 2023 M4.0 and 2025 M4.7 earthquakes ruptured connected, structurally segmented portions of the same fault with the later event rupturing deeper portions.
3. These observations indicate that the proximity of nearby (<3.5 km) operational hydraulic fracturing well to a particular fault was a key component in stimulating M4+ events.

Abstract:

On January 30, 2025, an M4.7 earthquake shook the Eagle Ford Shale, Texas, the region's second M4 event in under eighteen months. Unlike much of the central United States, where induced seismicity stems from wastewater disposal, most of the earthquakes in the Eagle Ford are linked to hydraulic fracturing (HF) (Fasola *et al.*, 2019; Fasola & Brudzinski, 2023). If HF-induced, the 2025 event would be the largest such earthquake in the United States, amid seismicity increasing in both magnitude and frequency. The seismicity appears to be associated with mapped normal faults in the Karnes Trough Fault Zone (KTFZ), but its detailed pattern and relationship to HF operations remain poorly characterized. This study leverages ~5 years of continuous TexNet recordings (~25 km station spacing) to better detect and locate this seismicity. We have developed a workflow (TM2DD) that integrates multistation template matching with automated per-template correlation thresholds, refines phase arrivals via template-detection cross correlation, and applies double-difference relocation using a local 1-D velocity model. This expands the detected catalog by 17.5-fold, with relocations revealing that the 2023 M4.0 and 2025 M4.7 sequences ruptured adjacent fault segments with 15-20 degree differences in dip angle. In addition, the larger event occurred at the deeper extent of the seismically active zone. All detected sequences correlate tightly in space and time with active HF wells within 3.5 km, with the deeper 2025 event showcasing mainshock - aftershock behaviour, whereas the shallower 2023 sequence is swarm-like. These results indicate that HF-induced seismicity in the KTFZ can propagate along adjacent, connected fault systems as nearby operations continue, with deeper segments potentially hosting larger, mainshock-dominated ruptures.

Introduction

Fluid injection associated with oil and gas operations has been linked to increased seismicity in multiple regions of the United States (Ellsworth, 2013). Some of the largest HF-induced earthquakes in the United States have occurred within Texas, including a M4.0 in May of 2018 (Schultz *et al.*, 2020). The seismic hazard is further compounded by operational practices such as zipper fracturing, which has been shown to triple the probability of seismicity (Fasola *et al.*, 2019). Despite this established hazard and an understanding of risk-amplifying factors,

regulatory frameworks and mitigation strategies in the region remain limited (Fasola & Brudzinski, 2023).

The Eagle Ford Shale is of particular interest as an area of induced seismicity due to operational activities (Ewing, 1990; Frohlich et al., 2016), as five M4.0 or larger earthquakes have occurred in the region since 2017, with the most recent being a M4.7 on January 30th, 2025 (TexNet, 2026). Both the frequency and magnitude of seismicity continue to increase (Figure 1), with most of the seismicity in the Eagle Ford having been attributed to hydraulic fracturing rather than salt water disposal (SWD) (McKeighan et al., 2022). This distinguishes it from other seismically active regions in the Central United States such as Oklahoma (Walsh & Zoback 2015), West Texas (Savvaiddis et al., 2020), and Kansas (Fasola et al., 2025), where wastewater disposal has been the primary driver. Interestingly, those regions saw a decline in seismicity following the implementation of targeted regulatory frameworks (Skoumal et al., 2024). This is a response that has yet to be mirrored in the Eagle Ford Shale.

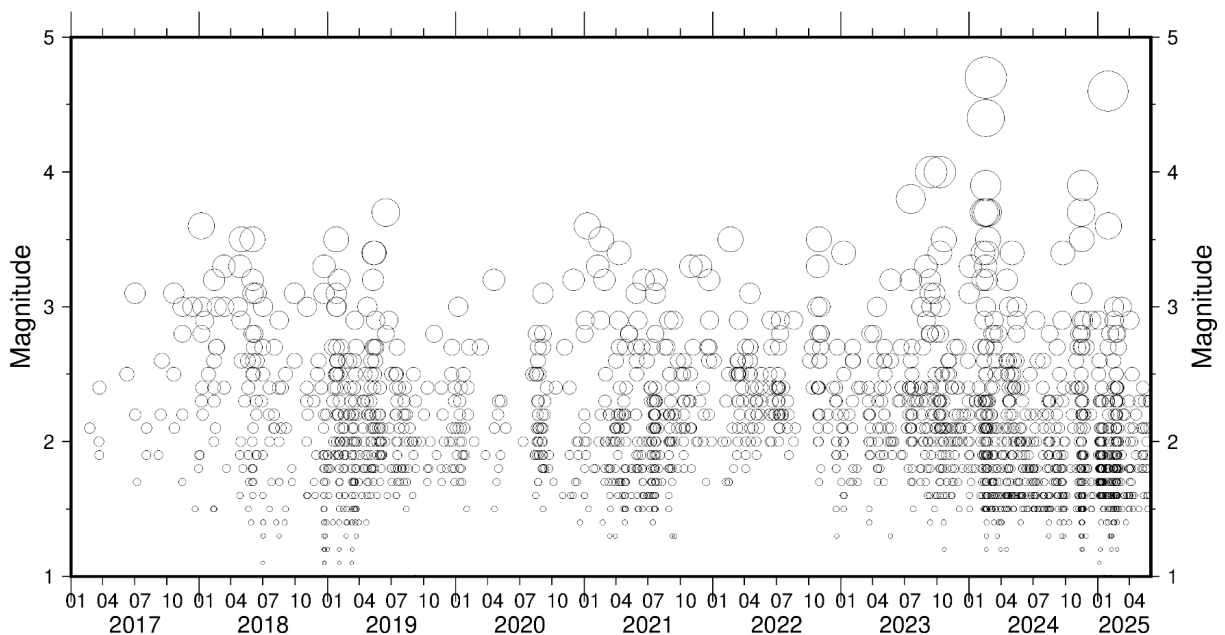


Figure 1. Magnitude over time where sizes of the circles correspond to the event's magnitude. Catalog is from USGS comcat that was compiled via obspy (Beyreuther et al., 2010).

Within the Eagle Ford Shale Play, multiple fault zones and industrial activity are present, with the Karnes Trough Fault Zone (KTFZ) hosting 77% of all HF-induced earthquakes (McKeighan et al., 2022) (Figure 2). The KTFZ is dominated by northeast-southwest striking normal faults, dipping between 45° to 80° , with the steepest dipping segments more prone to seismicity (McKeighan et al., 2022). Fasola et al., (2019) applied template matching to enhance this catalog and found increased event detection, followed with tighter spatiotemporal clustering of the events. In a follow up study, Fasola & Brudzinski (2023) proposed that fluid flux, defined as

volume per unit time per unit area, is a primary driver of fault reactivation, where proximity to pre-existing faults serves as a secondary control.

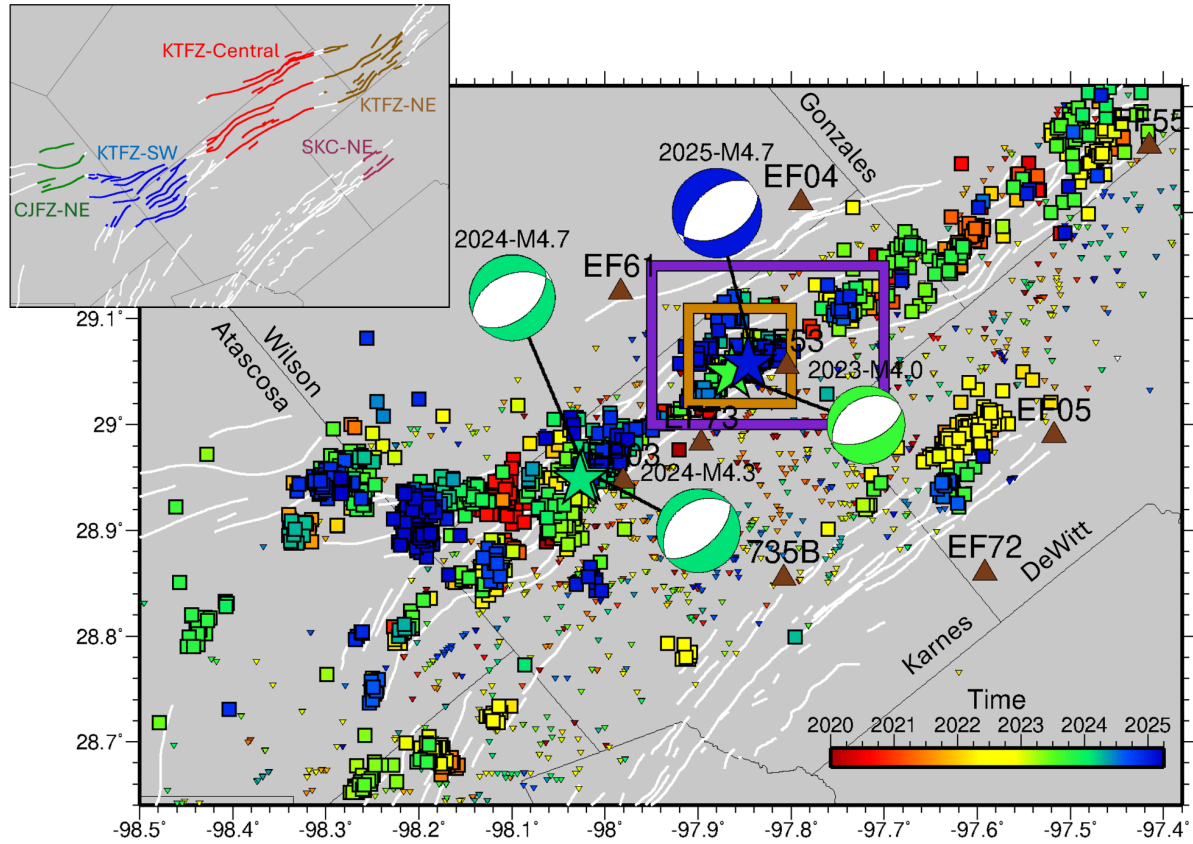


Figure 2. Map illustrating TexNet Seismicity in the Eagle Ford Shale Play. Squares represent the TexNet catalog locations, and are colored respectively by time of occurrence. Stars are events with magnitudes greater than 4, and are depicted by their respective focal mechanisms. Stations are represented by brown triangles and are labeled respectively, with faults being depicted in white. Operation HF wells are inverted triangles and are colored the same as the seismicity. Our template matching target area is depicted as a purple box, and our relocation target area an orange box. Thin black lines are county borders with their appropriate labels. The fault zones present are inset and are colored and named.

A double-difference (*hypoDD*) relocated catalog from Li et al., (2021) transformed diffuse TexNet seismicity into tight linear clusters where five out of the six clusters correlated with mapped faults. Their centroid moment tensor (CMT) solutions (e.g., normal faults with 60°–80° dips) when paired with the relocated hypocenters match the orientation of historical faults. However, these findings relied solely on TexNet’s catalog, so there were typically only a handful of earthquakes relocated to each fault. Nevertheless, we noted there was some evidence for earthquakes occurring several years apart on the same fault, which suggested the potential for

faults to be reactivated. These cases were not tied to specific HF wells, so it is unclear what may be causing the possible reactivation.

One strategy to better understand the spatio-temporal distribution of seismicity and potential drivers of fault reactivation is to apply template matching algorithms to expand beyond the existing TexNet catalogs and then apply double difference relocation based on the waveform cross-correlations (e.g., Kozłowska et al., 2018). Template matching has been used to correlate seismicity with hydraulic fracturing operations in the Eagle Ford Shale Play (Fasola et al., 2019; Fasola & Brudzinski, 2023), though detailed relocation of the resulting enhanced catalogs has not yet been attempted. Fasola et al. (2019) found that 87% of HF-correlated earthquakes occurred within 10 km of mapped faults, and normal faulting focal mechanisms combined with a 0.9 b-value indicate that slip is occurring on pre-existing faults rather than newly created fractures. McKeighan et al. (2022) identified 36 seismogenic faults out of 169 mapped structures in the Karnes Trough Fault Zone, but some clusters in the relocated catalog were offset ~1 km from mapped faults, pointing to the possible existence of unmapped fault segments (Li et al., 2021). Despite these findings, the relatively small number of events in each prior catalog leaves significant uncertainty in the spatiotemporal evolution to fully evaluate the nature of fault reactivation. Based on the limits of prior work, we seek to address five key research questions: 1) Is there any systematic pattern to which faults become activated? 2) Do multiple wells reactivate the same fault over time? 3) How does the proximity of hydraulic fracturing operations influence fault reactivation? 4) During repeated reactivation, does slip localize on the same fault segment or migrate over time? Resolving these questions requires a substantially larger, more precisely located catalog than what has been previously available for the KTFZ. Thus, we set a research goal to develop an openly available efficient workflow linking pre-existing template matching and relative relocation codes into a single pipeline that others could utilize as well.

Data Collection

Within the KTFZ, we selected a study region based on the occurrence of a M4.0 event in September, 2023, and a M4.7 event in January 2025 that were in close proximity but separated by eighteen months. The region of interest spans latitudes 29.00°–29.15°N and longitudes 97.70°–97.95°W, with a temporal focus on seismic events from January 1st, 2020 to April 1st, 2025 (Figure 3). Hypocenters were retrieved using a USGS rectangular search algorithm and compiled into a localized catalog, although TexNet is ultimately responsible for hypocentral locations retrieved in this region. Arrival time phase picks were collected directly from TexNet via web services. To maximize the size of the template catalog, we collected all events regardless of reported magnitude. Seismograms were collected from 10 stations (Figure 2), with most data retrieved from EarthScope, but stations EF53, EF55, EF61, EF72, and EF73 were downloaded from TexNet after the 1 year embargo period.

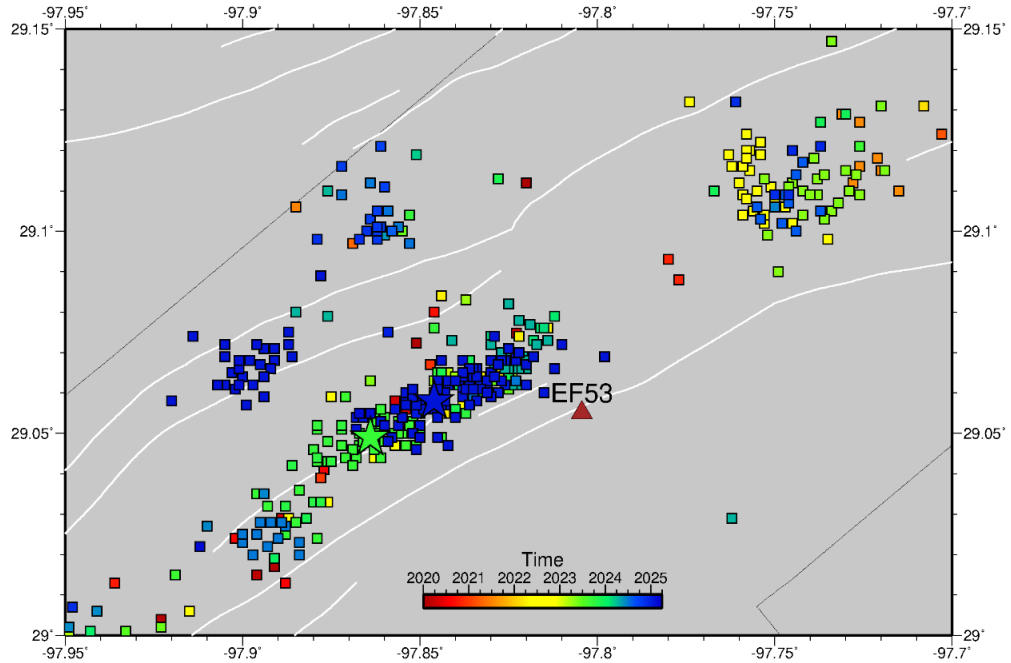


Figure 3. Illustration of the spatial and temporal distribution of catalog template events. Events, Faults, and stations are depicted the same as in Figure 2. There are a large number of sequences that have events close spatially and temporally.

TM2DD Workflow Development:

To improve both the completeness and location accuracy of the earthquake catalog, we developed TM2DD: a multi-step template matching to relocation workflow that exploits the waveform similarity of nearby events (Figure 4). TM2DD combines widely used, open-source seismological software with components we developed to create an end-to-end workflow that handles data formatting, transfer results between steps, and perform key analyses from detection through relocation. The workflow begins with multistation template matching to expand the TexNet catalog, which is then run through per-template correlation thresholds to remove noise dominated matches. We developed processing to propagate P and S phase picks from each template to its detections, systematically refined via cross correlation, and then the dataset is inverted for preliminary absolute locations of newly detected events. Finally, these preliminary locations and cross-correlation differential times are relocated with *hypodDD* (Waldhauser & Ellsworth, 2000). Each component is described in more detail in the following sections.

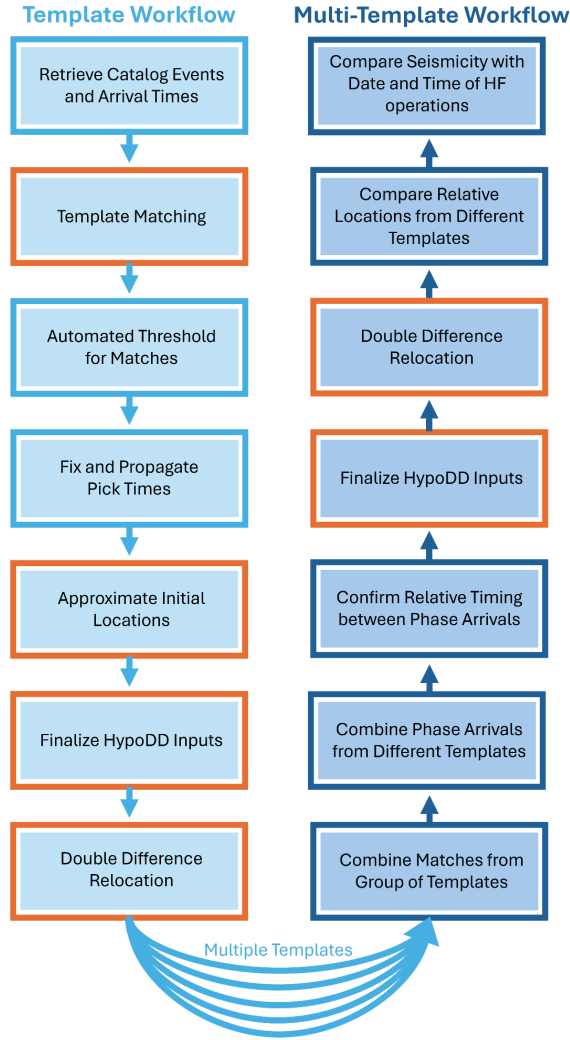


Figure 4. Schematic of the TM2DD workflow. Orange outlines denote established, open-source methods, and blue outlines denote components we developed. Outputs from the template workflow (light blue) were combined into multiple template groups (MTG), and fed into the multi-template workflow (dark blue), though the template workflow can also run independently.

Template Matching

Our template matching algorithm utilized the three nearest recording stations that have continuously recorded data through the time frame of interest. The stations are 3-component broadband stations operated by TexNet: 735B, EF03, and EF04. Our templates were constructed using 20 second long waveforms that were bandpass filtered from 3-15 Hz with a focus on the P wave arrival for the vertical component, and the S wave arrival for the horizontal component, with 5 s before the arrival time and 15 s after. The 20 second window length was chosen to accommodate the travel-time separation expected at our furthest source-to-station distances,

which reached approximately 50 km. At this distance, P-wave arrivals occur roughly 8 seconds into the recording while S-wave arrivals occur around 15 seconds.

The data was scanned for matches from January 1st, 2020 to April 1st, 2025 using each TexNet catalog event as a template. All templates and their matches were combined into a single expanded catalog. Duplicates were addressed by retaining only the match with the highest correlation coefficient within a 6-second window (based on the P-S separation expected at our typical ~25 km station spacing). Since template matching can identify significant levels of noise depending on the threshold of detection, we used a recently developed approach to determine the threshold for statistically significant matches (Khalkhali et al., in prep).

Automated Threshold:

Random noise, which we observed through manual review, follows a natural pattern where the number of matches decays logarithmically with increasing correlation coefficient (Figure 5). Real seismicity shows up as a departure from this logarithmic decay such that the number of matches is higher than expected from random noise. A line can be fit to the noise part of the decay curve in log-linear space to identify the correlation coefficient above which noise should not be able to generate matches, particularly if we account for the uncertainty due to the variation in slope (Figure 5) (Khalkhali et al., in prep). Using this approach allows us to identify an automated correlation threshold value that preserves matches but cuts out noise in an efficient manner for a large number of templates. The threshold of ~0.15 seen in Figure 5 is observed for the majority of our templates based on the 3 station template matching.

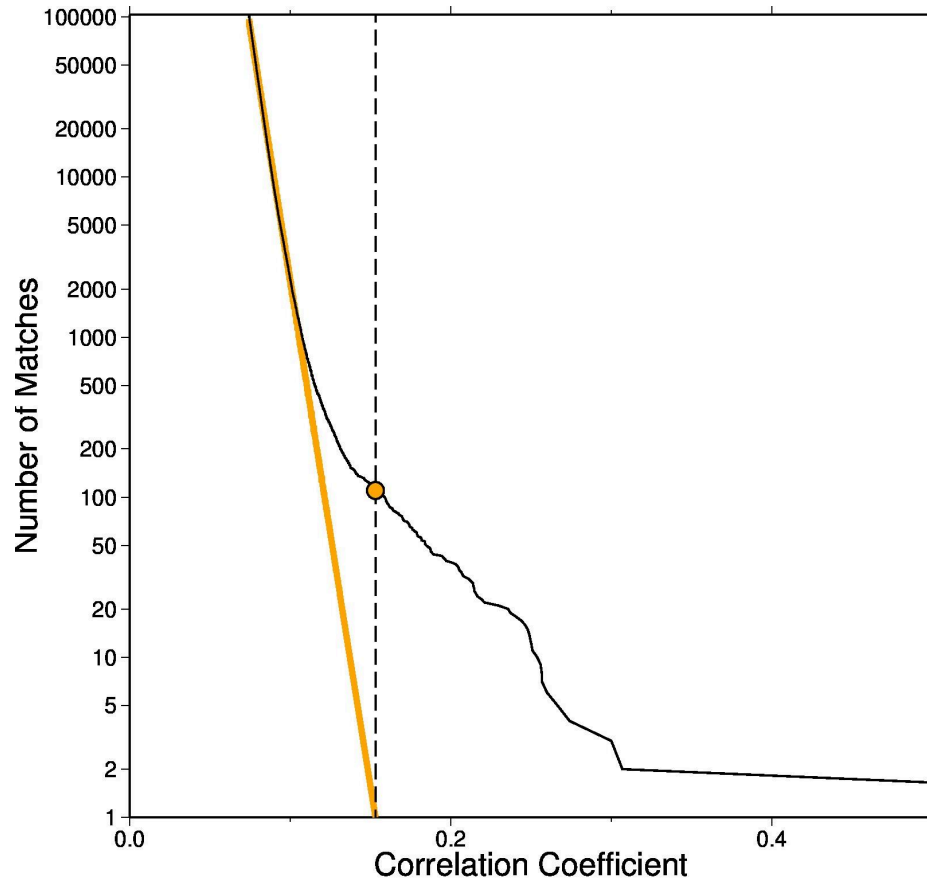


Figure 5. Example comparison of the cumulative number of matched events for a single template (plotted logarithmically) as the correlation coefficient threshold decreases. The orange line is fit to the noise portion of the cumulative distribution and is then used to define the correlation coefficient above which only real seismicity should be detected.

Fixing and Propagating Picks with Waveform Cross-Correlation:

Skoumal (2014) demonstrated that matched events typically lie within approximately one kilometer of their template events, as template matching relies on high waveform coherence which decreases with distance. The template matching method effectively detects small, repeating earthquakes with similar waveforms, all typically located within a quarter wavelength of each other (Skoumal, 2014; Geller & Mueller, 1980). Despite the spatial constraint of ≤ 1 km, location refinement of matched events remains necessary for precise analysis. Due to the potential for multiple fault segments less than a kilometer away, additional refinement of locations is necessary to constrain fault geometry. Our algorithm was designed to use the previously identified arrival times of the template event and the waveform cross-correlation between the template and the match to construct arrival times for the matched events.

We sought to use arrival time picks from TexNet for the template events. However, the majority of the automated picks provided by TexNet were found to be inaccurate upon manual inspection, arriving too early or too late relative to the analyst-observed arrival time. Approximately 60% of channels had usable automated picks, with the rest of the channels missing picks entirely or being inconsistent with manual observations. These inconsistencies were identified across every template, requiring manual review to align or create picks with the proper waveform arrivals. Once corrected, the arrival times were propagated to matched events using waveform cross-correlation to identify differential times relative to the template with precision substantially finer than what is achievable through manual picking alone (Schaff et al., 2004; Schaff & Waldhauser, 2010). Correlation windows were phase specific, with the vertical-component (P-phase) waveforms windowed from 0.5s before to 1.0s after the reference pick, while horizontal-component (S-Phase) waveforms used a window of 0.5s before to 1.5s after. For each template and station-channel, correlations were computed across all matches to establish each match arrival time. Before computing a correlation, each event pair was checked for data availability and waveform consistency, where pairs that were empty or missing SAC files and pairs whose end times differed by more than 10s were discarded. Match times without recordings or with correlations resulting in differences larger than 10 s were discarded to avoid correlating against incomplete or misaligned waveforms.

Following an initial round of cross-correlation, lag values for each event were averaged across all matched pairs at a given station-channel to obtain a single, refined time correction per event. This mean correction was applied to the existing pick time, updating the P and S phase arrival for that station channel, with the corrected S phase timing propagated across both horizontal components at a given station. Cross-correlation was then repeated using these realigned picks, producing final differential times with improved internal consistency relative to the initial pass. These differential times serve as the primary input for the preliminary location calculation and the eventual double-difference relocation described below.

Calculating the Matched Events Initial Absolute Location:

Initial absolute locations for matched events were computed using *elocate*, an efficient location routine from Computer Programs in Seismology (Herrmann, 2013). We used *elocate* with a local one-dimensional velocity model developed for the KTFZ (Fasola & Brudzinski, 2023) and P and S phase arrivals drawn separately from vertical- and horizontal- component picks. A starting location for each event was computed as the mean coordinate of the recording stations used, with depth determined via a grid search over candidate depths, where we selected the solution that showed the greatest stability across neighboring depth steps. The best-fit location and associated station residuals were retained for each event. This processing follows that of Kozłowska et al., (2018).

Finalizing HypoDD Inputs:

Cross-correlation outputs were compiled into the standard differential-time format required by *hypoDD*. For each event, phase, origin-time, and station information was extracted from the corresponding *elocate* output. Correlation coefficients were phase-labeled by component, with vertical-channel measurements assigned to the P phase and the horizontal-channel measurements to the S phase. Correlation coefficients were used as phase weights and weak correlations ($CC < 0.1$) were zeroed out during compilation as an initial noise-suppression step. Event pairs were formatted into the standard *dt.cc* differential-time file used by *hypoDD*.

Double-Difference Relocation:

Both absolute phase and differential times were input into *hypoDD* (Waldhauser & Ellsworth, 2000), a double-difference relocation algorithm that refines hypocenter locations by minimizing residuals between observed and model-predicted travel-time differences for closely spaced event pairs. Catalog-based differential times were first generated using *ph2dt*, a *hypoDD* preprocessing tool, and combined with the cross-correlation-derived differential times described above. The cross-correlation data was weighted more heavily for closely spaced pairs, with catalog data contributing to broader adjustments in accordance with standard *hypoDD* practice. Relocation used the same local 1-D velocity model from Fasola & Brudzinski (2023) that was applied during initial absolute location with *elocate*. Double-difference equations were solved using the least-squares (LSQR) method with damping applied to stabilize the inversion (Waldhauser & Ellsworth, 2000). Output included relocated hypocenter station residuals and iteration statistics for quality manual assessment (Table S3).

Multiple Template Workflow Implementation:

To apply the workflow across the study area, we input every TexNet catalog template (Salles et al., 2026) within our timeframe into the single-template portion of the workflow (light blue, Figure 4). Phase arrivals were sourced from TexNet and EarthScope (see Data and Resources). Each template was run through template matching and automated per-template threshold detection. Wherever stable results were obtained for a template and its matches (template families), the family was then run through *hypoDD*. Template families were combined into multiple template groups (MTGs) and run through the multi-template portion of the workflow (dark blue, Figure 4). When every catalog template was placed in a single MTG, *hypoDD* failed to produce stable output with our input parameters. We therefore subset the data into four prolific sequences: the two M4+ sequences in 2023 and 2025, and two sequences in 2022 and 2024 that correlated spatiotemporally with active HF operations. These sequences were relocated together in one 70 template subset (see Results), and the 2023 M4.0 and 2025 M4.7 individually.

Correlation with active HF wells was one factor in which template families produced stable *hypoDD* results when combined into an MTG. The main factors were P-S arrival time differences and waveform coherence. Because the events are closely spaced, small variations in P-S arrival times could destabilize the solution: a 0.1 s pick error corresponds to roughly 1 km of

location error. To maintain stability, each MTG began with two template families and grew by two per iteration. When *hypoDD* failed to produce stable output, the responsible template family was removed, which restored stability. These criteria determined which template families were relocated relative to one another and which remained separate. For the subset relocation tests, templates were further selected for high SNR and clear P- and S-wave arrivals.

Limited station coverage left depth poorly constrained, and this appeared as vertical scatter in otherwise well-constrained horizontal locations. To remove these outlying depths, we applied Random Sample Consensus (RANSAC; Fischler and Bolles, 1981) regression using scikit-learn (Pedregosa et al., 2011).

Template Matching Results

Texnet Catalog

Overall we were able to expand the TexNet catalog from 359 templates to 6280 matches (**Figure 6; Table S1a,b**). The enhancement was consistent across years, ranging from 11.8x to 20.8x annually. Annual matched-event totals rose from 177 in 2020 to 1,521 in 2023, and 1,494 in 2024, then reached 2,303 events in the first three months of 2025 (Table S1b). The months containing each M4+ event show comparable gains. September 2023 grew from 53 to 775 events (14.6x), and January 2025 grew from 84 to 1,668 events (19.9x).

The temporal pattern of the expanded catalog shows increases in both the rate and the maximum magnitude of seismicity. Between 2020 and 2025, the expanded catalog contains four main sequences, in 2022, 2023, 2024, and 2025, each corresponding with nearby HF operations. Frequency-magnitude analysis of the enhanced catalog indicates a magnitude of completeness of $M_c = 0.75$, roughly one magnitude unit lower than the original TexNet catalog (Figure S2). The corresponding b-value of 0.84 is consistent with the $b = 0.9$ reported by Fasola et al. (2019). Correlation coefficients for matched events are generally low relative to typical single-station template matching studies.

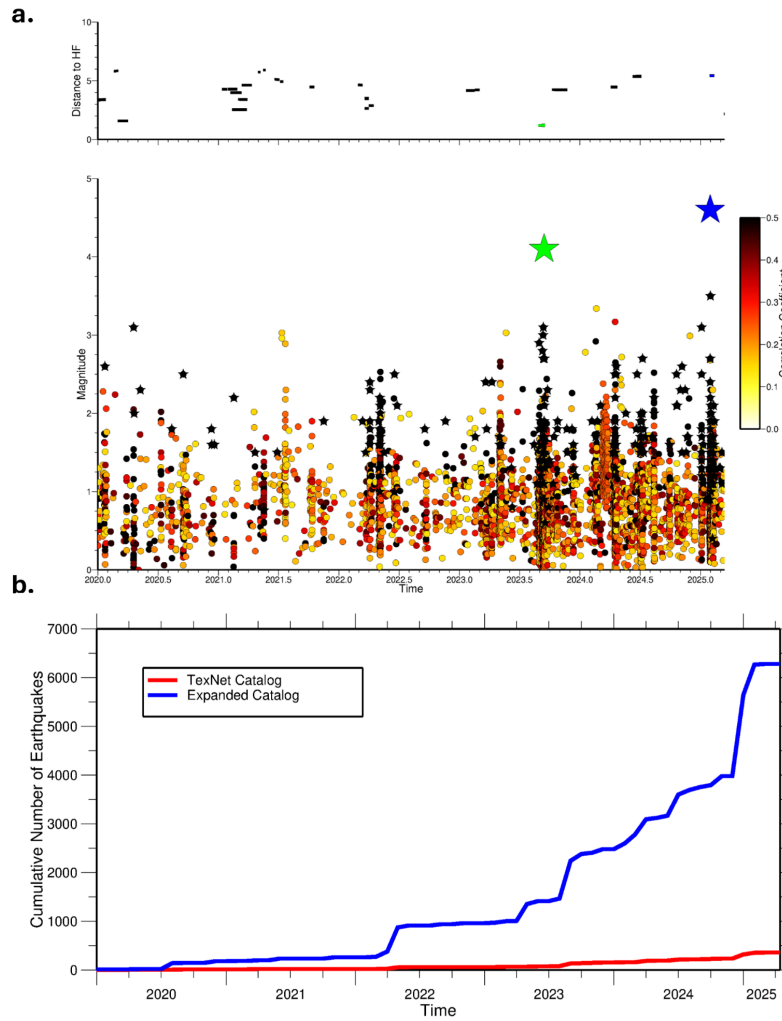


Figure 6. (a) Magnitude over time plot for TexNet catalog events (stars) and our matched events (circles). Matched events are colored by Correlation Coefficient, except for the 2023 M4.0 event and the 2025 M4.7 event which are colored in green and blue respectively. The correlated causative wells are colored to match their event. (b) Cumulative event over time plot for matched events (blue) vs TexNet template events (red) following the same timeframe as (a).

Sequence Characteristics:

Due to the four main sequences within our expanded catalog, we examined the temporal and magnitude characteristics of each in detail (**Figure 7**). Initial comparison highlights a progression in sequence behavior alongside the increase in maximum magnitude noted above.

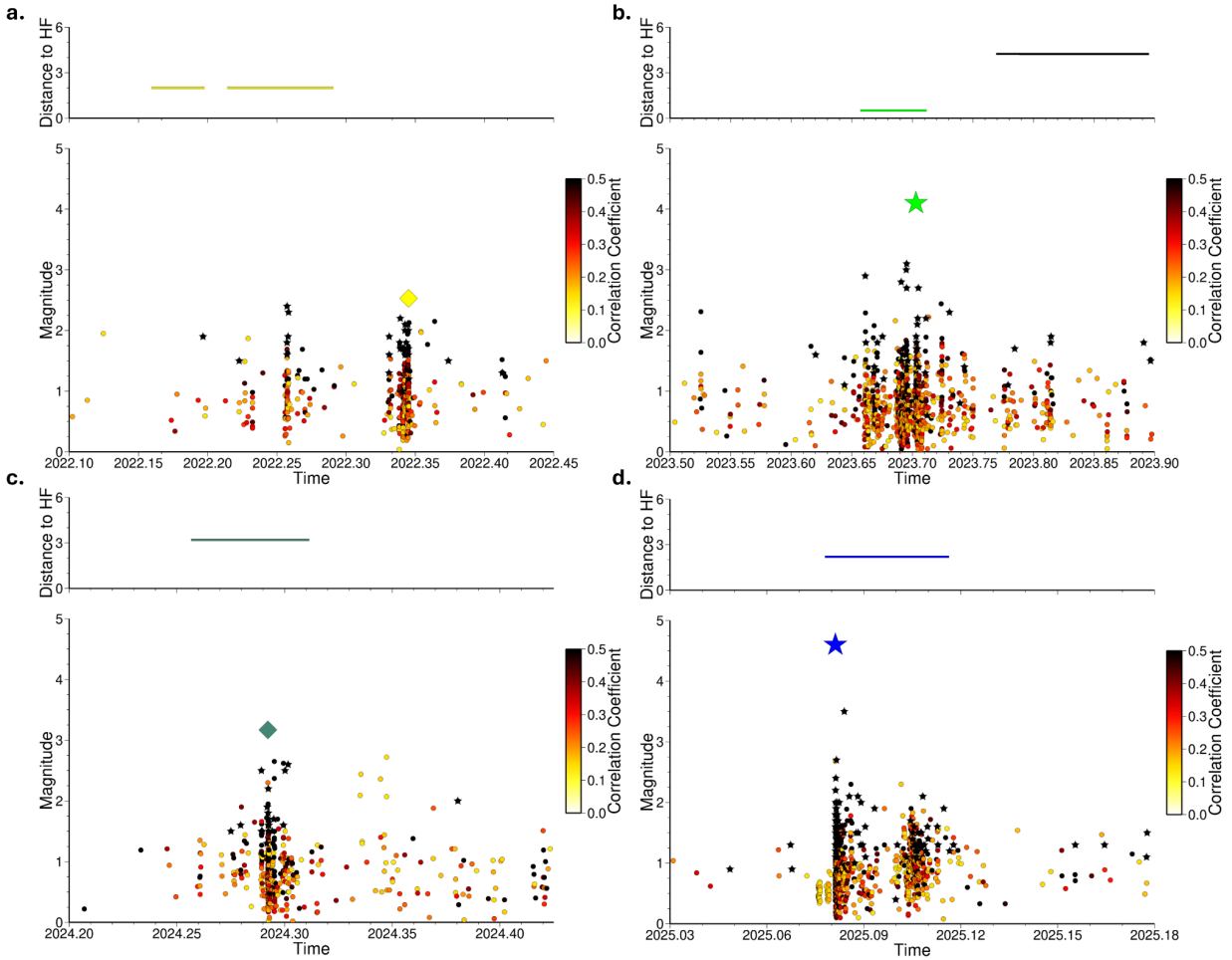


Figure 7. Magnitude-over-time plots for the 2022–2025 sequences (a–d). Matched events are colored the same as in Fig. 8 across all panels. In each panel, the correlated causative well is colored to match the largest magnitude of the sequence, shown as a diamond: (a) 2022 sequence, yellow diamond; (b) 2023 sequence, reflecting improved detection of the M4.0 template, green star; (c) 2024 sequence, seafoam diamond; (d) 2025 sequence, showcasing improved detection of the January M4.7 event, blue star. Panels follow the same plot type as Figure 7, with distance to wells being measured from the average distance between the M4.0 and M4.7 events.

2022 Sequence:

Observed in the expanded catalog for the 2022 sequence are multiple periods of increased seismicity that occur during / shortly after operational wells that are correlated in space and time (**Figure 7a**). Two wells are stimulated from early March to mid-April, with a brief pause in mid-March, and the largest burst near ~2022.35 followed about 2.5 weeks after stimulation ended. Isolated, low-magnitude events (M0.6-M1.9) occur sporadically between ~2022.10 and ~2022.20, with little clustering. Activity increases around ~2022.22, with two periods of heightened activity near ~2022.255 and ~2022.35, with the largest event occurring during the

latter. Magnitudes range from M0 to M2.7, which is notably lower than the 2023 and 2025 sequences.

2023 M4.0 Sequence:

Focusing on the 2023 M4.0 sequence, we observe a typical swarm pattern common with both HF and induced seismicity (**Figure 7b**)(Schultz et al., 2020). Multiple periods of increased seismicity are present throughout the sequence prior to and after the M4.0 event. There are four observed groups of increased seismicity throughout the sequence, occurring at ~2023.66, ~2023.69, ~2023.705, and ~2023.725 with the M4.0 occurring before the ~2023.705 burst. The correlated well was stimulated from late August to mid-September, and the M4.0 occurred near the end of stimulation. A second well, ~4.3 km away, was stimulated from mid-October to late November without a corresponding increase in seismicity. The magnitudes of this sequence range from M0 to M3.0, with the M4.0 being the highest.

2024 Sequence:

The 2024 sequence is characterized by a single, well-correlated increase in seismicity similar to the 2025 sequence rather than multiple groupings as seen in the 2022, and 2023 sequences (**Figure 7c**). A single continuously operating HF well correlation is observed throughout the duration of the sequence, with stimulation occurring through most of April, encompassing the peak of the sequence. Seismicity is concentrated in time around ~2024.285-2024.305, with the largest event occurring as the peak of the burst. Following this peak, a decay in magnitude is observed until about 2024.4, with signatures for being a mixed sequence. There are clear signs of a mainshock - aftershock sequence, with both decay and a magnitude peak, but also signs of a swarm sequence. The magnitudes range from M0 to approximately M3.2, showcasing the observed increase in max magnitude throughout the four sequences.

2025 M4.7 Sequence:

The temporal distribution of the M4.7 sequence shows more of a mainshock-aftershock pattern that is less common with HF-induced seismicity, and is more often associated with wastewater disposal (Chen et al., 2017;)(Figure 7d). Very little seismicity is seen building up to the M4.7 event whereas the 2023 M4.0 occurred after more than half of the events had occurred. The M4.7 occurred within days of the onset of stimulation of the correlated well, which continued into mid-February. There is clear magnitude separation from the aftershocks, with a typical magnitude decay observed and no increases in the rate of seismicity throughout the sequence aside from a secondary burst near ~2025.105 during stimulation..

Relocation Results

Expanded TexNet Catalog Subset Relocation

We tested relocation performance using a 70-template subset (Figure 8; see Methods). The subset included 6 templates from 2022, 17 from 2023 M4.0, 19 from 2024, and 28 from the 2025 M4.7

sequence. The workflow expanded the 70 templates to 1,199 matches, a 17.1-fold increase. This 70 template subset was derived from our template matching results (Figure 7a-d), where MTG's were created for each template that occurred during the panel timing (Figure 7a-d). Templates were added to the MTG in iterations of two, and templates that produced unstable *hypoDD* outputs were discarded. This trial and error process across all four panels resulted with 70 usable templates across the four sequences that produced stable *hypoDD* results.

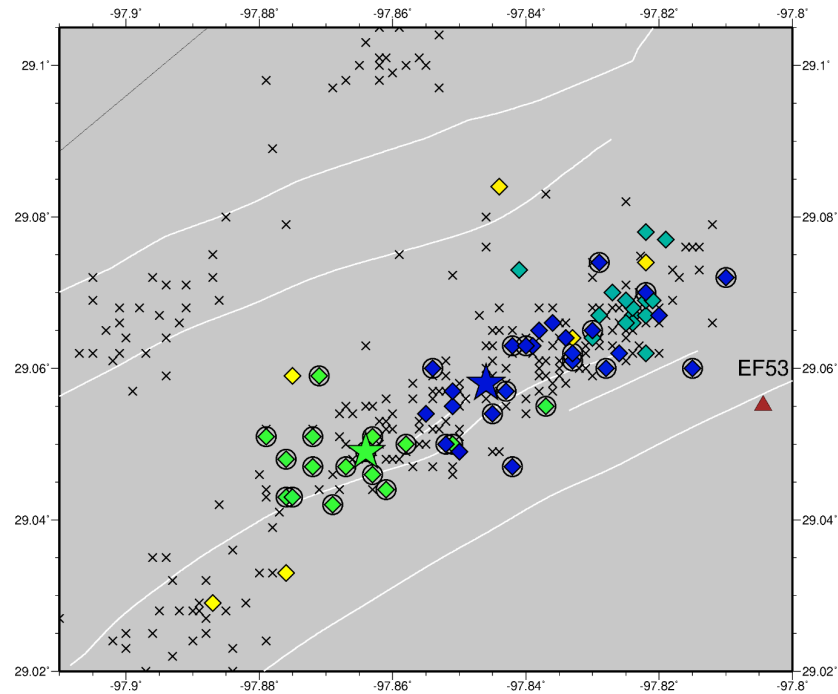


Figure 8. Depicts TexNet templates for all of our different tests. All TexNet templates used for template matching are x's (Figure 3). The 70 template subset used for template and relocation testing are diamonds colored by year, where yellow is 2022, green is 2023, turquoise is 2024 and blue is 2025. Templates from the subset that were used in the mesh construction are the colored diamonds circled in black. Faults are depicted in white, events larger than M4 as stars, and stations as brown upright triangles.

Relocating the 70 templates and their matches as a single MTG yielded 825 relocated events associated with the four sequences (Figure 9). Event locations evolve through each stage of the workflow. The original TexNet catalog events (squares, Figure 9) form a diffuse NE-SW swath roughly 4 km wide. Template matching adds events, and their initial absolute locations (x's, Figure 9) occupy the same swath. Relocating each template family independently (diamonds) tightens the events into family clusters but does not narrow the overall swath. Only when all families are relocated relative to one another does the swath collapse onto a narrow NE-SW striking fault system (circles) that follows the mapped fault trend. The relocated seismicity

extends ~7 km along a NE-SW trend (azimuth ~050°) and broadens along strike, from ~1 km wide at its southwestern end to ~2 km wide at its northeastern end.

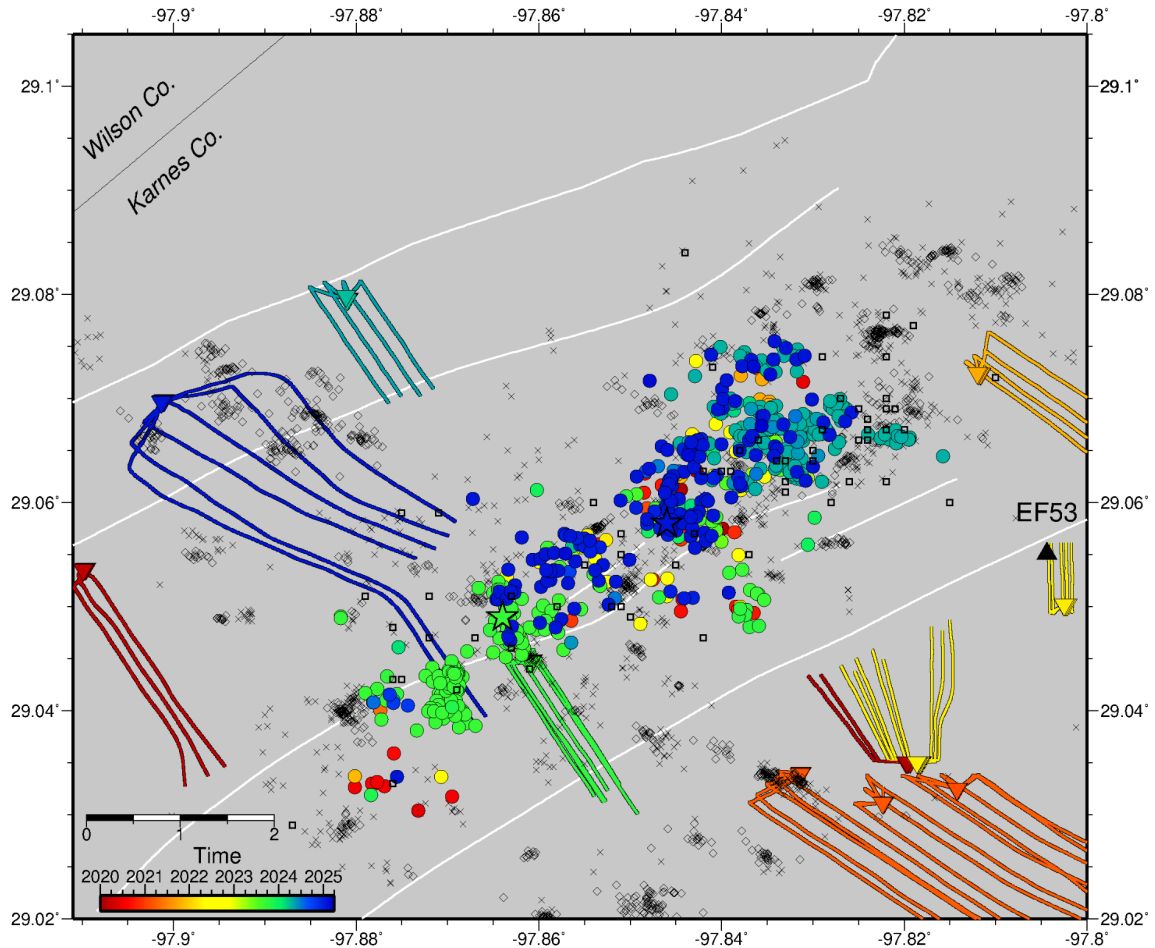


Figure 9. Expanded catalog produced using the detection and relocation workflow, yielding 825 total relocated events from the original 70 template catalog. Along with the relocated events, causative wells for each sequence are shown with their respective lateral legs. Events and causative wells are colored by year, with inverted triangles being wells, squares are TexNet catalog events, relocated events are circles, absolute locations as x's, relocated template families as diamonds, seismic stations as upright triangles, and mapped faults are in white.

The five wells correlated with the four sequences in 2022, 2023, 2024, and 2025 (Figure 7) each lie within 3.5 km of the center of their respective relocated seismicity. The correlated wells from 2022, 2024, and 2025 are observed extending towards the fault trace, and for 2025 they approach within 1 km of relocated seismicity (Figure 9). The correlated well for 2023 is observed extending away from the fault, but is directly on top of our relocated sequences. Other HF wells in the study area, stimulated primarily in 2020 and 2021, have lateral legs that extend away from the fault trace.

Relocation of 2023 M4.0 and 2025 M4.7 Sequences

To characterize fault activation during the M4+ sequences, we ran the 17 M4.0 2023 templates and the 15 M4.7 2025 templates through the workflow separately, because a single MTG containing all 32 events failed to produce a stable output (see Methods).

The 17 M4.0 2023 templates expanded to 348 events, of which 308 were relocated (Figure 10). The seismicity follows the mapped NE-SW fault trend, though its strike is closer to E-W (azimuth $\sim 086^\circ$) and seismicity is clumped along expected fault structure. Cross sections show the seismicity follows a southeast dip of $\sim 60\text{--}70^\circ$, which is consistent with the reported TexNet dip of $\sim 66^\circ$ (TexNet, 2026). Observed in our cross section are two parallel planes that could be potentially parallel fault planes (see Discussion). The sequence spans depths of ~ 2 to 6 km, and the M4.0 relocates at its top, near 2.4 km.

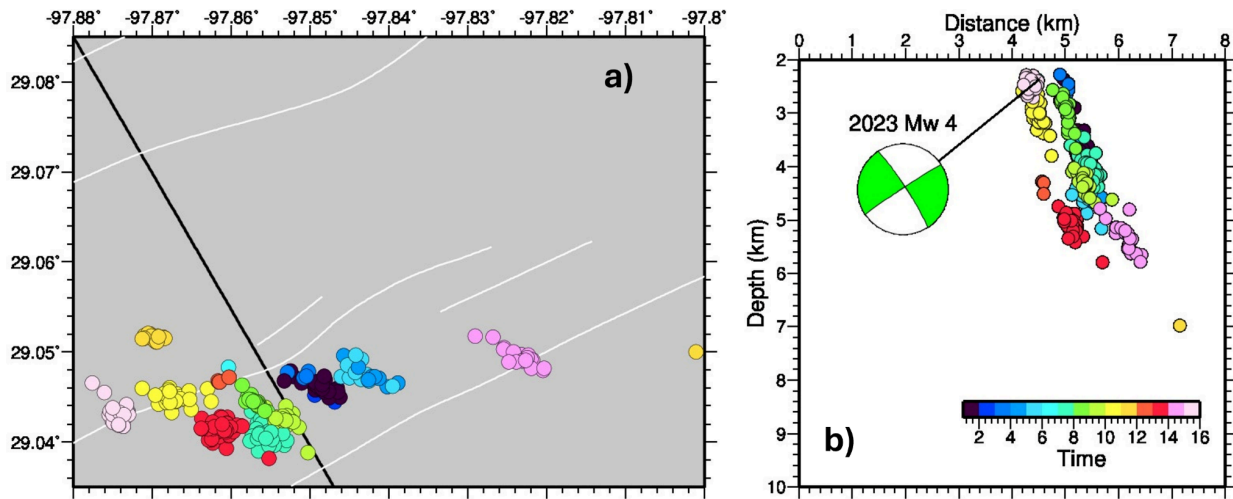


Figure 10. Results for the relocation of M4.0 2023 templates and matches. Matches are shown in the same color based on the template occurrence over time. (a) Map view of detected and relocated seismicity. The black line shows the cross-section line for (b) and mapped faults are in white. (b) Cross-section of seismicity that reveals a dip of $\sim 60^\circ$ in the southeast direction. The respective focal mechanism is shown for the M4.0 event, which also shows its shallow depth.

The 15 M4.7 templates expanded to 189 events, of which 173 were relocated (Figure 11). The sequence strikes NE-SW ($\sim 040\text{--}060^\circ$), consistent with the fault geometry mapped by McKeighan et al. (2022). It dips to the southeast, and visual inspection of the cross section suggests a dip of 50 to 70° , which is near the TexNet dip of $\sim 50^\circ$ (TexNet, 2026), although the seismicity is not tightly clustered into a single linear trend. Observed again is the parallel fault trace as in figure 10b (see Discussion). The sequence spans depths of ~ 2.5 to 6.5 km, and the M4.7 relocates as the deepest event, near 6.4 km. The two sequences therefore overlap in depth, but their mainshocks appear to have nucleated ~ 4 km apart vertically. Relocated depths for both mainshocks are consistent with TexNet focal depth solutions, which report a shallow ($\sim 2.5\text{--}4$ km) depth for the

2023 M4.0, and a deeper ($\sim 6\text{--}9\text{ km}$) depth for the 2025 M4.7 (TexNet, 2026). In both sequences, individual template families are elongated roughly WNW-ESE and arranged en echelon along the overall trend (Figures 10a, 11a), which suggests streaks on a southeastern dipping fault plane.

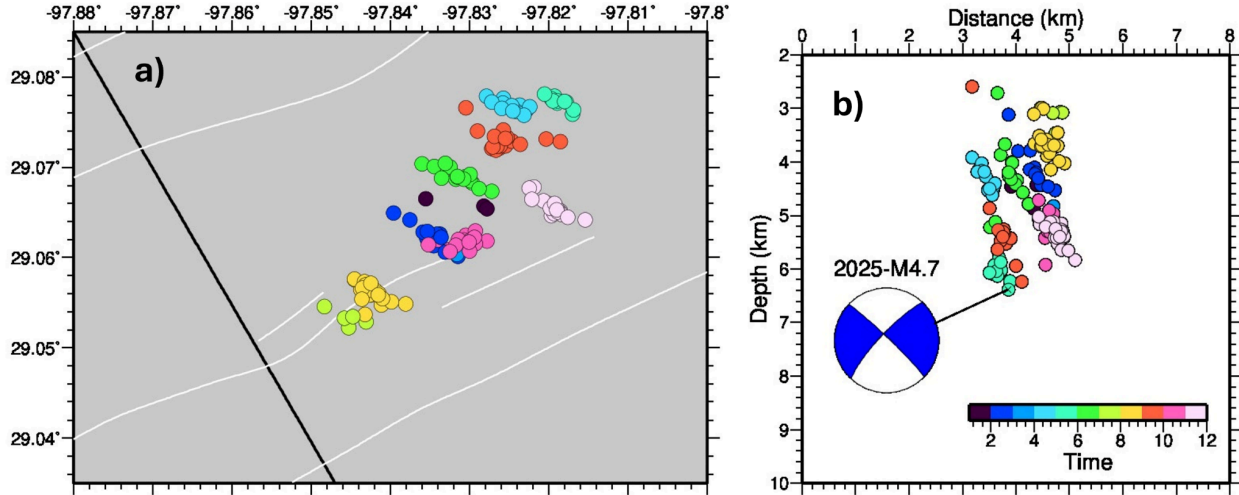


Figure 11. Results for the relocation of M4.7 2025 templates and matches. Format as in Figure 10. (a) Map view of detected and relocated seismicity. Observed is a northeast-southwest striking fault that appears to have its dip shallow out as we progress along strike to the northeast. (b) Cross-section of detected and relocated seismicity with the M4.7 focal mechanism shown. Observed is a shallower dip, with our relocated seismicity attempting to match it and the deepening of seismicity along strike in the northeast direction.

Fault Plane Fitting

To quantify fault geometry while suppressing depth scatter, we fit planes to the relocated seismicity using RANSAC with a 0.3 km residual threshold (see Methods). We fit each of the two M4 sequences independently and the two sequences combined, and then we constructed three-dimensional surfaces from the fitted planes (Figure 12).

The 2023 sequence yields a best-fit plane from 120 events with a dip of 60.36° ($R^2 = 0.986$, $\text{RMS} = 0.14\text{ km}$), consistent with the 66° TexNet focal mechanism dip and the dip observed in the cross-section. The 2025 sequence yields a plane from 70 events with a dip of 38.10° ($R^2 = 0.957$, $\text{RMS} = 0.17\text{ km}$). This is shallower than both the 51° TexNet focal mechanism dip (TexNet, 2026) and the 50 to 70° dip suggested by the cross section (Figure 11). The difference in dip between the two M4+ sequences may also be expressed in the broader distribution of seismicity. The shallower dip of the 2025 sequence coincides with the widening of seismicity along strike to the northeast (Figures 9,11), which suggests that fault geometry may influence the spatial distribution of seismicity. For the 2025 sequence, the RANSAC-derived dip is shallower than the dip suggested by visual inspection of the cross section (Figure 11b). We attribute this

primarily to the limitations of the visual method considering the broad swath of seismicity observed in the cross-section. In addition, the cross section depends on a manually selected profile line and is sensitive to vertical exaggeration and to depth uncertainty in individual events near the section line (see Methods). The RANSAC fit, by contrast, has a high R^2 and is stable across residual thresholds, so we consider it a more reliable estimate. Both estimates are subject to the same limited depth resolution, however, such that we treat the dips as approximate.

The combined fit retains 190 events but yields a substantially lower R^2 (0.683) and struggles to provide a meaningful dip ($<20^\circ$) due to the nature of trying to fit a complex surface where the two independently fit planes have contrasting strikes and dips (Figure 12a). When we apply the GMT *surface* function to the 190 combined events, it constructs a spatially continuous three-dimensional surface when the fitting routine is applied with a mask to ensure the surface only exists when it is within 1 km of an event (Figure 12b). The surface showcases a distinct bend along strike to accommodate the different azimuths and dips from the two sequences, where the contours also showcase both the change in dip, and the contortion of the surface to the north (Figure 12b). Moreover, the surface reveals a progression along dip that starts with steep geometry (Cool color tone; Figure 12b), corresponding with the steep dip of the 2023 M4.0 fault plane. As depths exceed ~ 4 km, the surface illustrates a shallower dip both in the surface and the contour projections (Warm color tone; Figure 12b), corresponding with the 2025 M4.7 fault plane solution.

The degraded RANSAC fit of the combined catalog bears on whether the two sequences share a fault. A single plane fit through both sequences agrees with neither sequence individually nor with either focal mechanism. We interpret this not as a failure of the method, but as an indication that a single planar model may not capture the fault surface. Several observations favor two distinct but connected segments over two unrelated faults. Relocated seismicity is spatially continuous across sequences (Figure 9, 12b), the sequences follow the same NE-SW trend, and the change in dip broadly coincides with the fault termination mapped by McKeighan et al. (2022). One possible explanation of the shallower dip of the deeper 2025 sequence is consistent with listric fault geometry, in which dip decreases with depth, a common characteristic of faults in sedimentary basins (McKeighan et al., 2022).

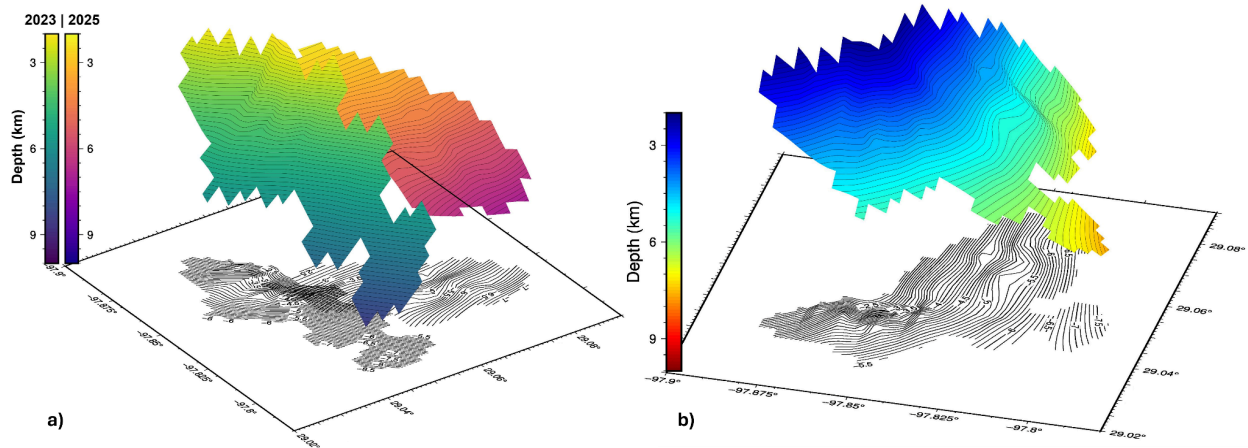


Figure 12. Three-dimensional latitude–longitude–depth plots of the 2023 and 2025 relocated earthquake sequences, shown via best-fit surfaces visualized using the surface function in GMT. (a) Surface fits for each of the two sequences plotted together, highlighting differences in spatial trajectory. The 2025 sequence is shallower and trends more NE–SW, while the 2023 sequence trends more E–W. (b) Best-fit surface computed jointly through both sequences, yielding a NE–SW striking fault plane with a SE dip.

Discussion, Limitations, and Implications

Five M4+ events have occurred in the KTFZ since 2017, indicating a significant seismic hazard in the region south of San Antonio. The expanded catalog shows that seismicity rates have risen alongside maximum magnitudes (Figure 6; Table S1). Concurrent research identifies increasing HF stimulation volume as the operational factor best correlated with this rise (Mazzio et al., in prep). The 2023 M4.0 and 2025 M4.7 are the most significant expressions of this trend, with a notable growth in magnitude in under two years. We cannot definitively explain this growth. The proximity of the two events, however, raises the question of whether they reflect independent sources or the progressive reactivation of a single fault system.

The four sequences show a progression in temporal behavior alongside their increasing maximum magnitudes (Figure 7). The 2022 and 2023 sequences are swarm-like. They contain multiple bursts of activity, and the 2023 sequence also sustains M3+ magnitude, both of which are characteristic of HF-induced seismicity (Shultz et al., 2020). The 2024 sequence shows mixed behaviour, with characteristics of both mainshock - aftershock and swarms. The 2025 sequence more closely resembles a mainshock - aftershock pattern, with clear magnitude separation and decay. Observed in our relocated sequence cross sections are two parallel fault traces. The probability of two parallel faults in close proximity is possible given the closely spaced mapped faults, however it could be explained by a processing artifact. This opens the door for future investigation.

We suggest that the contrast between the 2023 and 2025 sequences may relate to where each

mainshock occurred within its sequence. Within its relocated sequence, the M4.0 sits near the top and the M4.7 near the base. The reported focal depths from TexNet place the M4.7 deeper than the M4.0 (TexNet, 2026). Considering the absolute depth is poorly constrained in *hypoDD* and each sequence was relocated independently, we treat these as relative positions rather than absolute depths. With that caveat, a shallower M4.0 would sit closer to the stimulated interval, where sustained pore pressure perturbation can drive swarm-like activity (Shapiro et al., 2009; Schultz et al., 2020). A deeper M4.7 would be more consistent with stress transfer triggering slip on a critically stressed fault (De Barros et al., 2019). Larger events nucleating on deeper portions of a fault have been observed in prior HF-induced settings (Kozłowska et al., 2018), which were interpreted to be due to the deeper fault being more mature (Goebel et al., 2017; Perrin et al., 2016).

Each of the four sequences correlates in space and time with nearby HF operations (Figures 7, 9), which supports HF stimulation as the likely causative mechanism. The b-value of 0.84 is consistent with slip on pre-existing fault structures. Wells that did not coincide with sequences are also informative. A well stimulated ~4.3 km away in late 2023 was not followed by an increase in seismicity (Figure 7b). This pattern is consistent with proximity to pre-existing faults acting as a secondary control on reactivation (Fasola et al., 2019; 2023).

These observations carry implications for seismic hazard assessment in the KTFZ. Successive M4+ events on adjacent portions of the same fault raise the possibility that continued stimulation near connected fault structures could reactivate progressively larger portions of the fault. The Railroad Commission of Texas has implemented seismicity response frameworks in the Permian Basin, including injection curtailments and magnitude-triggered suspension rules for saltwater disposal wells (Railroad Commission of Texas, 2022). No comparable framework specific to HF-induced seismicity exists in the Eagle Ford Shale.

Conclusions

Template matching and relocation of seismicity in the KTFZ expanded the available catalog from 359 to 6,280 events, a 17.5-fold increase, and show that seismicity rates have risen substantially since 2020. The 2023 M4.0 and 2025 M4.7 sequences occurred on adjacent portions of the same northeast - southwest trending fault but behaved differently. The shallower M4.0 (2-4 km) produced swarm-like activity consistent with proximity to nearby injection zones, while the deeper M4.7 (6-9 km) followed a mainshock - aftershock pattern consistent with stress transfer onto a critically stressed fault. All four temporal sequences on this fault correlate with active HF wells within 3.5 km, whereas more distant wells with laterals oriented away from the fault do not. This supports HF operations as a primary causative mechanism, where proximity of operations to the fault serves as a secondary control. Independent plane fitting reveals a ~20 degree difference in dip between the two M4+ sequences, which can be interpreted as two distinct, potentially connected fault segments separated by a structural warp. Together, these

results indicate that HF-induced seismicity in the KTFZ can propagate along connected fault structures rather than remaining confined to isolated sources. Given the absence of an HF-specific seismicity response framework in the Eagle Ford Shale, our efficient workflow offers a practical means of constraining fault locations and geometries in similar HF-active regions.

Data and Resources

The TM2DD workflow, with all the following processes, is available at (https://github.com/JamesKirchenwiitz/Enhanced_Detection_Relocation) and will be archived upon final submission. Earthquake hypocenters were obtained from the U.S. Geological Survey (USGS) Comprehensive Catalog (ComCat; <https://earthquake.usgs.gov/earthquakes/search/>, last accessed April 2026), to which TexNet contributes its locations, and were cross referenced against the publicly available TexNet Earthquake Catalog (<https://texnet.beg.utexas.edu/>, last accessed April 2026) to ensure consistency across both sources. Phase arrival times were retrieved from TexNet as publicly available QuakeML files. Continuous waveform data from the Texas Seismological Network (TX) were obtained through Earthscope and are publicly available (<https://ds.iris.edu/ds/nodes/dmc/data/>). Data from stations EF53, EF55, EF61, EF72, and EF73 were downloaded following their one-year embargo expired and are now publicly available. Double-difference relocation was performed with *hypoDD*, including the necessary preprocessing tools (Waldhauser and Ellsworth, 2000; <https://www.idea.columbia.edu/~felixw/hypoDD.html>). Initial Absolute locations were computed with *elocate* from Computer Programs in Seismology (Herrmann, 2013; <https://www.eas.slu.edu/eqc/eqccps.html>). Waveform preprocessing used the Seismic Analysis Code (SAC; Goldstein and Snoke, 2005), and waveform cross-correlation was performed with the in-house routine *cor2sac4*. *Obspy* (Beyreuther et al., 2010) was implemented for reading and processing QuakeML and the USGS ComCat files. RANSAC regression was performed with *scikit-learn* (Pedregosa et al., 2011). Figures were produced with the Generic Mapping Tools (GMT; Wessel et al., 2013). Well information was collected from the RRC and is publicly available (<https://www.rrc.texas.gov/resource-center/research/research-queries/>). We acknowledge the use of Claude Opus 5.5 to generate an initial preliminary review for this manuscript, asking it for detailed feedback in the form a peer reviewer would provide, and then we evaluated the feedback and manually revised the manuscript when appropriate.

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Supplemental Materials:

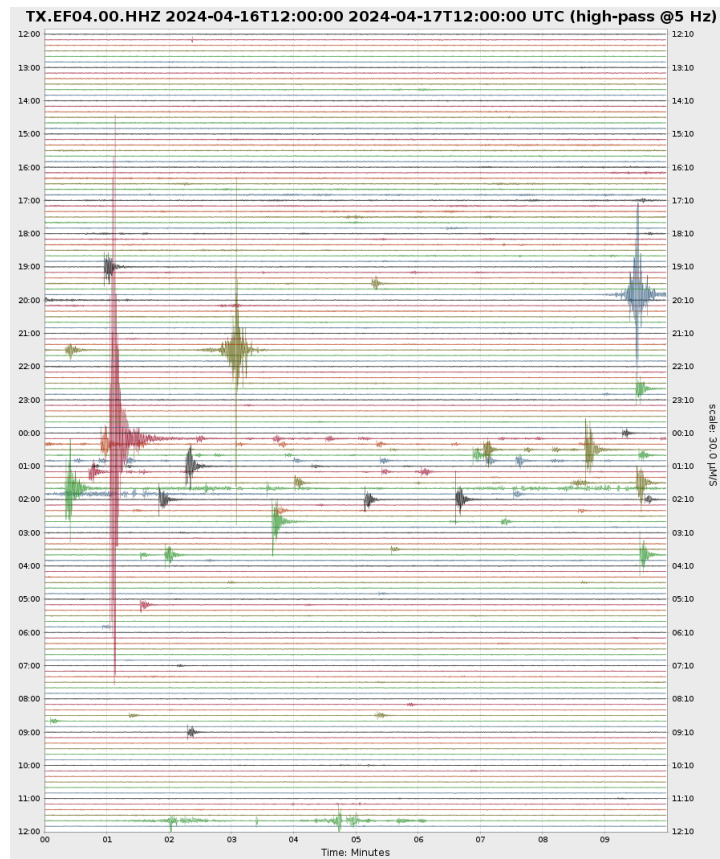


Figure S1. Helicorder plot for station EF04 on April 16, 2024, showcasing the waveform associated with the M3.2 matched event from the 2024 sequence. The clear, coherent signal confirms this is an authentic detection rather than a false positive.

Year	01	02	03	04	05	06	07	08	09	10	11	12
2020	10	0	0	5	2	0	4	118	6	0	2	30
2021	0	12	0	13	0	30	0	0	0	0	28	0
2022	0	0	16	107	489	41	0	0	26	0	23	0
2023	0	9	26	11	345	59	0	56	775	138	24	78
2024	0	116	179	318	22	48	431	99	57	42	182	0
2025	1668	624	11									

Table S2. HypoDD parameters utilized for the relocation in this study.

	Parameter	Value
<i>ph2dt</i>	MAXSEP (km)	7
	MAXNGH	10
	MINLNK / MINOBS / MAXOBS	6 / 6 / 9
	MAXDIST (km)	500
<i>hypoDD</i>	Data (IDAT, IPHA)	cc + catalog, P and S
	DIST (km)	500
	OBSCC / OBSCT	0 / 4
	Solver	LSQR
	Damping	20
	Iterations	12
<i>Velocity model</i>	Layers, Vp/Vs	13, 1.83

	Cross-correlation data				Catalog data			
Iter.	P	S	Res.	Dist.	P	S	Res.	Dist.
1-6	1.0	0.5	-	-	0.01	-	-	-
7-12	1.0	0.5	5	3	0.01	-	10	20