Dear Editor and reviewers:

We thank you for the insightful suggestions and comments, which greatly improved this paper. Following your suggestions and comments, we have revised the manuscript accordingly. Below, we provide a point-by-point response to all comments. The comments are in black and our replies are in blue. We also highlighted changes in the manuscript in red.

Response to Reviewer #1

In the manuscript "Large earthquakes along the Mendocino oceanic transform fault hardly have any foreshocks," Liu et al. investigate foreshock activity preceding three large-magnitude earthquakes (1994, 2016, and 2024) on the Mendocino Transform Fault (MTF). The authors report an apparent lack of elevated foreshock activity before all three events. They contrast this behavior with transform faults along the East Pacific Rise (EPR), where large earthquakes are commonly preceded by enhanced foreshock sequences. Based on this comparison, the manuscript argues that elevated foreshock productivity is not a general characteristic of oceanic transform faults (OTFs), even where aseismic slip is prevalent.

The topic is important and timely. Understanding whether foreshock activity reflects a general nucleation mechanism has direct implications for earthquake physics and forecasting. I agree that the MTF appears to show lower foreshock productivity compared to EPR transform faults. However, several key arguments in the manuscript require further clarification and stronger supporting evidence before broader conclusions about OTF behavior can be justified.

Thank you for your comments and constructive suggestions, we have revised the manuscript accordingly. Below please find our point-by-point responses.

Major:

1. Is MTF an oceanic transform fault with prevalent aseismic slip?

A central premise of the manuscript is that MTF represents an OTF with substantial aseismic slip, and therefore the absence of foreshocks challenges the idea that aseismic slip promotes foreshock sequences. However, it is not clearly established that the rupture zones of the three studied events are indeed characterized by high creeping fractions.

The 1994, 2016, and 2024 earthquakes ruptured three successive segments along MTF. To support the argument, the authors should estimate the percentage of slip released seismically versus aseismically along the longitude range −126.5{degree sign} to −124.5{degree sign}. The creeping fraction reported in Shi et al. (2021) does not include the 2024 M7 event. With the occurrence of this recent large earthquake, the seismic versus aseismic slip budget should be recalculated.

Furthermore, the 70% aseismic slip estimate from Materna et al. (2018) is derived from a section of the fault closer to the coast (> −124.75{degree sign}), which overlaps only partially with the 2024 rupture zone and does not fully represent the rupture areas of the three events considered here. Some of the repeating earthquakes used to infer aseismic slip even overlap with the 2024 rupture. Therefore, the 70% aseismic fraction may be an overestimate for the segments examined in this manuscript.

Without a revised slip budget specific to the studied rupture zones, it is premature to classify these segments as representative of creeping OTFs.

We totally understand your concern. In the revision, we estimate seismic coupling along the Mendocino OTF (longitude: −126.5° ~ −124.5°) through December 2024. The results indicate that the Mendocino OTF exhibits a significant creeping fraction, with an average seismic coupling of 39%. The easternmost segment of the Mendocino OTF also shows <50% seismic coupling after including the 2024 M7.0 earthquake. Note that the period for estimating the seismic coupling is conservatively defined as 74 years (i.e., 1950~2024), but the actual earthquake cycle could be longer, implying that the seismic coupling estimated in our study is likely overestimated. We have clarified this in the revision and added the corresponding figure and text in the supporting information. [Lines 284-287]

"We re-estimate the seismic coupling ratio for the Mendocino OTF (Fig. S7 and Text S1) using an earthquake catalog from January 1950 to December 2024 and find that the average seismic coupling ratio of our study segment (-126.5° to -124.5°) is ~39%, which is comparable to the range reported for East Pacific Rise OTFs (~12%–39%) (Shi et al., 2022)."

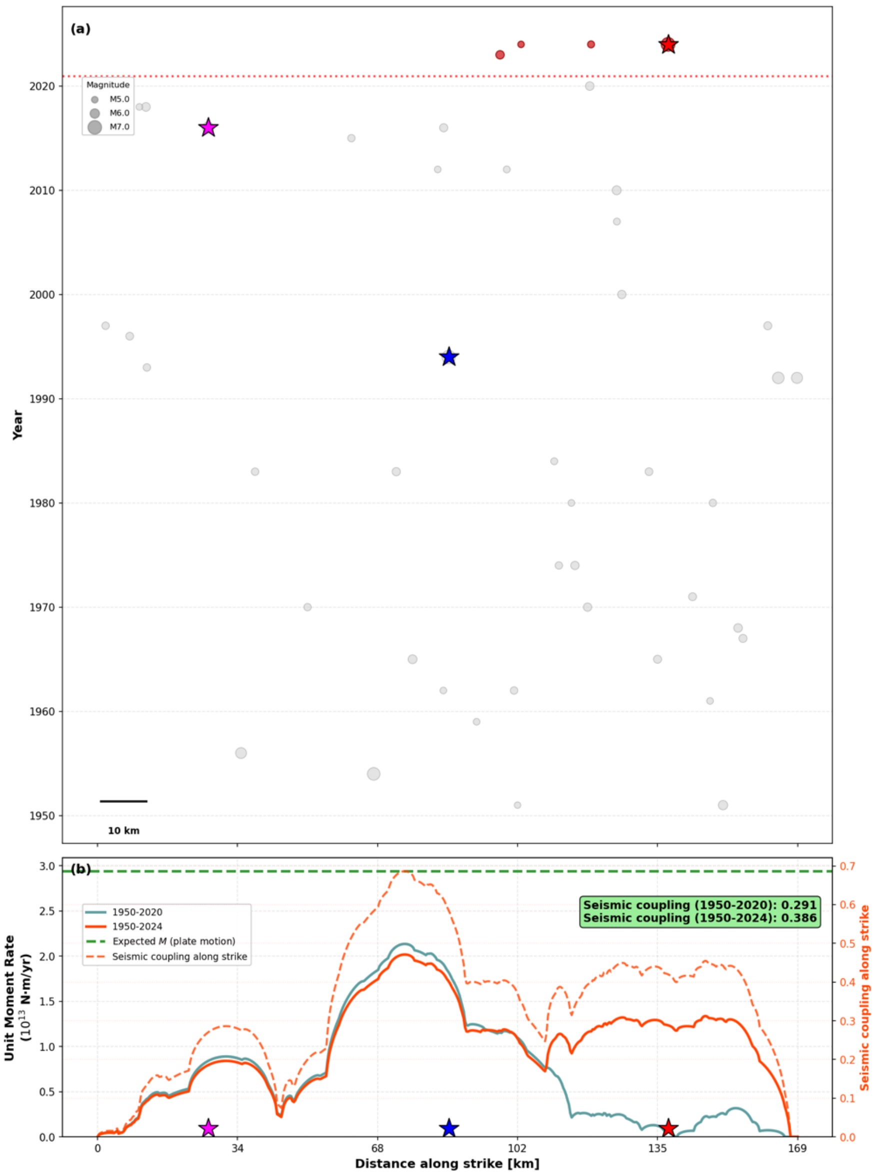

Figure S7. Seismic coupling behavior along the Mendocino OTF. (a) Along-strike distribution versus time of Mw ≥ 5.0 strike-slip earthquakes (circles) between 126.5°W and 124.5°W from 1950 to 2024. Symbol size scales with magnitude. The 1950–2020 earthquake catalog is adopted from Shi et al. (2022), and four events from December 1, 2020 to December 31, 2024 (red circles), including the 2024 Mw 7.0 earthquake, are added from the Global Centroid Moment Tensor Project (GCMT) catalog. Stars denote the 2024 Mw 7.0 (red), 2016 Mw 6.6 (magenta), and 1994 Mw 7.0 (blue) mainshocks. (b) Along-strike seismic moment rate (solid lines) for 1950-2020 (blue) and 1950-2024 (orange), with the expected tectonic moment rate E= μwV (green dotted line). The dashed orange line shows the along-strike variation in seismic coupling for 1950–2024. Seismic coupling (green box) is defined as the ratio of observed to expected moment rate averaged over the entire study segment. See Text S1 for details of the seismic coupling calculation.

Text S1. Estimation of seismic coupling

The along-strike seismic moment rate is calculated following Shi et al. (2022) by estimating rupture length from magnitude (Wells and Coppersmith, 1994) and distributing seismic moment along strike using an elliptical crack model (Scholz, 2019). The expected tectonic moment rate is estimated as $E = \mu w V$*, where* μ *is the shear modulus (30 GPa) (Shi et al. 2022), V is the fault slip rate (49 mm/yr) (Shi et al. 2022), and w is the seismogenic width (20 km) adopted from Oppenheimer et al. (1993). Seismic coupling is defined as the ratio of observed seismic moment rate to the expected tectonic moment rate. Because the time period used to estimate seismic coupling (1950–2024; 74 years) is likely shorter than a full earthquake cycle, the estimated coupling may be overestimated.*

2. Is lack of foreshocks a "general characteristic" of OTFs?

The manuscript's second key point claims that elevated foreshock activity is not a general feature of OTFs. However, this conclusion is based primarily on comparison between MTF and the EPR system. EPR transform faults are among the fastest-slipping faults on Earth. Their high slip rates imply elevated temperatures and distinct thermal structures compared to MTF. To strengthen the argument, it would be more appropriate to compare MTF with another OTF that has similar slip rate and comparable thermal structure, or provide direct evidence that other OTFs also lack of foreshocks.

Our main conclusion is not “lack of foreshocks is a general behavior of OTFs”. Instead, the main point of our study is that elevated foreshocks as seen in East Pacific Rise OTFs are not a general feature of OTFs. Lack of foreshocks have also been noted for transform faults in the Equatorial Atlantic Ocean (Parnell-Turner et al. 2022) and the Juan de Fuca OTFs (McGuire, 2003), which combined with our results suggest that lack of foreshocks is at least the behavior of multiple OTF systems. Therefore, the prevalence of foreshocks observed at East Pacific Rise might be an anomaly due to its high slip rate instead of a general behavior of OTFs. We have made it clear in the revision. [Lines 291-292, 294-296 and 305-308]

“...suggesting that anomalously elevated foreshock activity is not a general characteristic of OTF earthquakes.”

“Previous regional hydroacoustic monitoring studies had similarly hinted at the lack of foreshock activity along the Mid-Atlantic (Parnell-Turner et al. 2022) and Juan de Fuca OTFs (McGuire 2003).”

“This could be due to the fast-spreading East Pacific Rise OTFs having younger and hotter lithosphere which is more prone to strong, episodic slow slips than intermediate- and slow-spreading OTFs such as the Mendocino OTF (Liu et al.

2012).”

Additionally, MTF is not a typical OTF, either. Unlike ridge-ridge transforms, it subducts at its eastern end and is subject to strong north-south compression. These tectonic complexities make it unclear how representative MTF is of global OTF behavior.

Without evidence from additional OTFs, the claim that lack of foreshocks is a general OTF characteristic appears overstated.

Once again, our claim is not that “lack of foreshocks is a general OTF characteristic” and is instead that “elevated foreshocks as seen at East Pacific Rise OTFs is not a general OTF characteristic”. In addition, while MTF is not a “typical” OTF, our additional analysis shows that it has a similar seismic coupling ratio as the other OTFs (Shi et al., 2022). Furthermore, in addition to MTF, there are also other OTFs, such as OTFs in the Equatorial Atlantic Ocean and the Juan de Fuca OTFs, with low foreshock productivity. [Lines 284-287, 291-292, and 294-296]

“We re-estimate the seismic coupling ratio for the Mendocino OTF (Fig. S7 and Text S1) using an earthquake catalog from January 1950 to December 2024 and find that the average seismic coupling ratio of our study segment (-126.5° to -124.5°) is ~39%, which is comparable to the range reported for East Pacific Rise OTFs (~12%–39%) (Shi et al., 2022).”

“...suggesting that anomalously elevated foreshock activity is not a general characteristic of OTF earthquakes.”

“Previous regional hydroacoustic monitoring studies had similarly hinted at the lack of foreshock activity along the Mid-Atlantic (Parnell-Turner et al. 2022) and Juan de Fuca OTFs (McGuire 2003).”

Line 280: please provide citation for the statement regarding Juan de Fuca.

We have added an appropriate citation for the statement regarding Juan de Fuca. [Line 295]

3. Definition of foreshock

The manuscript defines foreshocks as earthquakes occurring within the eventual mainshock rupture zone. This is a restrictive definition and requires further justification. For example, the M7 Ridgecrest event is proceeded by an event on a conjugate fault. It would be better to clearly define their definition of "foreshock" and justify why earthquakes outside the rupture zone but spatially close are excluded. Does ETAS require the foreshocks to be located within the rupture zone?

There is no standard definition for foreshocks so far. We thus adopted two widely used methods to define foreshocks of the Mendocino OTF earthquakes:1) earthquakes which occurred within the co-seismic rupture zone of the three large Mendocino earthquakes; and 2) earthquakes which occurred within specified spatio-temporal windows from the mainshock. The former is used to examine whether foreshocks occurred directly within the eventual rupture area prior to the mainshock (Figure 2), which could indicate localized aseismic nucleation processes. Whereas the latter captures statistical foreshock behavior and enables direct comparison with the previous study of East Pacific Rise OTFs and Southern California earthquakes (Figure 3; McGuire et al. 2005). We have made it clear in the revision. [Lines 201-204]

"There is no standard definition for foreshocks so far. Therefore, we adopted two widely used methods to define foreshocks of the Mendocino OTF mainshocks: 1) earthquakes which occurred within the co-seismic rupture zone of the three large Mendocino earthquakes; and 2) earthquakes which occurred within specified spatio-temporal windows from the mainshocks."

The manuscript appears to mix the concepts of foreshock activity and aseismic nucleation. These are related but not identical. A clearer distinction between statistical foreshocks and physical nucleation processes would improve the interpretation.

We are sorry that the descriptions in the previous version of the manuscript misled you. In the revision, we have clarified the distinction between statistical foreshocks and physical nucleation processes. [Lines 206-207 and 226-228]

"Method 1 is mainly used to identify potential localized aseismic nucleation processes of the three large Mendocino OTF earthquakes."

"Method 2 can be used to illuminate statistical foreshock behavior, enabling a direct comparison with the previous observations of East Pacific Rise OTFs and Southern California earthquakes (McGuire et al. 2005)."

4. Repeating earthquake

Repeating earthquakes are identified from ~4000 events in the USGS catalog, yet their properties (location, timing, magnitude, etc) are not presented in the manuscript. I suggest the author to add a supplementary figure to show the map and depth views of repeating earthquakes and a table listing their location, depth, magnitude, and time.

Line 201-203: We don't know where the repeating earthquakes are and whether they exist in the three mainshock zones at all.

In the revision, we added a figure in the supporting information to exhibit the distribution of repeating earthquakes. In addition, the full repeating-earthquake catalog has been uploaded to Zenodo.

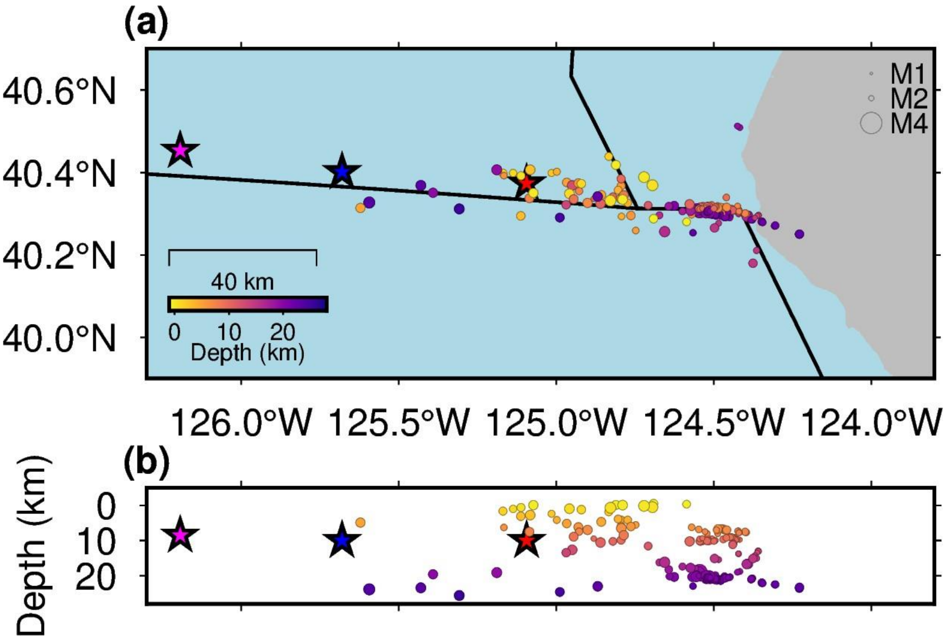

Figure S4. Distribution of repeating earthquakes along the Mendocino OTF. (a) Map view of 224 repeating earthquakes, with circle size scaled by magnitude and color indicating depth. Red, magenta, and blue stars mark the 2024 Mw 7.0, 2016 Mw 6.6, and 1994 Mw 7.0 mainshocks, respectively. Black lines indicate plate boundaries. (b) Longitude–depth cross-section of the repeating earthquakes in (a).

Because the three rupture zones are farther offshore than the Materna et al. (2018) study area, detection capability may be limited. Given that match-filter techniques were applied for the 2016 event, the authors should comment on the detection capability of the USGS catalog and how this may bias the inferred absence of repeating earthquakes or foreshocks.

We agree that the detection capability of relatively small earthquakes within the three rupture zones is limited due to the lack of nearby station constraints, especially for the 2016 event. Therefore, following the strategy adopted in McGuire et al. (2005), we only use $M_L \geq M_C$ events in foreshock detection and corresponding analysis to mitigate the effect of the missed small earthquakes.

The 2016 event is the farthest one from the land seismic stations among the three large Mendocino earthquakes. Hence, the magnitude completeness of the 2016 event's source area is relatively larger. The purpose of MFT is to decrease the magnitude threshold (i.e., Mc) within the scanning period of two months, which can improve the detection ability of potential foreshocks. However, the repeating earthquake detection mainly depends on the magnitude completeness across the entire study period. Thus, the decreased magnitude threshold within the short time period of two months does not substantially improve repeating earthquake detection. Considering the larger magnitude completeness of earthquakes within the rupture zone of the 2016 event, the template events are selected from the USGS catalog, which includes more events than the DD catalog. We have made it clear in the revision. [Lines 156-163, 195-198, and 238-240]

"While the 2016 Mendocino OTF earthquake sequence was continuously recorded by the onshore seismic stations, the remoteness of this event makes it challenging to identify P- and S-wave arrival times of relatively small earthquakes via machine-learning-based phase pickers. In addition, for the DD catalog, waveform cross-correlation-based relocation possibly ruled out some earthquakes without enough neighboring events given the small number of cataloged events. Therefore, we apply GPU-M&L over the same 60-day window using 214 magnitude ≥ 2 United States Geological Survey Earthquake (USGS) cataloged earthquakes (U.S. Geological Survey 2025) from 2008 to 2024 (40.2∘–41.0∘N, 127.0∘–125.8∘W) as templates."

"It should be mentioned that the repeating earthquake detection mainly depends on the Mc across the entire study period. Thus, the decreased magnitude threshold via GPU-M&L within the short scanning period of two months does not substantially improve repeating earthquake detection."

"To mitigate the effect of missed small earthquakes, only events with ML > Mc or the acoustic source level completeness (MASL) are adopted in the calculation of foreshock-to-aftershock ratios (Fig. S3d)."

5. The argument for the 3rd key point is not well developed.

The manuscript transitions from lack of foreshocks to implications for nucleation without clearly establishing the causal link. A clearer explanation is needed for why the absence of foreshocks imply small extent of aseismic nucleation?

We are sorry for the unclear writing. The absence of foreshocks suggests that there is no clear evidence of aseismic-nucleation-related seismicity preceding large Mendocino oceanic transform fault earthquakes. In the revision, we have corrected key point 3 and the corresponding description in the abstract. [Lines 17-18 and 47-48]

"No clear evidence of aseismic-nucleation-related seismicity preceding large Mendocino oceanic transform fault earthquakes"

Line 286: please provide citation for statements regarding continental earthquakes and the size of aseismic nucleation zones. The paragraph primarily discusses EPR faults but then generalizes to continental systems without support.

Thank you for your careful review, and we agree that we cannot directly generalize observations from OTFs to continental faults. In the revision, we have clarified that the limited foreshocks of OTF earthquakes suggest that there is no clear evidence of extensive aseismic nucleation-related seismicity prior to large OTF earthquakes. [Lines 300-301]

"there is no clear evidence of extensive aseismic nucleation-related seismicity prior to large OTF earthquakes."

Minor:

1. Line 86: delete) after "earthquakes"

Done.

2. Citation formatting:

Line 135: Gong and Fan (Gong and Fan 2022)

Line 185: Materna et al. (Materna et al. 2018),

Line 215: McGuire et al. (McGuire et al. 2005)

Thank you for your careful review. We have corrected the citation format in the revision.

3. Figure 2 caption needs substantial revision for clarity.

It is unclear where 0 km is on map.

The 0 km refers to the location of (40.45°N 127.1°W) along the Mendocino OTF. We have clarified it in the revision. [Line 216]

Line 209: no black thin line in (a)

Black thin lines represent the cumulative number of foreshocks that occurred within the corresponding rupture zones. The absence of the black line in (a) means no foreshocks occurred within the rupture zone of the 1994 mainshock. We removed this sentence in the revision.

How were rupture dimensions and locations estimated for the three mainshocks?

The rupture zone of the 1994 mainshock is based on second-moment analysis (McGuire et al. 2002), the 2016 mainshock's rupture is inferred from an empirical magnitude–rupture length scaling relationship (de Melo et al. 2025) centered at the USGS hypocenter, and the 2024 mainshock's estimated rupture zone is constrained by distributed acoustic sensing observations (Atterholt et al. 2025). We have made it clear in the revision. [Lines 219-223]

4. Even though the earthquake catalog is available on Zenodo, I strongly recommend including supplementary figures showing map and depth views of the earthquake distribution.

Accepted.

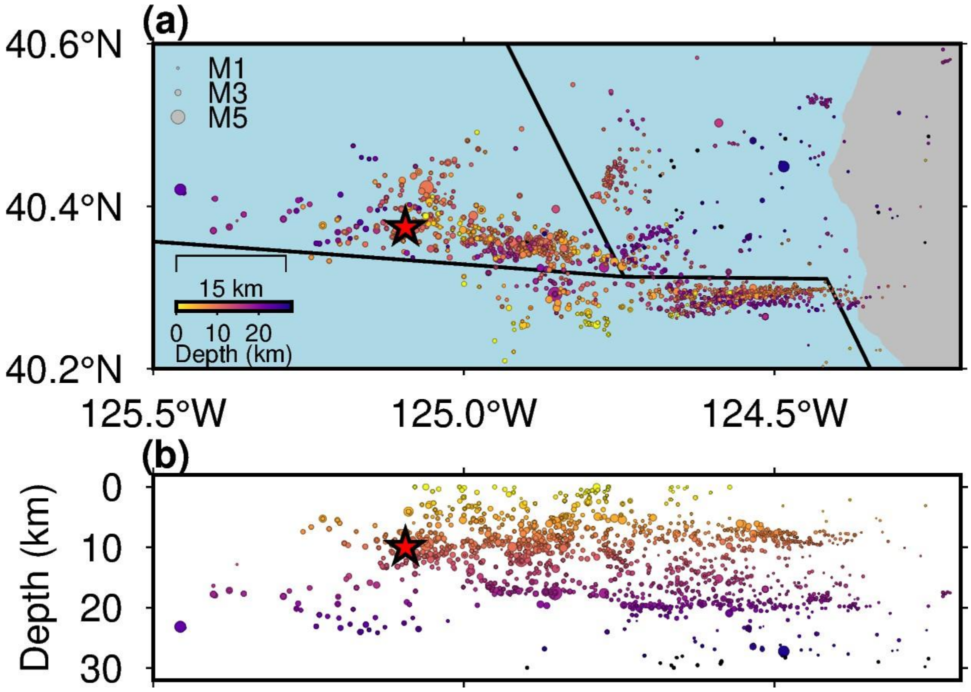

Figure S1. Earthquake distribution for the 2024 Mendocino OTF earthquake sequence. (a) Map view showing epicenters of 8,478 earthquakes in the GPU-M&L catalog, with size and color indicating magnitude and depth, respectively. The red star marks the 2024 Mw 7.0 mainshock. Black lines indicate plate boundaries. (b) Longitude–depth cross-section of the earthquakes in (a).

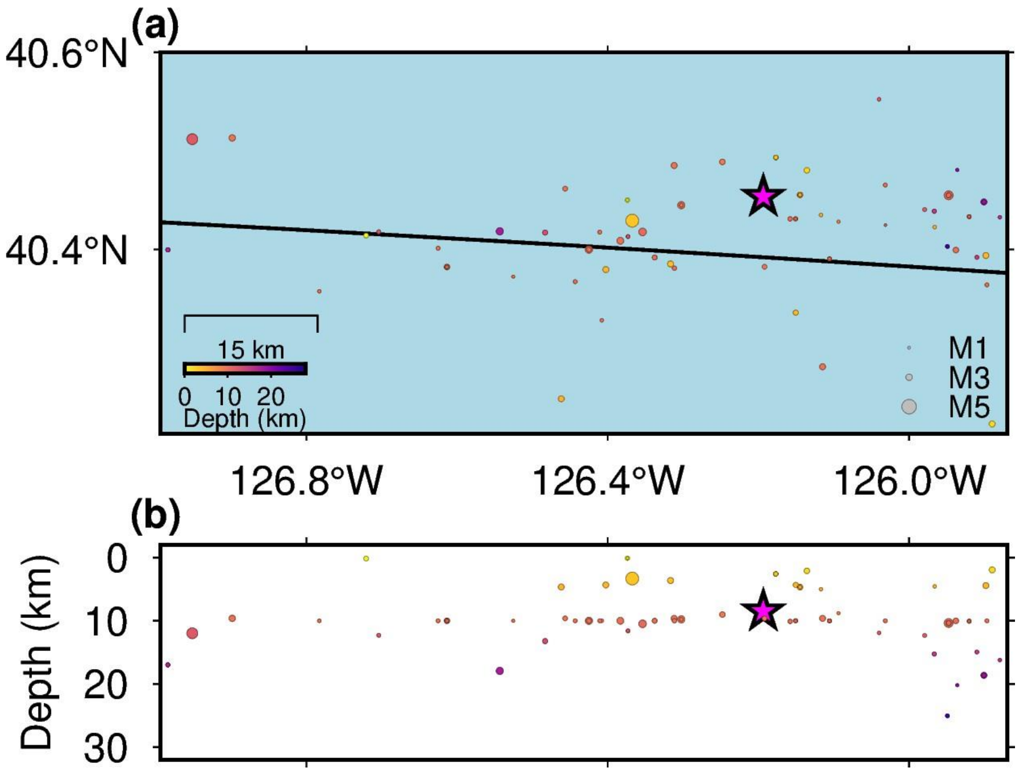

Figure S2. Similar to Fig. S1, but for the 2016 Mendocino OTF earthquake sequence.

5. Stars in Figure 1. Are they centroid or epicenter?

All stars in Figure 1 represent epicenters. [Line 116]

Response to Reviewer #2

The authors produced a ML earthquake catalog for the 2024 M7.0 Mendocino earthquake. They also improved catalogs for the 2016 M6.6 earthquake. None showed significant foreshocks. They also compare foreshock to aftershock ratio between Southern California, EPR, and Mendocino. They showed that these three systems have very different foreshock to aftershock ratio. They suggested that EPR is special because they have exceptionally frequent and/strong aseismic slip transients.

Overall, the results seem to be robust. I suggest to publish with some minor revisions.

Thank you for recognizing our work. We have revised the manuscript accordingly. Below please find our point-by-point responses.

Line 43: change to "foreshock activity is very limited within the rupture zone"

Accepted.

Line 49: The entire paper focuses on foreshock to aftershock ratio. It seems strange to conclude about aseismic nucleation zone.

In models involving precursory aseismic slip, elevated foreshock productivity is commonly interpreted as reflecting progressive nucleation toward dynamic rupture (McGuire et al. 2005; Bouchon et al. 2013). Quantifying the foreshock-to-aftershock ratio is a statistical method used to detect potential foreshocks and nucleation processes (McGuire et al., 2005). To better deliver this point, we state that the limited foreshocks of OTF earthquakes suggest that there is no clear evidence of aseismic-nucleation-related seismicity preceding large Mendocino OTF earthquakes in the revision. [Lines 47-48]

Line 61: delete "eventual"

Accepted.

Line 76-82: Too long. I suggest to break the sentence into short ones.

We have split this sentence to improve readability in the revision. [Lines 75-81]

"It has long been observed that some earthquakes are preceded by smaller events known as foreshocks (Reasenberg 1999). The contentious debate regarding the implication of foreshocks for short-term earthquake predictability has generally centered around whether foreshocks are simply the product of inter-event stress

transfer, with the largest earthquake (mainshock) that follows being a random outcome of stress triggering (Helmstetter and Sornette 2003), or are fundamentally different from ordinary clustered seismicity and reflect an underlying precursory aseismic slip (Kato et al. 2012; Bouchon et al. 2013; Ruiz et al. 2014).”

Line 88: Burgmann and Chadwell 2014 is a strange citation here. That paper is on seafloor geodesy.

We have removed this citation in the revision.

Line 90-96: Too long. Suggest to break into two sentences.

In the revision, we divided it into shorter sentences as suggested. [Lines 89-95]

“This prevailing view primarily stems from observations at the East Pacific Rise OTFs where regional hydroacoustic monitoring from 1996 to 2001 found that 19 Mw 5.3−6.2 mainshocks have an average foreshock-to-aftershock ratio that is an order of magnitude higher than Southern California strike-slip earthquakes and could be retrospectively predicted with significant probability gain using the foreshocks (McGuire et al. 2005). Besides, a subsequent OBS deployment in 2008 captured thousands of foreshocks in the week before a Mw 6.0 earthquake (McGuire et al. 2012). ”

Line 133: How many events were detected before GPU-M&L?

The initial machine-learning workflow detected 1,776 events. We have made it clear in the revision. [Line 128]

Line 165: "Following the same procedures" is very confusing. Does it start from EQTransformer or from GPU M&L? If from EQTransformer, line 158-160 stated that ML phase picking is challenging.

The procedure starts from GPU-M&L. We have clarified this in the revision. [Line 164]

Line 166: 145 earthquakes seem quite small, comparing to 8,478 for the 2024 M7.0 earthquake. Even it is a combination of higher Mc and smaller main event, the number seems small. Any thoughts?

The significantly fewer aftershocks following the 2016 earthquake compared to the 2024 earthquake can be explained by two main factors. First, the 2016 earthquake occurred farther from land seismic stations, which limit the detection of small aftershocks. For instance, the ML<1 aftershocks account for only ~0.8% of the total aftershocks for the 2016 event, whereas they represent ~63% of the total aftershocks for the 2021 event. Second, the 2016 mainshock (Mw 6.6) is smaller than the 2024 event (Mw 7.0) and therefore is expected to generate fewer aftershocks based on established scaling relationships between mainshock magnitude and aftershock productivity. We have made it clear in the revision. [Lines 166-169]

"The much fewer earthquakes of the 2016 sequence than the 2024 sequence are mainly attributed to 1) the poorer detectability of small earthquakes due to the lack of nearby stations; and 2) the smaller magnitude of the 2016 mainshock, which results in fewer aftershocks."

Line 217-219: What earthquake catalog was used in these calculation? USGS?

15 Mw 5.5–7.0 Mendocino OTF mainshocks (January 1984–2025), 19 Mw 5.3–6.2 East Pacific Rise OTFs mainshocks (May 1996–December 2001) and 9 Mw 6.0–7.3 Southern California mainshocks (January 1981–December 2024) that were adopted in the calculation of foreshock-to-aftershock ratio are from the USGS catalog, the hydroacoustic catalog of McGuire et al. (2005), and the Southern California Earthquake Data Center (SCEDC) catalog, respectively. We have clarified this in the revision. [Lines 229-232]

Line 222: Mc = 2.0 seems too large for Southern California. Is this correct? I would think that given the large number of seismometers, Southern California should have a smaller Mc.

We are sorry that our previous descriptions misled you. To enable the direct comparison with McGuire et al. (2015), we adopt the same Mc of 2.0 for the Southern California catalog in the calculation of the foreshock-to-aftershock ratio. We have clarified this in the revision. [Lines 241-242]

"Note that while the SCEDC catalog is extended to December 2024 and includes 2 additional Mw≥ 6 mainshocks, we still allocate its Mc as 2.0 to better compare with McGuire et al. (2005)."

Figure 3b seems unnecessary. It is hard to understand in some way and contains the same information as Figure 3a.xx

This panel has been removed from the main text and is now included in the supplementary material as Figure S5b.