

TiMEpy: A Python Package for Analyzing Tidal Modulation of Fast and Slow Earthquakes

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Abstract Tidal stresses provide a natural perturbation for investigating earthquake nucleation and fault properties. We present TiMEpy, an open-source Python package for analyzing tidal modulation of ordinary earthquakes and slow earthquakes. The package integrates catalog selection and optional declustering, conversion of tidal strain to resolved fault stress, and analyses of earthquake occurrence as a function of tidal phase and stress level. It estimates the preferred phase, phase modulation amplitude, and stress sensitivity within a reproducible workflow that supports temporal and spatial analyses. Applications to the pre-2019 Ridgecrest earthquake catalog and tectonic tremor in Taiwan illustrate the workflow. Sensitivity tests examine the effects of selected sliding-window and spatial-selection parameters in the Ridgecrest application. These examples demonstrate the package's use while highlighting the importance of catalog completeness, temporal clustering, and model assumptions when interpreting tidal modulation.

1 Introduction

Earthquakes, the sudden release of energy in the Earth's crust, are influenced by a complex interplay of factors, including tectonic stresses, fault properties, and external forces (Ader et al., 2012). Among these external forces, tidal stresses induced by the gravitational pull of the Moon and Sun have long been hypothesized to modulate earthquake activity. The relationship between tidal forces and earthquake triggering has been a topic of debate and investigation for over a century. While some studies have suggested a correlation between tidal stresses and earthquake occurrence (e.g., Cochran et al., 2004; Cotton, 1922; Tanaka, 2012; Ide et al., 2016), others have found little to no evidence of such a connection (e.g., Heaton, 1982; Shudde and Barr, 1977; Vidale et al., 1998; Wang and Shearer, 2015). This ongoing debate stems from the complexity of earthquake mechanics, the subtlety of tidal influences, and the difficulty of statistically isolating tidal effects from other factors controlling earthquake timing (e.g., Vidale et al., 1998; Scholz

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et al., 2019; Lu et al., 2025b). Compared with fast earthquakes, slow earthquakes, such as low-frequency earthquakes (e.g., Shelly et al., 2007; Lu, 2026) and tectonic tremors (e.g., Obara, 2002; Lu and Ide, 2026), have shown an exponential relationship between tremor rates and tidal stress (e.g., Ide, 2010; Ide et al., 2015; Lu et al., 2026a), although the degree of sensitivity varies by region (e.g., Beeler et al., 2013; Houston, 2015; Ide et al., 2015; Lu et al., 2026a; Shelly et al., 2026; Thomas et al., 2012; Xue et al., 2025; Yabe et al., 2015). These observations motivate systematic investigations of earthquake responses to tidal forcing across different fault environments.

Several factors complicate the identification and interpretation of tidal modulation. Limited event numbers reduce statistical power, while variations in catalog completeness and detection capability can obscure or produce apparent temporal patterns. Temporal clustering can also affect significance estimates because the conventional interpretation of Schuster p -values assumes independent event phases under a Poisson null model (Ader and Avouac, 2013; Wang and Shearer, 2015). Declustering is one option for addressing event dependence. Whether and how to apply it remains an open methodological question that depends on the research objective, catalog characteristics, and statistical framework. Tidal stresses may modulate both background and clustered seismicity; the selected treatment of clustering therefore defines the activity represented in the analysis. Recent advances in earthquake detection techniques, including machine learning (e.g., Zhu and Beroza, 2019) and template matching (e.g., Beaucé et al., 2017; Lu et al., 2021), have enabled the construction of increasingly detailed catalogs across diverse tectonic settings and long observation periods (e.g., Lu et al., 2026b; Ross et al., 2019b), providing new opportunities to investigate earthquake–tide relationships while requiring careful treatment of catalog properties and statistical assumptions (e.g., Beaucé et al., 2023; Guo et al., 2026; Lu et al., 2025b).

A range of statistical methods has been developed to examine different aspects of tidal modulation. Schuster’s test evaluates whether earthquake occurrences are preferentially concentrated at particular tidal phases (Schuster, 1897). The Schuster spectrum extends this analysis across a range of periods and provides additional diagnostics for distinguishing periodic signals from patterns associated with residual clustering (e.g., Ader and Avouac, 2013; Li and Luo, 2022). Alternatively, the two-rate Poisson approach compares occurrence rates under specified tidal conditions, such as periods of positive and negative stress or intervals surrounding tidal extrema (Bucholz and Steacy, 2016). Phase-based and stress-level models provide further complementary information by characterizing the preferred timing of earthquake occurrence within tidal cycles and the dependence of occurrence rates on stress magnitude. These approaches provide complementary ways to investigate tidal modulation, with the choice guided by the scientific objective, catalog characteristics, and statistical assumptions.

Here, we present TiMEpy, an open-source Python package that uses tidal phase information to detect and quantify modulation of earthquake occurrence within tidal cycles. It estimates the preferred phase and phase modulation amplitude from observed-to-reference phase distributions, and provides complementary stress-level analysis to quantify how occurrence rates vary with tidal loading. Catalog selection, optional declustering, and tidal strain-to-stress conversion are connected within a reproducible workflow for ordinary and slow earthquakes. Users can also supply compatible catalogs prepared using other selection or clustering treatments directly to the tidal analysis module. The modular structure supports comparisons across temporal windows and spatial regions.

2 Overview of TiMEpy

The workflow of TiMEpy, illustrated in Figure 1, comprises two interconnected modules: Preprocessing and Analysis. Preprocessing selects the study catalog and optionally applies declustering according to the research objective. Users may retain the selected catalog or supply a compatible catalog prepared externally. Tidal strain data are converted into stress tensors and resolved onto a specified fault plane using the adopted elastic parameters and focal mechanism.

Within the Analysis module, the selected catalog is combined with tidal stress data to extract the tidal phase and stress level at each event's origin time. Phase-based analysis characterizes the preferred timing and strength of modulation within tidal cycles, while stress-level analysis estimates the dependence of occurrence rates on stress magnitude. These analyses can be applied to the whole study region, spatial grids, or successive time windows.

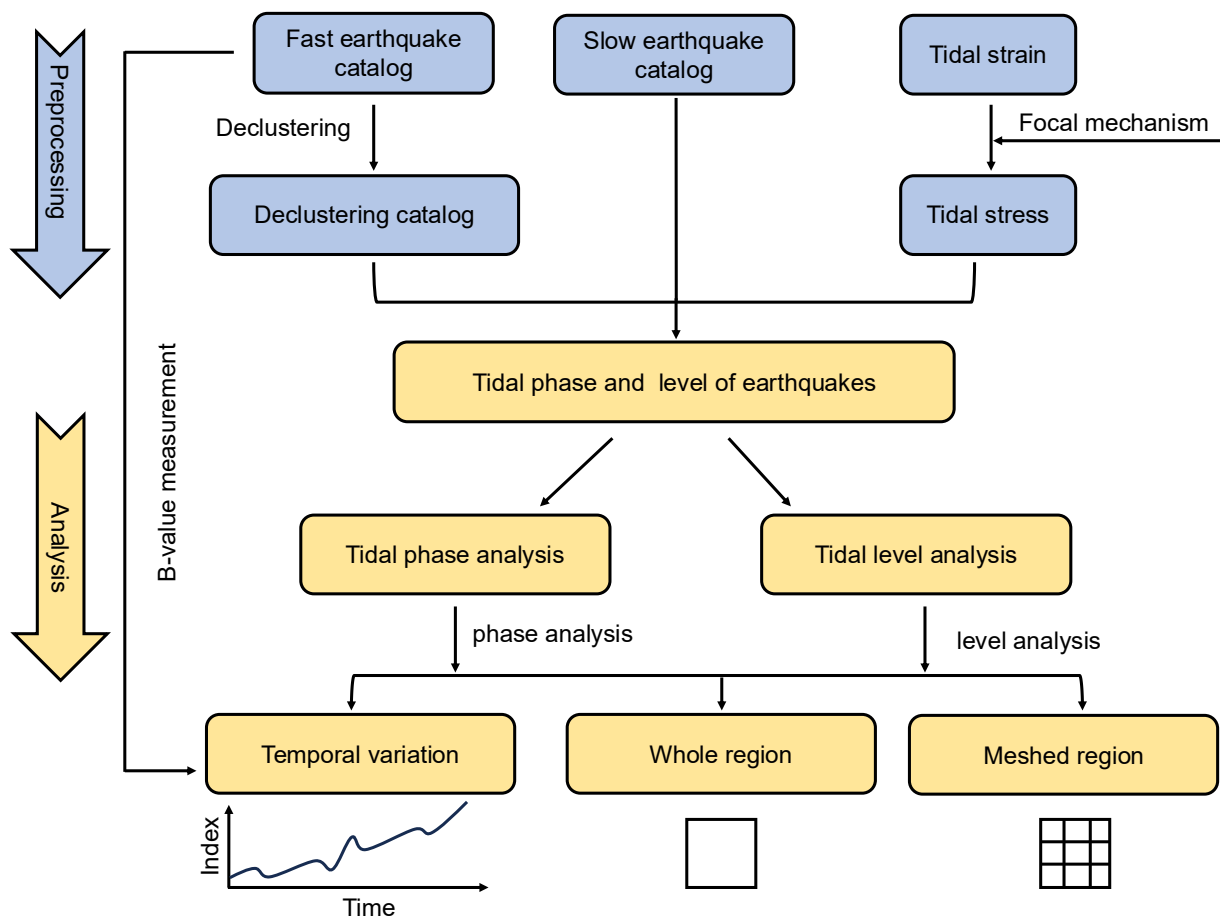


Figure 1 Basic flow of the TiMEpy package.

3 Implementation

3.1 Earthquake selection

TiMEpy accepts earthquake catalogs covering either broad areas or individual regions. Users define the study area, time range, and filtering criteria to select events for subsequent analysis. Supported spatial selections include squares,

rectangles, and circles, with rotation available for aligning selection regions with geological structures.

Before any optional declustering, users can apply a specified magnitude threshold or automatically estimate the magnitude of completeness, M_c . In automatic mode, M_c is estimated after spatial, depth, and temporal selection and before magnitude filtering using the maximum curvature method (MAXC) (Wiemer and Wyss, 2000). With the default settings, a non-cumulative frequency-magnitude distribution is constructed using bins of width 0.1, and the center of the bin containing the largest number of events is identified as M_{peak} . A correction of +0.2 magnitude units is then applied to reduce potential underestimation associated with MAXC (Woessner and Wiemer, 2005), giving $M_c = M_{\text{peak}} + 0.2$. If several bins share the maximum count, the lowest-magnitude peak is selected. Automatic estimation requires at least 50 events with finite magnitudes before magnitude filtering; this is a practical sample-size requirement rather than a statistical completeness test. A single M_c is estimated for the selected catalog and time interval, and only events with $M \geq M_c$ are retained for subsequent tidal analysis and, if selected, declustering. A single catalog-wide M_c does not assess temporal or day-night variations in detection capability. Users should examine these variations when relevant to the tidal periods of interest; magnitude filtering alone does not establish that detection-related periodicities have been excluded.

3.2 Earthquake declustering

Temporal clustering introduces dependence between earthquake occurrences and can affect the statistical interpretation of tidal analyses. For example, conventional Schuster significance estimates assume independent event phases under a Poisson null model in the absence of tidal modulation (Ader and Avouac, 2013; Wang and Shearer, 2015). Declustering is one possible treatment of this dependence, but the decision to apply it remains open and depends on the scientific question and statistical framework. Tidal stresses may modulate both background and clustered seismicity, so declustering does not isolate events caused by tides. TiMEpy treats declustering as optional preprocessing and allows tidal analysis of catalogs prepared with or without it.

TiMEpy provides two built-in declustering options: the Nearest-Neighbor Algorithm (NNA) (Zaliapin and Ben-Zion, 2013) and the Reasenber method (Reasenber, 1985). The NNA uses a space-time-magnitude proximity metric to distinguish clustered and background modes (see Text S1 in the Supplementary Material). The Reasenber method identifies linked events using spatial and temporal interaction criteria. These options provide convenient preprocessing within the workflow. Users can select a treatment suited to their research objective and examine how the retained catalog changes, given that catalog partitions vary among algorithms (Perry and Bendick, 2024).

Other catalog-preparation approaches can be used through the same modular workflow. For example, users may prepare a catalog using ETAS-based stochastic declustering (e.g., Ogata, 1988; Zhuang et al., 2002; Zhuang and Ogata, 2006) and supply the resulting event catalog to TiMEpy in the required input format. ETAS fitting is not implemented in the current release; NNA and Reasenber are the built-in options.

TiMEpy provides cumulative-count and spatial-temporal plots to compare catalogs before and after the chosen preprocessing. These plots show which event sequences and spatial concentrations are retained or removed and help users document their catalog selection. They are descriptive diagnostics and do not by themselves establish event independence or Poissonian behavior.

3.3 Strain-to-Stress conversion

TiMEpy uses the six independent components of the symmetric tidal strain tensor, expressed in an east-north-up coordinate system (Figure 2a). These components can be prepared from tidal strain programs such as TidalStrain2 (Hirose et al., 2019) or SPOTL (Agnew, 2012). Assuming linear isotropic elasticity, the tidal stress perturbation tensor is calculated as

$$\Delta\sigma_{ij} = \lambda\delta_{ij}\varepsilon_{kk} + 2\mu\varepsilon_{ij}, \quad (1)$$

Here, δ_{ij} is the Kronecker delta, repeated indices imply summation, and ε_{kk} is volumetric strain. The Lamé parameters are $\lambda = \rho(V_p^2 - 2V_s^2)$ and $\mu = \rho V_s^2$, where ρ is density and V_p and V_s are the P- and S-wave velocities.

For a fault with specified strike, dip, and rake, let $\mathbf{n}$ denote the unit normal vector and $\mathbf{s}$ the unit slip vector. Both vectors must be expressed in the same coordinate basis as the stress tensor. The resolved normal stress and shear stress in the slip direction are then

$$\Delta\sigma_n = n_i\Delta\sigma_{ij}n_j, \quad (2)$$

$$\Delta\tau = s_i\Delta\sigma_{ij}n_j. \quad (3)$$

Normal stress is positive for tension or unclamping, and shear stress is positive in the prescribed slip direction. With this sign convention, the Coulomb failure stress perturbation is

$$\Delta CFS = \Delta\tau + \mu'\Delta\sigma_n, \quad (4)$$

where μ' is the apparent friction coefficient. Positive Coulomb stress promotes slip on the assumed fault. The coordinate transformations, complete rotation matrices, and their equivalence to the vector projection above are provided in Text S2 in the Supplementary Material.

3.4 Earthquake occurrence in relation to tidal phase and level

After obtaining the tidal stress, we determine the tidal phase angle and level. The local tidal minima before and after each event are assigned phase angles of -180° and $+180^\circ$, respectively, while the maximum tidal value between these two minima is set to 0° (Cochran et al., 2004). The tidal phase angle and tidal level at the time of the earthquake are estimated using linear interpolation within the time intervals from -180° to 0° or from 0° to $+180^\circ$ (Figure 2b). Here, tidal level is defined as the strain or stress value, with a positive or negative sign relative to the zero line.

3.5 Tidal modulation by tidal phase

We quantify tidal phase modulation by comparing the phase distribution of earthquake occurrences with a reference distribution obtained by uniform time sampling (e.g., Beaucé et al., 2023; Lu et al., 2025b). The methodology proceeds as follows:

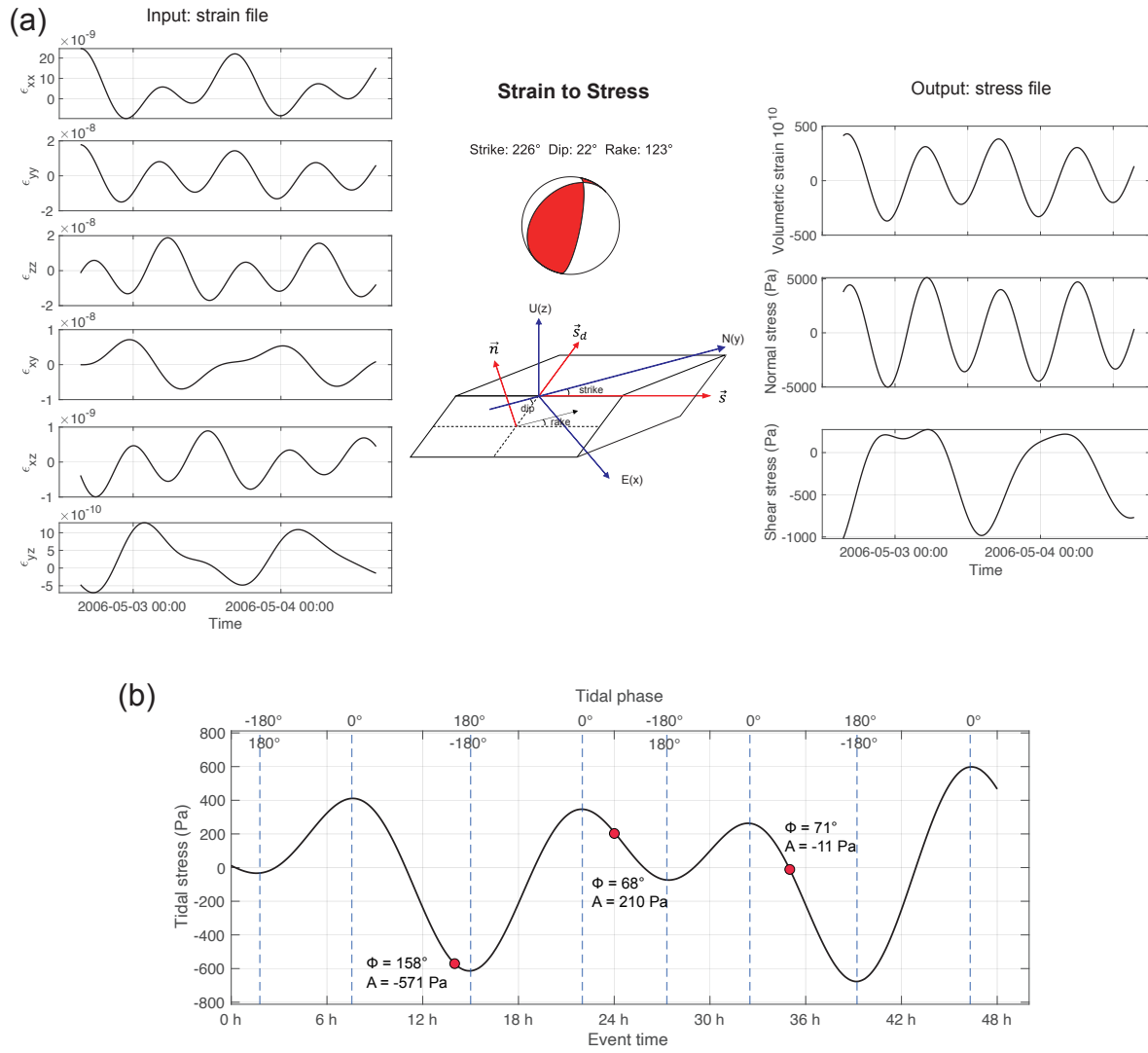


Figure 2 (a) The process of converting the input strain time series (left panels) into volumetric, normal, and shear stress components (right panels) using the specified fault-plane parameters. (b) Estimation of tidal phase angles (ϕ) and tidal stress (A) at earthquake occurrence times (circle) from the temporal variations in tidal stress.

For each earthquake in the selected catalog, the tidal phase angle ϕ is calculated using the interpolation scheme described above. The resulting phase angles are grouped into bins and normalized by the total number of earthquakes to obtain the observed phase distribution, $f_{\text{obs}}(\phi)$. We then sample the same study interval at hourly intervals and calculate the corresponding tidal phases. These reference samples are grouped into the same bins and normalized by their total number to obtain $f_{\text{ref}}(\phi)$. This reference distribution represents the fraction of time spent in each phase bin and accounts for unequal phase occupancy over the study interval.

The relative occurrence rate is calculated as

$$R_{\phi}(\phi) = \frac{f_{\text{obs}}(\phi)}{f_{\text{ref}}(\phi)}. \quad (5)$$

The ratio is evaluated for bins with nonzero reference exposure. Values above or below unity indicate enhanced or reduced earthquake occurrence relative to the reference distribution, respectively.

To characterize the preferred phase and strength of modulation, we fit the binned ratios with an empirical exponential cosine function:

$$R_{\phi}(\phi) = \exp [P \cos(\phi - \phi_0)] . \quad (6)$$

Here, $P \geq 0$ is the dimensionless phase modulation amplitude, and ϕ_0 is the preferred phase at which the fitted occurrence rate reaches its maximum. For weak modulation,

$$R_{\phi}(\phi) \approx 1 + P \cos(\phi - \phi_0), \quad P \ll 1, \quad (7)$$

so the exponential function approaches the commonly used cosine form when $P \ll 1$. The exponential form remains positive for strong modulation, whereas the cosine form can predict negative occurrence rates when $P > 1$.

Together, P and ϕ_0 describe the strength and timing of the phase-dependent response. Larger P indicates a stronger contrast between the preferred and least-favored phases, while ϕ_0 identifies the position of the peak within the tidal cycle. These fitted parameters describe the phase-dependent response of the selected catalog; their interpretation should account for catalog completeness, temporal clustering, and the adopted model.

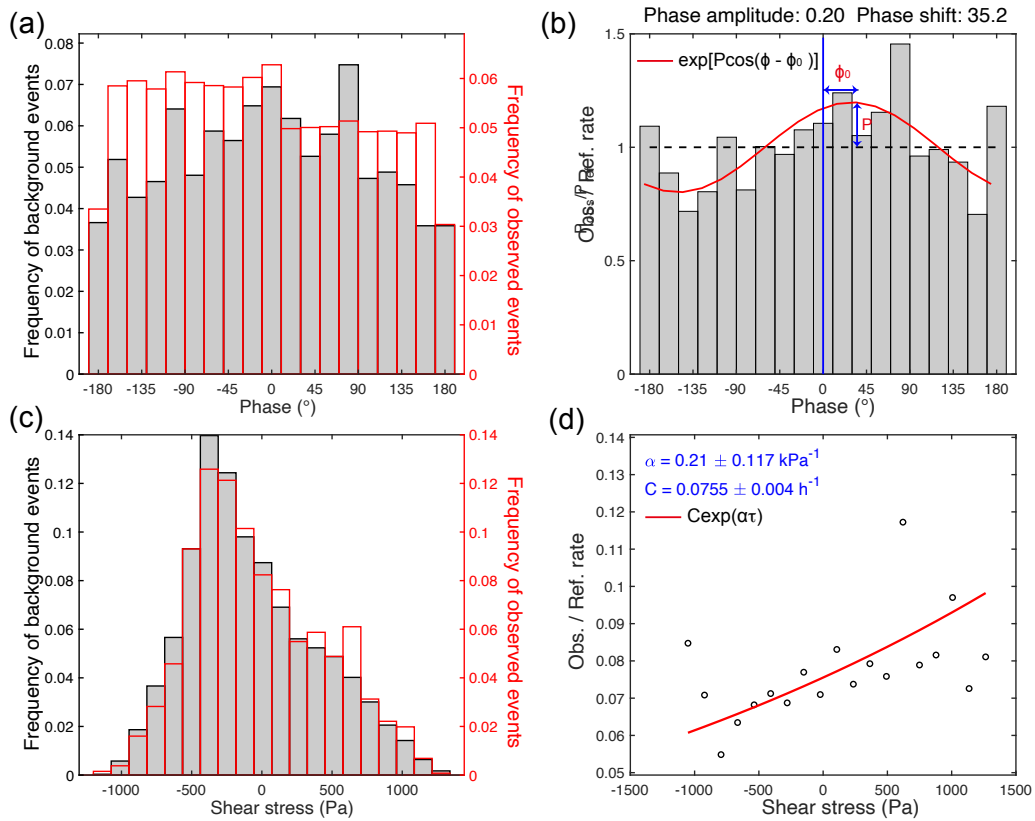


Figure 3 Phase-based and stress-level analyses of tidal modulation. (a) Normalized phase distributions for the hourly reference samples (gray filled bars) and earthquakes (red outlined bars). (b) Observed-to-reference phase ratio (gray bars) and the empirical exponential cosine fit (red curve); ϕ_0 denotes the preferred phase. (c) Normalized stress distributions for reference samples (gray) and earthquakes (red outlines). (d) Earthquake occurrence rate versus stress (open circles) and the exponential stress-rate model (red curve).

3.6 Tidal modulation by tidal level

To evaluate how earthquake occurrence rates vary with tidal stress, we compare the stress distribution at earthquake origin times with the time spent at each stress level (e.g., Houston, 2015; Ide et al., 2015; Lu et al., 2025a; Yabe et al.,

2015). Tidal stress is sampled at hourly intervals throughout the study period to estimate the reference stress distribution. For stress bin j , T_j denotes its total exposure time, estimated from these samples, and N_j denotes the number of earthquakes in the same bin. In Figure 3c, the gray distribution represents the exposure to each stress level, and the red distribution represents the observed events. Dividing the observed event counts by the corresponding exposure times gives the empirical earthquake rate:

$$R(\tau_j) = \frac{N_j}{T_j} = \frac{N}{T} \frac{f_{\text{obs}}(\tau_j)}{f_{\text{ref}}(\tau_j)}, \quad (8)$$

Here, τ_j is the representative stress of bin j , N is the total number of earthquakes, and T is the total exposure time. The normalized distributions are $f_{\text{obs}}(\tau_j) = N_j/N$ and $f_{\text{ref}}(\tau_j) = T_j/T$. Their ratio describes the occurrence rate relative to the mean rate N/T .

We model the earthquake rate as an exponential function of tidal stress:

$$R(\tau) = C \exp(\alpha\tau), \quad (9)$$

where $R(\tau)$ is the earthquake rate, C is a reference earthquake rate when tidal stress is zero, τ is the tidal stress, and α is the tidal sensitivity. This exponential relationship between tidal stress and earthquake occurrence has been supported by observational studies (Beeler and Lockner, 2003; Houston, 2015; Ide et al., 2015) as well as by theoretical analyses using a simple spring-block system with rate-and-state friction (RSF) (Ader et al., 2012). We estimate α and C by minimizing the binned negative log-likelihood objective under an inhomogeneous Poisson working model. At the optimum, we evaluate the analytical Hessian of this objective and approximate the parameter covariance matrix by its inverse. The standard error of each parameter is the square root of the corresponding diagonal element, and the reported uncertainty is twice this standard error. Under the Poisson working model and a local Gaussian approximation to the parameter estimates, these bounds are interpreted as approximate, model-based 95% confidence intervals. They describe local fitting uncertainty conditional on the stress bins retained by the implementation and do not account for residual temporal clustering or uncertainty in the tidal stress model (see Text S3 in the Supplementary Material for details).

3.7 Package features

Python is an ideal choice for developing projects like TiMEpy thanks to its ease of use and readability, along with a vast ecosystem of libraries (e.g., NumPy, Pandas, SciPy, Matplotlib). TiMEpy is a novel framework for tidal modulation built on the Python workflow and closely integrated with the seismological ecosystem, including ObsPy (Beyreuther et al., 2010). In TiMEpy, each process is executed as a separate step, and individual steps can be seamlessly linked to other research tasks, such as catalog preparation and independent statistical analyses. The adjustable parameters are stored in `input_params.py`. The schematic (Figure 4) illustrates an example workflow. The main functions included in the TiMEpy package are:

1. Earthquake declustering.
2. Associating earthquake timing information with tidal stress.

3. Tidal modulation analysis based on stress level and phase.

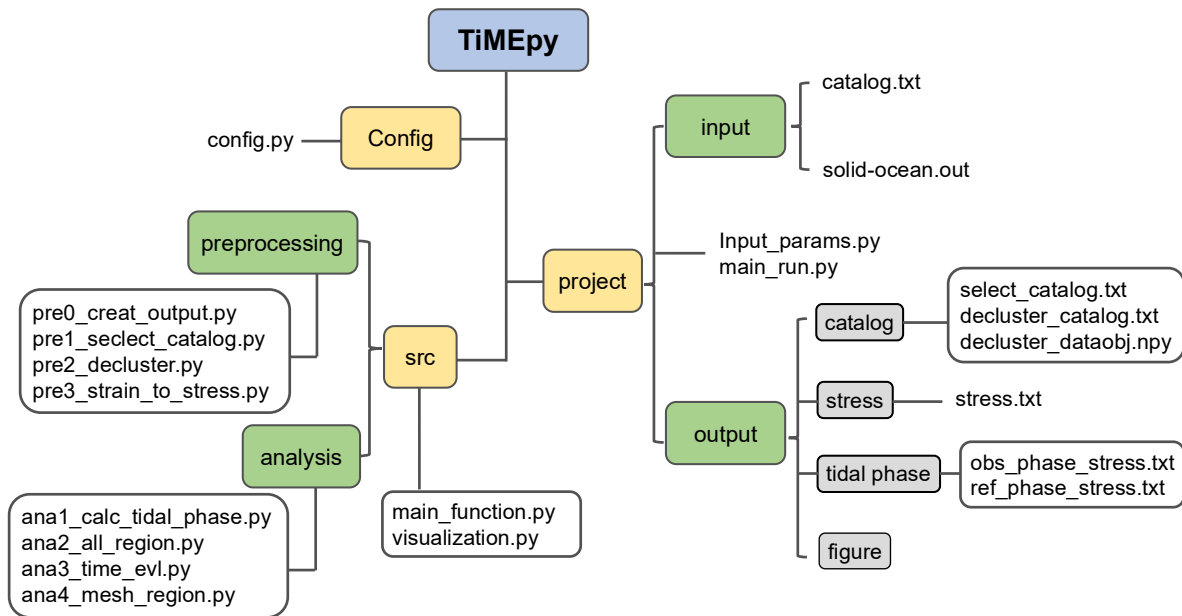


Figure 4 Schematic diagram illustrating the usage of the TiMEpy package. The yellow box denotes the first directory of the package, and the green box denotes the second directory. The .py files in the Config folder generate images and store file names, while the Src folder contains TiMEpy’s core functions. The Project folder can be renamed to match different study areas by simply updating the input params file.

4 Applications

4.1 2019 M7.1 Ridgecrest, California Earthquake

A nearly 20-year hiatus in major seismic activity in southern California ended on July 4, 2019, when a sequence of intersecting earthquakes occurred near Ridgecrest. Among these events was the significant M_w 7.1 Ridgecrest earthquake (Ross et al., 2019a; Yue et al., 2021). To shed light on the region’s seismic behavior leading up to this event, Beaucé et al. (2023) analyzed 10 years of continuous seismic waveforms preceding the 2019 Ridgecrest, CA earthquake sequence. By employing earthquake detection and location methods based on machine learning and template matching, they detected 191,569 earthquakes. Their enhanced catalog revealed that seismicity became strongly modulated by the tides approximately two years before the mainshock. They used a stacking procedure to address clustering in their analysis. We use an updated version of their catalog to illustrate the TiMEpy workflow and compare the inferred temporal pattern with their published result.

We used an updated version of the catalog developed by Beaucé et al. (2023), containing fewer events than the original release, and selected a fault-zone region broadly consistent with their study area. After applying the spatial, depth, and time filters, the selected catalog contained 20,848 events. Before declustering, we estimated the magnitude of completeness, M_c , using the maximum-curvature method with 0.1-magnitude bins (Wiemer and Wyss, 2000). The non-cumulative magnitude–frequency distribution peaks at $M = -0.20$; adding a correction of $+0.20$ magnitude units (Woessner and Wiemer, 2005) gives $M_c = 0.00$ (Figure S1 in the Supplementary Material). We retained the 8,309 events with $M \geq M_c$ and then applied the NNA to obtain the declustered catalog for tidal analysis (Figure 5b; see also

Figure S2 in the Supplementary Material). Cumulative event counts before and after declustering were inspected to assess the reduction in prominent clustered sequences.

Tidal strains were calculated using TidalStrain2 and converted to stresses resolved on the mainshock fault plane, with strike = 321° , dip = 81° , and rake = 180° (Table S2 in the Supplementary Material). The resolved shear and normal stresses were combined to obtain tidal Coulomb stress using an apparent friction coefficient of $\mu' = 0.6$, following the convention defined in Section 3.3. Figure 5d compares the declustered earthquake occurrences with the calculated tidal Coulomb stress. We computed ϕ_0 and P in overlapping 3.4-year windows with 3-month steps, with these parameters adopted from Beaucé et al. (2023) (Table S1 in the Supplementary Material). Each window comprises at least about 1,600 events (Figure S3 in the Supplementary Material). Tidal phase analysis reveals that after 2018, the tidal phase shift angle gradually converges toward 0° , while the amplitude of tidal phase steadily increases (Figures 6a and 6b). Additionally, the tidal sensitivity results also indicate enhanced tidal modulation (Figure 6c). We selected one window for illustration, with its phase and stress-level fits shown in Figures 6d and 6e.

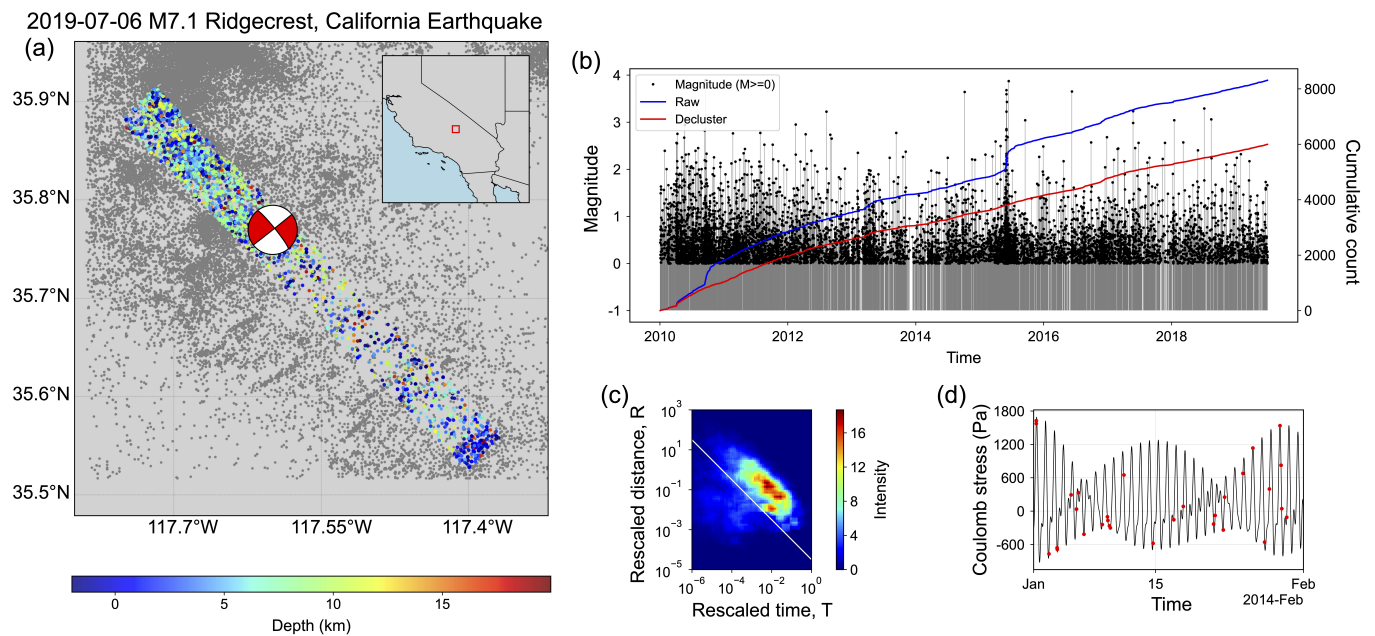


Figure 5 Catalog selection, declustering, and tidal stress analysis for the Ridgecrest region. (a) Spatial distribution of earthquakes near Ridgecrest. Gray dots show events in the updated catalog of Beaucé et al. (2023), whereas colored dots show the events retained after spatial, depth, temporal, and magnitude filtering and subsequent declustering. Colors indicate focal depth. The beachball represents the focal mechanism of the 2019 M_w 7.1 mainshock, and the inset shows the regional location. (b) Earthquake magnitudes versus time (black points) and cumulative event counts before (blue) and after (red) declustering. The catalog before declustering contains 8,309 events with $M \geq M_c = 0.0$. (c) Joint distribution of the rescaled temporal (T) and spatial (R) components of nearest-neighbor proximity, with the white line indicating the declustering threshold. (d) A one-month example of tidal Coulomb stress resolved on the mainshock fault plane (strike = 321° , dip = 81° , and rake = 180°), using an apparent friction coefficient of $\mu' = 0.6$. Red dots indicate the stress values at the occurrence times of declustered earthquakes.

We also tested 3.0- and 2.5-year windows with 91- and 60-day steps, and widened the selection rectangle from $0.05^\circ \times 0.50^\circ$ to $0.08^\circ \times 0.50^\circ$ (Table S3; Figures S4–S8 in the Supplementary Material). The overall increase in tidal modulation before the mainshock remains apparent across the tested configurations, supporting the robustness of this pattern within the parameter ranges examined. All configurations in Table S3 use overlapping windows; non-overlapping windows were not tested.

Together, these analyses identify enhanced tidal modulation during approximately the final 1.5 years before the

M_w 7.1 mainshock. This pattern is broadly consistent with the pre-mainshock enhancement reported by Beaucé et al. (2023), despite differences in catalog version and treatment of earthquake clustering.

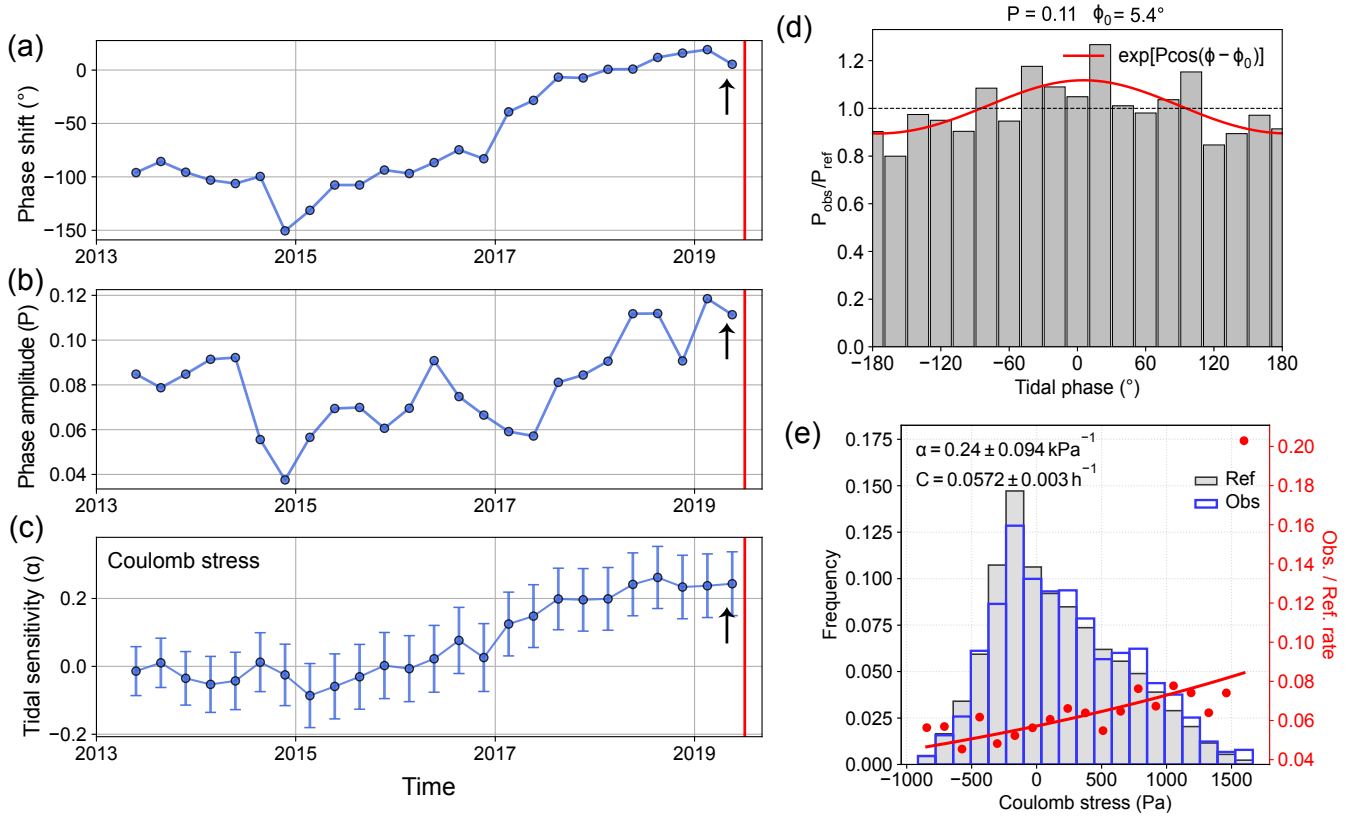


Figure 6 Temporal variations in tidal modulation before the 2019 M_w 7.1 Ridgecrest earthquake. (a) Preferred tidal phase ϕ_0 , where 0° corresponds to maximum Coulomb stress. (b) Phase modulation amplitude P . (c) Tidal sensitivity α estimated from the stress-level analysis. Results in (a)–(c) are calculated using overlapping 3.4-year windows advanced in 3-month steps, with each point plotted at the end of its window. Error bars in (c) indicate approximate, model-based 95% confidence intervals (see Text S3 in the Supplementary Material). Vertical red lines mark the mainshock. (d) Observed-to-reference phase distribution ratio (gray bars) and the fitted exponential cosine function, $\exp[P \cos(\phi - \phi_0)]$ (red curve); the dashed horizontal line indicates unity. (e) Normalized distributions of hourly sampled Coulomb stress (gray filled bars) and earthquake occurrences (blue outlined bars). Red circles show the earthquake occurrence rate in each stress bin (right axis), and the red curve shows the exponential model fitted by maximum likelihood. Panels (d) and (e) correspond to the window indicated by arrows in (a)–(c).

4.2 2012–2022 Tectonic Tremors in Taiwan

Using continuous seismic data from multiple recently available stations in Taiwan, Ide and Chen (2024) applied the envelope correlation method to detect approximately 7,000 tremor events between 2012 and 2022. This tremor catalog provides an application of TiMEpy to slow earthquakes. We selected a prominent tremor cluster located beneath the Central Mountain Range, comprising 4,666 tremors—the largest and most significant tremor cluster identified in Taiwan (Ide and Chen, 2024) (Figure 7a). Although tremor activity is temporally clustered (Idehara et al., 2014), we retain the tremor detections without declustering to characterize the tidal dependence of the overall activity rate, including activity within tremor episodes, following previous rate-based tremor studies (Houston, 2015; Yabe et al., 2015) (Figure 7b). The focal mechanism we adopted is derived from Ide et al. (2015) and represents a low-angle reverse faulting process (strike = 54° , dip = 13° , rake = 120°), which has been substantiated by evidence of low-angle reverse slip on the fault plane in this region (Ide and Chen, 2024).

Figure 7c displays a comparison between the timing of the 4,666 tremors and the tidal shear stress. It clearly demonstrates that tremors occur when the tidal shear stress is positive, as highlighted by the red dots. The relationship between tidal stress and tremor rate in this cluster reveals that, as shear stress increases, the tremor rate exhibits a nonlinear increase, with a tidal sensitivity reaching as high as $\alpha = 1.42$ (Figure 7d). Compared to regions such as Nankai and Cascadia (Yabe et al., 2015), the tidal sensitivity in this case is significantly higher. This value is lower than the sensitivity of 2.1 reported by Ide et al. (2015) for the 2007–2012 tremor catalog. Differences in catalog coverage, event selection, tidal stress calculations, and fitting procedures may contribute to this discrepancy. A consistent analysis of both catalogs would be needed to assess whether it also reflects temporal changes in tremor sensitivity. Additionally, the preferred tidal phase is approximately 20° , and the phase modulation amplitude is exceptionally high (Figure 7e).

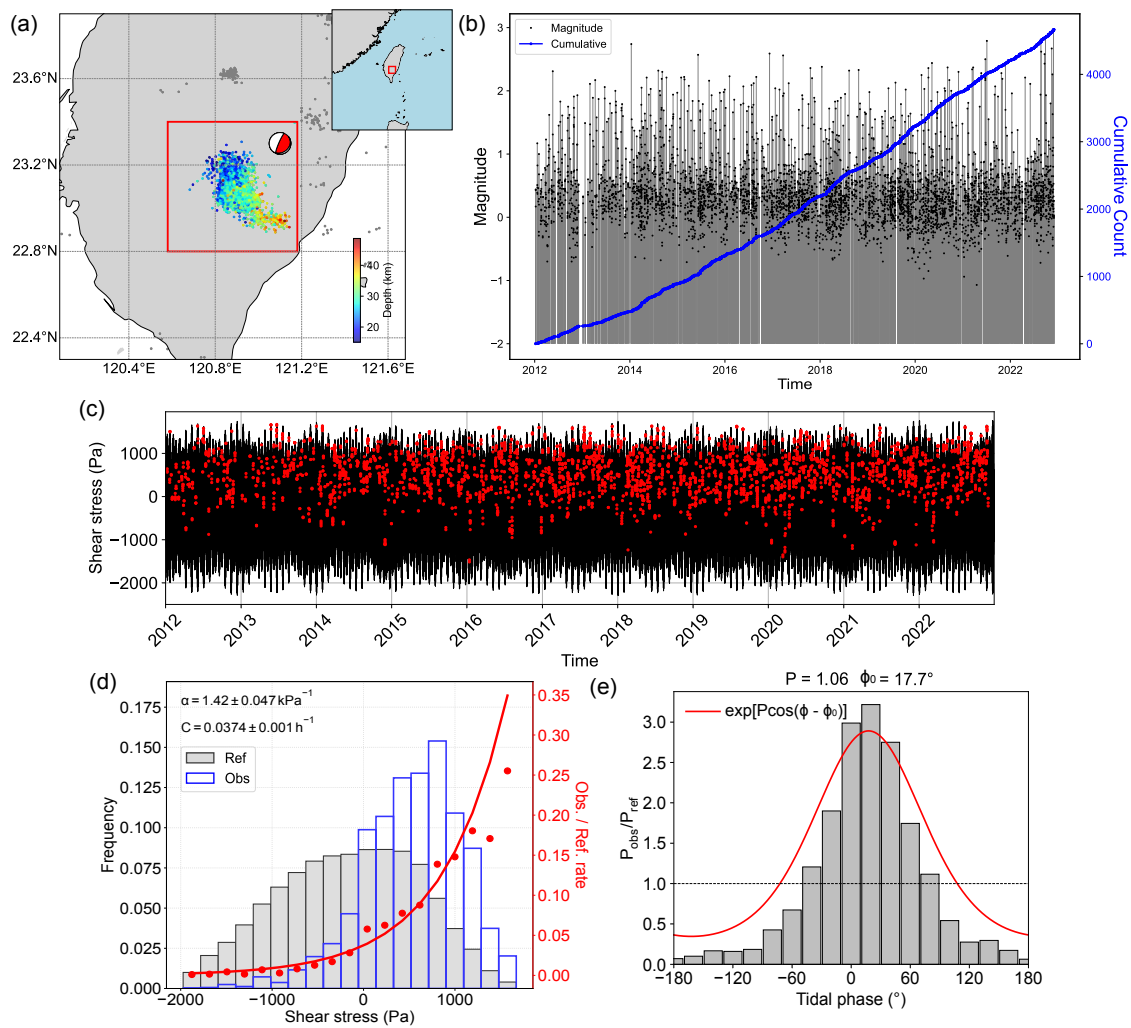


Figure 7 Tectonic tremor activity and tidal modulation in Taiwan. (a) Spatial distribution of tremors, color-coded by depth. (b) Magnitude–time ($M-T$) distribution and cumulative number of tremors. (c) Temporal variation in tidal shear stress, with red dots indicating tremor occurrence times. (d) Same analysis as in Figure 6e. (e) Same analysis as in Figure 6d.

5 Discussion and Conclusions

TiMEpy uses tidal phase information to characterize when earthquakes preferentially occur within the loading cycle and complements this analysis with the dependence of occurrence rates on tidal stress. The Ridgecrest application

illustrates these analyses using an updated version of the catalog developed by [Beaucé et al. \(2023\)](#). We varied the sliding-window length and step and widened the spatial selection from $0.05^\circ \times 0.50^\circ$ to $0.08^\circ \times 0.50^\circ$ (Table S3; Figures S4–S8 in the Supplementary Material). The pre-mainshock increase in modulation remains apparent within these tested configurations, although the estimated parameters vary. These tests assess the sensitivity of this temporal pattern within the parameter choices examined.

To make tidal modulation analysis accessible and reproducible, we developed TiMEpy as an open-source Python package for ordinary and slow earthquakes. Its core analysis uses tidal phase information to detect and quantify modulation and stress-level information to estimate tidal sensitivity. Whether and how to decluster remains an open methodological question, to be considered in relation to the research objective and statistical assumptions. The package therefore provides simple, optional preprocessing tools and accepts compatible catalogs prepared externally. A catalog selected using another detection method or clustering treatment, including ETAS-based declustering ([Zhuang et al., 2002](#)), can be passed to the analysis module in the required event-catalog format. This connection concerns the resulting event catalog; method-specific outputs such as event weights or stacked rates may require additional conversion or adaptation. Users can also analyze catalogs without declustering, as in the tremor example, while accounting for event dependence in the interpretation of fitted parameters and uncertainties.

Future applications of TiMEpy could use the relationship between seismicity and tidal stress to constrain fault properties and earthquake nucleation processes. When interpreted within appropriate physical models, the strength, preferred phase, and frequency dependence of tidal modulation may provide constraints on background effective normal stress, frictional properties, and nucleation timescales ([Beaucé et al., 2026](#); [Beeler and Lockner, 2003](#); [Lu et al., 2025b](#); [Srirattanakul and Avouac, 2026](#)). For slow earthquakes, tidal responses can also provide complementary constraints on focal mechanisms, including fault orientation and slip direction ([Lu et al., 2026a](#); [Shelly et al., 2026](#)). Comparisons between ordinary earthquakes and low frequency earthquakes may further help clarify the roles of aseismic loading and pore-fluid processes in controlling fault slip ([Beeler et al., 2013](#); [Zhao et al., 2025](#)). TiMEpy can support these investigations by providing a consistent and reproducible workflow for quantifying tidal responses across different fault environments and comparing observations with physical model predictions.

TiMEpy provides a reproducible workflow for investigating tidal modulation using event-phase information and complementary stress-level analysis. Its modular design connects catalog preparation, stress calculation, and tidal analysis while allowing users to select the catalog treatment appropriate to their scientific question. These functions support comparisons of tidal responses across regions and time intervals and their interpretation within physical models.

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Data and code availability

The software described in this study is documented and publicly available in the repository at <https://github.com/Weifan-Lu/TiMEpy>. The TidalStrain.2 can be accessed at <https://www.mri-jma.go.jp/Dep/sei/fhirore/research/en.TidalStrain.html>. The Ridgecrest earthquake catalog is available on the Zenodo platform at <https://zenodo.org/records/8393318>. The 2012-2022 tectonic tremor catalog is available at <http://www-solid.eps.s.u-tokyo.ac.jp/sloweq/?page=map>.

Competing interests

The authors acknowledge that there are no conflicts of interest recorded.

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