A worked example of the TAMC-FRANJAMAR framework:

Retrospective multi-station analysis of the 2011 Great Tohoku Earthquake and othes cases.

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A Additional events and reproducibility

The FRANJAMAR framework was applied to the 30 largest earthquakes in the study catalog under fixed parameters and standardized processing conditions. Only selected cases are presented here for illustrative purposes. The full TAMC-FRANJAMAR pipeline is publicly available, allowing any user to download additional events and reproduce or extend the analysis under identical conditions. This design emphasizes transparency, reproducibility, and critical evaluation rather than selective case reporting. As a general analytical framework, TAMC–FRANJAMAR does not claim to provide uniformly optimal performance across all possible seismic contexts. Its effectiveness depends on data availability, network geometry, signal quality, and the suitability of the chosen null hypotheses for a given setting. Consequently, some events may yield weak, ambiguous, or null-compatible outcomes under specific configurations.

This limitation is not treated as a flaw, but as an inherent property of a falsifiable statistical framework. Negative or inconclusive results are considered informative, as they delineate the conditions under which collective network organization is not detected. The framework is therefore designed to support critical evaluation and comparative analysis rather than to guarantee positive findings. Interpretation of the graphical outputs produced by the framework must be carried out at the level of the system rather than at the level of individual curves or isolated metrics. Each figure represents a projection of collective network behavior under a specific analytical lens, and no single panel or metric is intended to be interpreted in isolation.

Meaningful interpretation arises from the joint consideration of temporal structure, synchronization patterns, null-model comparisons, and robustness analyses. Apparent anomalies or features in individual plots may occur under null conditions and should not be construed as precursors or deterministic indicators. The framework is therefore designed to support integrative, system-level interpretation rather than pointwise signal inspection. Because the FRANJAMAR framework is explicitly defined at the level of multistation coherence, the interpretation of individual plots or isolated metrics is, by construction, inconsistent with the logic of the method. Each graphical output represents only a partial projection of a higher-dimensional collective state and cannot be meaningfully interpreted outside the context of the full system-level analysis. Accordingly, the figures presented in this appendix are intended to be read comparatively and relationally, as complementary views of the same underlying collective dynamics, rather than as independent evidentiary elements. Their role is illustrative: to support the system-level interpretation derived from the joint behavior of all metrics, null models, and robustness tests. This perspective is essential for avoiding overinterpretation of isolated features and for preserving the internal consistency of the framework FRANJAMAR.

B Scope and purpose

This document provides a complete worked example illustrating the application of the TAMC-FRANJAMAR framework to a major earthquake: the 2011 Mw 9.1 Great Tohoku Earthquake (Japan). It is intended as a *technical companion* to the main framework description and is designed to be read independently.

The purpose of this document is methodological and pedagogical. It demonstrates how the framework is executed step by step, how its outputs are generated, and how the resulting figures should be interpreted within the conservative statistical philosophy of the framework. This document does not present new scientific claims, does not assess predictive capability, and does not establish physical causality.

C Event definition and analysis window

The selected event corresponds to the 2011 Great Tohoku Earthquake (Japan). The analysis window is fixed *a priori* to the **24 hours preceding the mainshock**, with the origin time of the mainshock defined as $t = 0$. All figures and time series are expressed in relative time with respect to this reference.

D Station selection and control-day consistency

A minimum of **five seismic stations** is required for execution. The same station set is used consistently across:

- the event window,
- all matched control-day windows,
- null-model realizations, and
- placebo tests.

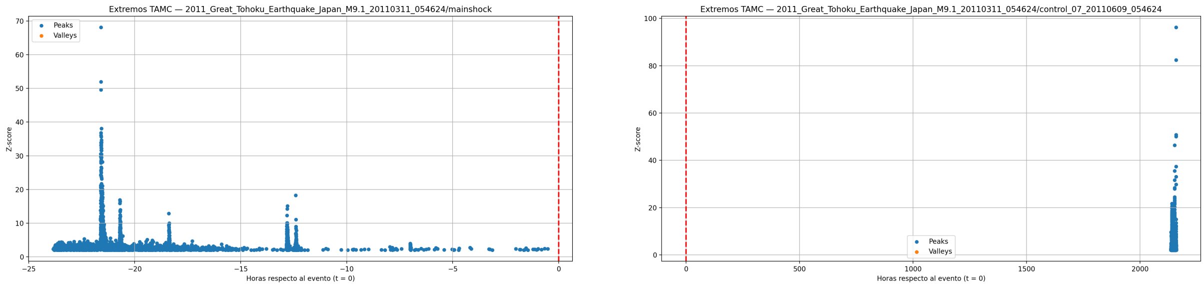
All control windows have the same duration (24 h) and temporal alignment as the event window. This constraint ensures that comparisons between event and control windows are not confounded by changes in network geometry, station availability, or window length.

E Execution workflow

The analysis corresponds to a full event-based execution of the TAMC FRANJAMAR framework. The workflow consists of:

1. Event selection and window definition.
2. Automated or manual ingestion of continuous waveform data.
3. Preprocessing, optional rotation, and extraction of standardized station-level metrics.
4. Detection of statistically extreme activity (peaks and valleys).
5. Aggregation into network-level phases and summary metrics.
6. Generation of matched control-day ensembles.
7. Validation through empirical null models and placebo tests.

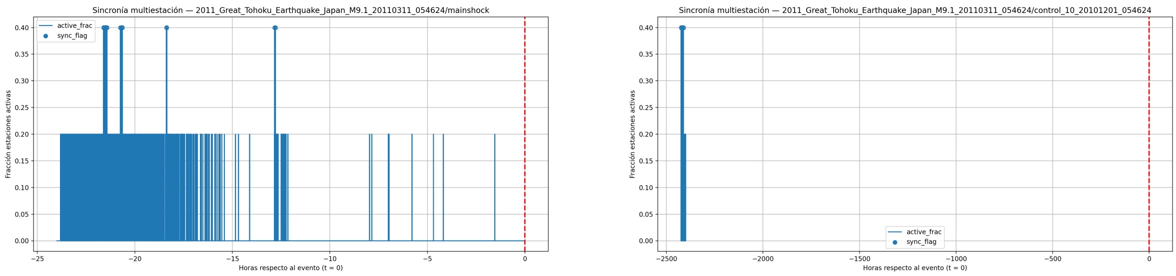
All parameters and thresholds are fixed *a priori* and applied uniformly.



(a) 24h pre-mainshock.

(b) Representative matched control day.

Figure 1: Detected extreme activity for the event window and a representative matched control day. Both panels are generated using identical station sets, window lengths, and visualization parameters.



(a) 24 h pre-mainshock window.

(b) Representative matched control day.

Figure 2: Network-level synchronization metrics for the Tohoku 2011 case. The fraction of simultaneously active stations is shown for (a) the 24 h pre-mainshock window and (b) a representative matched control day. Higher values indicate increased network coherence. Both panels are generated using identical station sets, temporal windows, and analysis parameters.

F Extreme activity and temporal organization

Figure 1 compares detected extreme activity for the event window and a representative matched control day. Both panels are generated using identical station sets, window lengths, and visualization parameters.

These figures are descriptive. Visual clustering or intermittency motivates quantitative summaries and statistical validation rather than serving as evidence on its own.

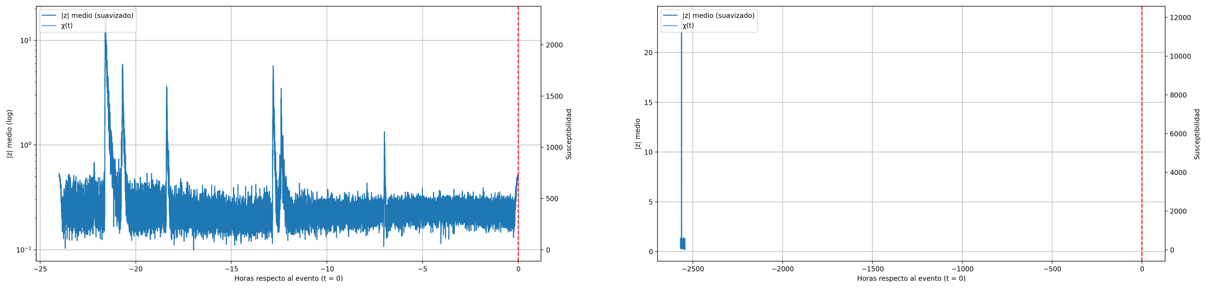
G Network-level synchronization

Figure 2 summarizes collective network behavior using synchronization metrics. Higher fractions of simultaneously active stations indicate increased network coherence, but interpretation is conditional on comparison with control windows and robustness tests.

This behavior is further illustrated by aggregate activity timelines (Figure 3), which provide a continuous, network-level representation of standardized activity and susceptibility.

In the 24 h pre-mainshock window, the aggregate activity does not evolve uniformly in time but exhibits sustained fluctuations punctuated by intermittent episodes of elevated amplitude. These fluctuations persist over extended portions of the window rather than appearing as isolated spikes, suggesting a temporally structured form of collective variability.

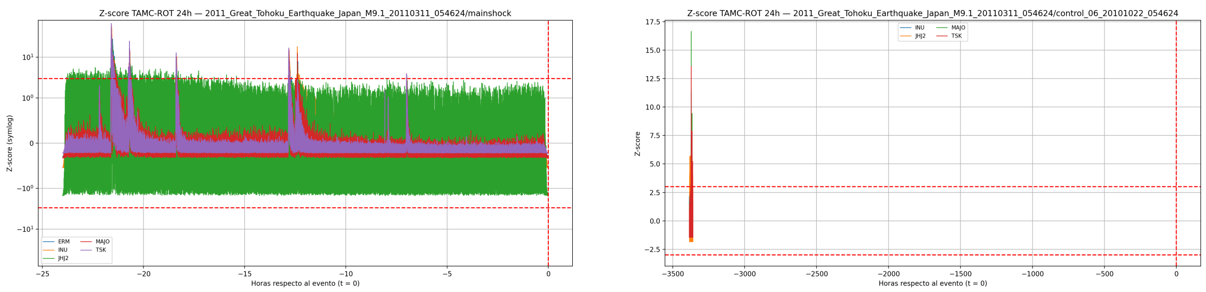
By contrast, the representative matched control day shows a comparatively stable aggregate profile, with reduced amplitude variability and an absence of prolonged elevated phases, despite being generated under identical station sets and processing parameters.



(a) 24 h pre-mainshock window (Tohoku 2011). (b) Representative matched control day.

Figure 3: Aggregate activity timeline for the 2011 Great Tohoku earthquake. The mean absolute standardized activity and susceptibility are shown for (a) the 24 h pre-mainshock window and (b) a representative matched control day. Both panels are generated using identical station sets, temporal windows, and analysis parameters.

Importantly, this representation does not rely on discrete thresholding or event detection. Instead, it reflects the continuous evolution of network-level activity, complementing the discrete synchronization metrics and extreme-event analyses presented above.



(a) 24 h pre-mainshock window (Tohoku 2011). (b) Representative matched control day.

Figure 4: Multistation standardized activity (Z-scores) for the 2011 Great Tohoku earthquake. Station-level Z-score time series are shown for (a) the 24 h pre-mainshock window and (b) a representative matched control day. Horizontal dashed lines indicate fixed significance thresholds. Both panels are generated using identical station sets, temporal windows, and analysis parameters.

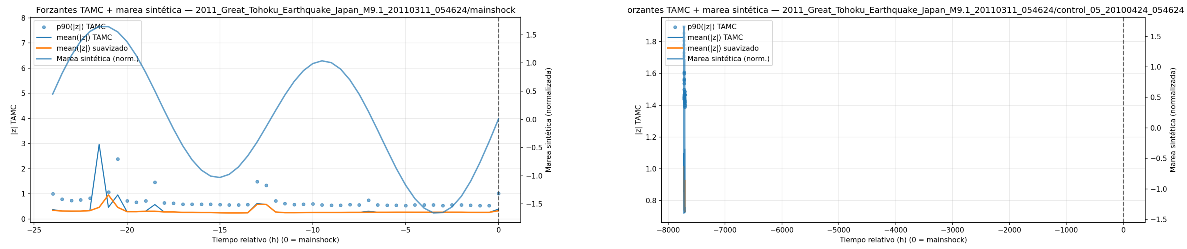
In contrast to the aggregate measures shown above, the multistation Z-score representation provides a station-resolved view of standardized activity. During the 24 h pre-mainshock window, multiple stations exhibit temporally aligned extreme excursions that exceed fixed significance thresholds, indicating that elevated activity is not confined to a single location or metric.

Importantly, these excursions occur within restricted time intervals and involve overlapping subsets of stations, suggesting transient episodes of network-wide organization rather than isolated, independent anomalies. In the representative matched control day, Z-score fluctuations remain largely bounded and temporally uncoordinated across stations, despite being computed using identical processing parameters.

This contrast reinforces the interpretation that the event window is characterized by enhanced collective organization at multiple observational levels, while typical control days exhibit more diffuse and weakly correlated station-level variability.

H External forcing and tidal modulation

The framework allows optional inclusion of external forcing proxies for contextual analysis. In this example, a synthetic tidal signal is overlaid with summary TAMC-FRANJAMAR measures.



(a) 24 h pre-mainshock window.

(b) Representative matched control day.

Figure 5: External forcing proxies for the Tohoku 2011 case. The same temporal window length and station set are used for (a) the 24 h pre-mainshock window and (b) a representative matched control day. These forcings are shown for contextual comparison and are not interpreted as causal drivers.

Tidal forcing is not interpreted as a causal mechanism. Instead, within a complex-systems perspective, it is treated as a weak external modulation that may influence the timing of collective activity in a system already close to instability.

I Interpretation guide

This document provides a disciplined reading of the figures. Apparent patterns in the event window are interpreted only relative to control windows and validated statistically via null models and placebo tests. No predictive claims, deterministic precursors, or causal inferences are made.

J Integrated interpretation of the Tohoku 2011 results

To provide a qualitative interpretation of the observed event-level behavior, a conceptual representation of the inferred dynamical cycle is shown in Figure 6.

The set of figures presented for the 2011 Great Tohoku Earthquake reveals a coherent and internally consistent temporal organization of network-level activity during the approximately 24 hours preceding the mainshock. While each individual observable captures a different projection of the system's dynamics, a key result of the TAMC-FRANJAMAR framework is that *synchronization episodes appear consistently across all representations and within the same restricted pre-event time interval.*

Quantitative context. While this document emphasizes qualitative organization and temporal coherence, it is important to note that the patterns described above are supported by explicit quantitative contrasts performed within the TAMC-FRANJAMAR framework. In the Tohoku 2011 case, network-level metrics associated with synchronization frequency, temporal concentration of extremes, and fraction of simultaneously active stations place the event window in the upper tail of the corresponding control-day distributions. In contrast, matched control days cluster around baseline values and exhibit broader dispersion without consistent temporal alignment across metrics. These quantitative relationships, documented in the core framework analyses, provide statistical grounding for the integrated interpretation presented here and confirm that the observed synchronization–relaxation dynamics are not solely a consequence of visual inspection.

J.1 Extreme activity and temporal concentration

The extreme-activity scatter plots show that statistically large deviations are not uniformly distributed throughout the 24-hour window. Instead, they appear concentrated in a limited

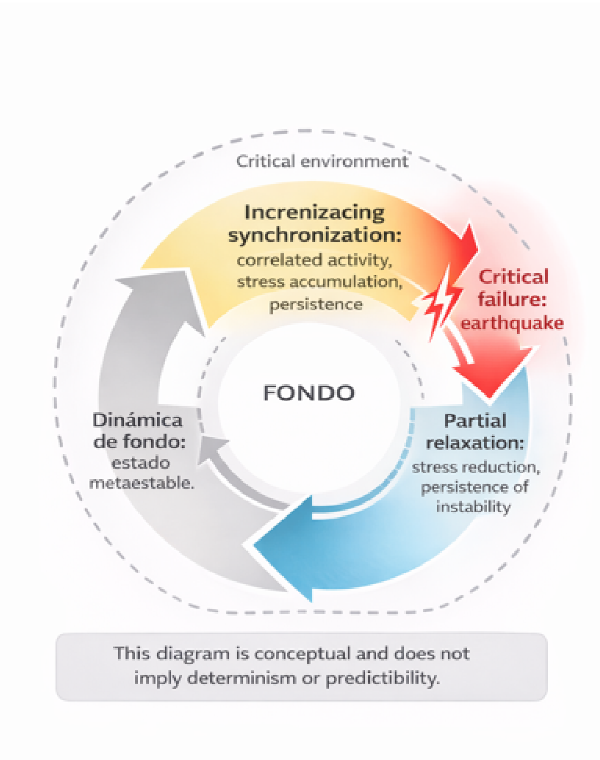


Figure 6: Conceptual diagram illustrating the background–synchronization–partial relaxation–failure cycle inferred from the Tohoku 2011 results within a near-critical seismic system. Increasing synchronization corresponds to correlated activity, stress accumulation, and temporal persistence at the network level. Partial relaxation phases may reduce stress while maintaining system-wide instability. The final failure (earthquake) represents a critical transition rather than a deterministic outcome. This diagram is illustrative and does not imply causality, determinism, or predictive capability.

Table 1: Qualitative summary of network-level contrasts between the Tohoku 2011 event window and matched control days. Percentile ranges refer to the position of the event metric within the empirical control-day distribution.

Metric	Event vs Control	Relative Position
Extreme activity clustering	Higher	Upper tail
Temporal concentration	Higher	Upper tail
Fraction of synchronized stations	Higher	Upper tail
Synchronization–relaxation cycles	Present	Rare in controls
Tidal phase alignment	Conditional	Event-biased

number of temporal clusters, particularly during the final ∼20–22 hours before the mainshock. Importantly, these clusters are not isolated to a single station or a single metric, but recur across multiple stations and extreme definitions.

This temporal concentration suggests that the system does not evolve smoothly toward the event, but rather undergoes intermittent episodes of elevated collective activity separated by quieter intervals. Such intermittency is a hallmark of systems approaching critical transitions, where stress redistribution and local relaxations coexist with global organization.

J.2 Multi-station synchronization as a collective signature

The synchronization metrics provide a crucial complementary perspective. Peaks in the fraction of simultaneously active stations occur at the same times at which extreme activity clusters are observed. This coincidence indicates that the detected extremes are not merely local anomalies but are temporally coordinated across a significant portion of the network.

In the TAMC-FRANJAMAR interpretation, synchronization reflects the emergence of transient coherence among spatially distributed elements. These coherence episodes are followed by partial relaxations, in which activity decreases before reorganizing again. The repeated appearance of synchronization–relaxation cycles within the same pre-event window supports the view that the system undergoes a sequence of metastable configurations rather than a monotonic buildup.

J.3 Consistency across observables

A central strength of the framework is that the same temporal structure is visible across distinct observables: extreme-value statistics, binned counts, multi-station synchronization, and aggregated standardized activity. The recurrence of synchronization episodes across all these representations reduces the likelihood that the observed patterns arise from a specific metric choice or visualization artifact.

Rather than relying on a single precursor-like signal, the framework identifies a *convergent temporal organization* across heterogeneous measures. This convergence is what distinguishes the event window from typical control days, where similar observables tend to be less temporally aligned and more weakly synchronized.

J.4 External forcing as a weak temporal modulator

The overlay of synthetic tidal forcing provides additional context for interpreting the timing of synchronization episodes. In the event window, several coherence peaks occur preferentially near specific tidal phases. Within the framework's interpretation, this alignment is not treated as causal in a deterministic sense.

Instead, tidal forcing is considered a weak external modulation that may influence the timing of transitions between metastable states in a system already close to failure. In this view, the forcing does not create the instability but can bias the timing of collective reorganizations. The relevance of this modulation is assessed comparatively: only alignments that are atypical relative to matched control days are considered potentially meaningful.

J.5 Synchronization–relaxation dynamics prior to failure

Taken together, the figures support a qualitative picture in which the seismic network undergoes repeated cycles of synchronization and relaxation during the final pre-mainshock day. Each synchronization episode corresponds to a transient increase in collective activity and coherence, followed by partial release and reorganization.

The mainshock itself can be interpreted as the terminal event of this process, occurring after the system fails to fully relax from a preceding collective state. Importantly, the framework does not assume that such dynamics are universal or necessary for all earthquakes. Instead, it provides a structured way to detect and evaluate them when they occur.

J.6 Limits of interpretation

Despite the apparent coherence of the pre-event organization, no deterministic inference is drawn. The presence of synchronization episodes does not imply predictability, nor does it define a unique physical mechanism. The framework remains strictly retrospective and comparative: patterns are interpreted only relative to control windows, null models, and robustness tests.

Equally important, the absence of such organization in other events would be interpreted as a genuine negative result rather than a failure of the method. The value of the framework lies in its ability to make both organized and unorganized pre-event dynamics explicit at the network level.

K Summary

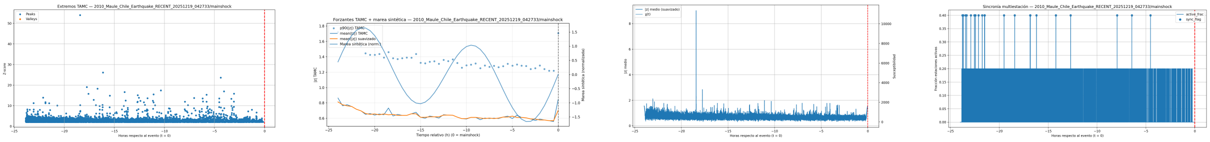
This worked example demonstrates the reproducible execution of the TAMC-FRANJAMAR framework on a major earthquake using fixed parameters, consistent station selection, and matched control days. It serves as a concrete technical reference for users seeking to reproduce or extend the analysis while preserving the conservative, non-predictive philosophy of the framework. Within the TAMC-FRANJAMAR framework, the 2011 Tohoku earthquake is characterized by sustained and recurrent synchronization–relaxation cycles confined to a narrowly defined pre-event time window. Rather than exhibiting a single precursor-like signal or a monotonic escalation toward failure, the observed dynamics indicate a system fluctuating between metastable collective states prior to the mainshock.

In this interpretation, the preparatory phase is marked by repeated episodes of partial network-level organization that do not fully relax back to baseline conditions. These intermittent synchronization episodes suggest a system operating near a critical regime, where collective coherence emerges transiently but fails to stabilize before the final rupture.

Importantly, this characterization is empirical and comparative in nature. It arises from systematic contrasts with matched control days and validated null-model ensembles, and it does not imply universality, deterministic precursors, or predictive capability. Instead, it illustrates how the TAMC-FRANJAMAR framework captures event-specific modes of collective organization within a conservative, retrospective statistical setting.

K.1 Maule 2010: a contrasting collective regime

This subsection summarizes the weakest and least coherent pre-event regime.



(a) Extreme events (b) Aggregate activity and forcing (c) Activity timeline (d) Multistation synchronization

Figure 7: Summary of TAMC-FRANJAMAR observables for the 24 h pre-event window of the 2010 Maule earthquake. (a) Distribution of detected extreme events. (b) Aggregate TAMC-FRANJAMAR activity metrics and external forcing proxies. (c) Temporal evolution of activity and susceptibility. (d) Fraction of simultaneously active stations highlighting multistation synchronization episodes. All panels are generated using identical parameters, station sets, and processing choices as in the Tohoku analysis.

Within the TAMC-FRANJAMAR framework, the 2010 Maule earthquake (Mw 8.8) provides a fully developed counterexample to the sustained synchronization regime identified for Tohoku. Applying the identical analysis pipeline, station selection, and validation procedures reveals a fundamentally different mode of collective pre-event organization in the 24 h preceding failure.

Rather than exhibiting prolonged synchronization–relaxation cycles concentrated within a narrow temporal window, the Maule sequence is characterized by punctuated and heterogeneous activity. Collective organization, when present, remains transient and fragmented, failing to consolidate into a metastable network-wide state. This distinction is evident across all observables summarized in Figure 7.

Aggregate activity and susceptibility metrics remain close to baseline levels for most of the pre-event window, interrupted by intermittent extreme excursions. Unlike the Tohoku case, these excursions do not accumulate into a sustained elevated phase. Instead, they appear as isolated or weakly clustered bursts embedded within an otherwise weakly coherent background. Multistation synchronization episodes are detectable, but they are short-lived, temporally dispersed, and do not organize into a persistent collective regime.

Extreme-event statistics further reinforce this contrast. Although the Maule window contains numerous statistically significant extreme peaks, their temporal distribution lacks the persistence, clustering, and progressive buildup observed in near-critical synchronization regimes. Extreme activity decays rapidly following each burst, indicating partial and localized stress release without long-range temporal organization.

From a system-level perspective, Maule 2010 occupies a distinct region of the TAMC-FRANJAMAR dynamical space—one dominated by intermittent activation rather than metastable collective coherence. The system repeatedly approaches, but does not remain near, a synchronized critical state prior to final rupture. In this sense, Maule demonstrates that large earthquakes can arise from fault systems that never fully enter a prolonged near-critical collective regime.

Importantly, this result is not a failure of the framework but a demonstration of its discriminative capacity. By enforcing identical parameters, station sets, and null-model validation procedures, the TAMC-FRANJAMAR pipeline resolves qualitative differences in collective preparation without event-specific tuning or predictive assumptions.

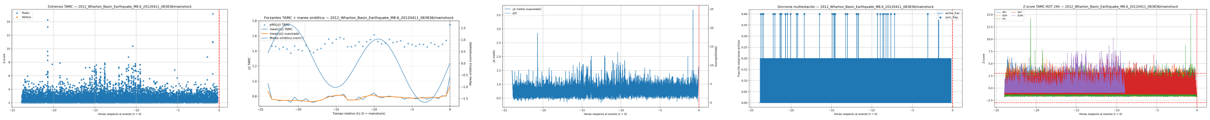
Historically, the Maule earthquake played a central role in motivating the present investigation. The coexistence of abundant extreme activity with the apparent absence of sustained precursory organization raised a fundamental question: can large earthquakes occur without prolonged collective synchronization? The Maule analysis indicates that the answer is affirmative. Together with the Tohoku case, Maule establishes that large-magnitude events may emerge from fundamentally different modes of collective dynamics, underscoring the need for frameworks that characterize diversity rather than seek universal precursors.

As with all results presented here, this interpretation is strictly retrospective and statistical.

No predictive claims are implied. Maule and Tohoku thus form a complementary pair: equally large events, analyzed with identical tools, yet exhibiting sharply distinct collective pre-event regimes.

K.2 Wharton Basin 2012: a stress test for the TAMC-FRANJAMAR framework

Unlike the Tohoku and Maule earthquakes, the Wharton Basin sequence does not display a clear or sustained buildup of multistation synchronization prior to the mainshock. Aggregate activity metrics remain comparatively diffuse, with elevated variability distributed broadly across the pre-event window rather than concentrated into a narrow temporal regime. Extreme events are present, but they appear scattered and weakly organized, lacking the clustering or persistence observed in cases associated with near-critical collective dynamics.



(a) Extreme events (b) Aggregate activity (c) Activity timeline (d) Multistation synchronization (e) Z-score distribution

Figure 8: Summary of TAMC observables for the 24 h pre-event window of the 2012 Wharton Basin earthquake (Mw 8.6). Panels show (a) detected extreme events, (b) aggregate TAMC-FRANJAMAR activity and external forcing proxies, (c) temporal evolution of activity metrics, (d) fraction of simultaneously active stations indicating multistation synchronization, and (e) distribution of station-level Z-scores. In contrast to Tohoku and Maule, the Wharton Basin event exhibits weakly organized, spatially diffuse activity without sustained collective synchronization.

The 2012 Wharton Basin earthquake (Mw 8.6) provides a particularly instructive counterexample within the TAMC-FRANJAMAR analysis, as it represents one of the cases in which the framework exhibits its weakest and least coherent pre-event response. This event is therefore included deliberately, not as a success case, but as a stress test that helps delimit the domain of applicability of the method.

Multistation synchronization indicators further reinforce this contrast. Episodes of elevated active-station fraction occur sporadically, without forming a coherent temporal pattern or progressing toward a metastable synchronized state. In this sense, the system appears dominated by high-dimensional noise-like fluctuations rather than collective organization. From the perspective of the TAMC-FRANJAMAR framework, the Wharton Basin case does not enter a recognizable synchronization–relaxation cycle prior to failure.

This behavior is consistent with the tectonic and geometrical characteristics of the Wharton Basin region, which is dominated by complex intraplate strike-slip faulting rather than a single, strongly coupled megathrust interface. Such configurations are expected to reduce the degree of coherent large-scale coupling across the monitoring network, thereby limiting the emergence of collective precursory dynamics detectable by multistation coherence metrics.

Importantly, this case illustrates a fundamental point of the TAMC-FRANJAMAR philosophy: the framework does not guarantee the presence of organized pre-event dynamics for every large earthquake. Its purpose is not to enforce a universal precursor model, but to characterize, in a consistent and reproducible way, whether a given event exhibits system-level collective behavior that distinguishes it from matched control periods.

In this sense, the apparent "failure" of the framework for the Wharton Basin earthquake constitutes a meaningful result in itself. It demonstrates that the method is sensitive to genuine differences in collective organization across events, and that the absence of a coherent

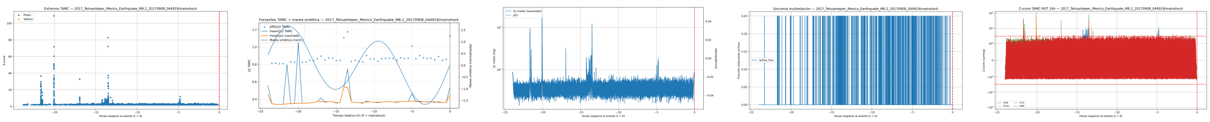
TAMC-FRANJAMAR signature should be interpreted as an empirical outcome rather than as a methodological limitation. Including such cases is therefore essential for avoiding selection bias and for maintaining a conservative, non-predictive interpretation of the results.

The absence of sustained multistation synchronization and the predominance of temporally isolated extreme excursions suggest that the 2012 Wharton Basin earthquake may be governed by a rupture mechanism fundamentally different from those observed in subduction-zone megathrust events. Rather than emerging from a progressively organized collective state, the observed dynamics are consistent with a rapid failure process characterized by weak large-scale coupling and limited precursory reorganization.

A key contribution of the TAMC-FRANJAMAR approach lies in its explicitly collective perspective. By construction, the framework does not seek information in isolated stations, individual anomalies, or single observables, but in the coherence structure emerging across the network as a whole. This system-level viewpoint enables the identification of distinct dynamical regimes that are not readily accessible through traditional single-station or event-centric analyses.

Accordingly, the results presented here are not intended to replace existing seismological interpretations, but to complement them by revealing aspects of collective organization and breakdown that remain invisible when the system is decomposed into independent components.

K.3 Tehuantepec 2017: intermittent organization and fragmented coherence



(a) Extreme events (b) Aggregate activity and forcing (c) Activity timeline (d) Multistation synchronization (e) Multistation Z-score

Figure 9: Summary of TAMC-FRANJAMAR observables for the 24 h pre-event window of the 2017 Tehuantepec (Mexico) earthquake. (a) Distribution of detected extreme events. (b) Aggregate TAMC-FRANJAMAR activity metrics and external forcing proxies. (c) Temporal evolution of activity and susceptibility. (d) Fraction of simultaneously active stations highlighting intermittent multistation synchronization. (e) Multistation Z-score illustrating the absence of sustained collective amplification. All panels are generated using identical parameters, station sets, and processing choices as in the previous case studies.

Intermittent organization and fragmented coherence. Within the TAMC-FRANJAMAR framework, the 2017 Tehuantepec (Mexico) earthquake (Mw 8.2) exhibits a collective behavior that differs markedly from both the sustained synchronization regime observed for Tohoku and the largely unorganized dynamics identified for the Wharton Basin event. Instead, this case is characterized by an intermittent and spatially fragmented form of collective organization.

The pre-event window shows repeated episodes of elevated aggregate activity and extreme excursions, but these episodes are not accompanied by persistent multistation synchronization. Rather than forming a coherent, system-wide organized state, synchronization appears sporadic and uneven, with brief clusters of coordinated activity embedded within an otherwise heterogeneous background. This contrasts with the quasi-metastable collective regime observed prior to Tohoku and with the predominantly isolated extreme behavior observed for Wharton Basin.

The multistation synchronization metrics indicate frequent activation of subsets of the network, yet without convergence toward a stable or sustained collective phase. In this sense, the system appears capable of transient coordination but unable to maintain it across the full network or over extended periods. Such behavior is consistent with a regime of partial coupling, in which local or regional coherence emerges intermittently but does not propagate into a global collective state.

From a dynamical perspective, this places the Tehuantepec event in an intermediate regime between organized criticality and abrupt, weakly coupled failure. The presence of multiple extreme excursions and elevated activity levels suggests significant internal stress and reconfiguration, but the lack of sustained multistation coherence indicates that these processes do not culminate in a unified collective organization prior to rupture.

Importantly, as in the previous cases, this interpretation is strictly empirical and comparative. The TAMC-FRANJAMAR framework does not assign predictive meaning to individual anomalies or isolated patterns. Instead, the Tehuantepec case highlights how different tectonic settings and rupture mechanisms can manifest distinct modes of collective behavior when examined through a multistation coherence lens.

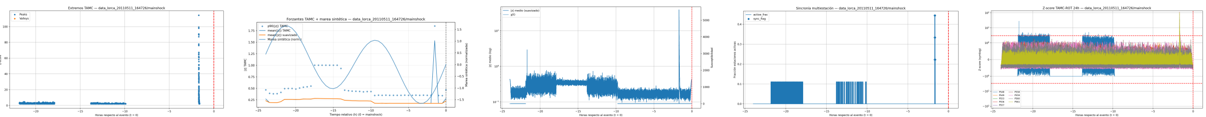
Taken together, the contrast between Tohoku, Maule, Wharton Basin, and Tehuantepec underscores a central contribution of the TAMC-FRANJAMAR approach: its ability to discriminate between qualitatively different collective regimes without relying on event-specific tuning or post hoc interpretation. The observed diversity of pre-event dynamics reinforces the view that large earthquakes cannot be characterized by a single universal preparatory pattern, but rather by a spectrum of collective organizational modes shaped by underlying physical processes.

K.4 Lorca 2011: an unexpected collective signature in a moderate local event

The 2011 Lorca earthquake (Spain) provides a particularly informative stress test for the TAMC–FRANJAMAR framework because it lies far from the typical target class of giant subduction megathrusts. In fact, this event was initially selected precisely as a likely *null* example: a moderate, shallow, local earthquake for which we expected that any multistation coherence would be weak, short-lived, or absent under the same fixed processing conditions applied to the larger events.

Contrary to that expectation, the Lorca case exhibits structured, event-related organization across the network when the observables are read jointly. The system does not display the prolonged and highly persistent synchronization regime observed for Tohoku, nor the strongly punctuated behavior found in some other large events. Instead, Lorca is characterized by *intermittent* collective episodes: localized bursts of synchronization and extreme excursions appearing in separated temporal windows, suggesting transient phases of coupling rather than a single sustained pre-event regime.

This result is important for two reasons. First, it supports the conservative interpretation that an apparent "absence" or "presence" of a TAMC signature is itself an empirical outcome, not a guarantee of success or failure of the method. Second, it shows that the collective perspective can reveal coherent structure even in comparatively small events, where single-station interpretations may be dominated by local noise, site effects, or heterogeneous station behavior. As throughout this appendix, the panels below should be interpreted comparatively and relationally—as complementary projections of the same underlying collective dynamics—rather than as independent evidentiary elements.



(a) Extreme events (b) Aggregate activity and forcing (c) Activity timeline (d) Multistation synchronization (e) Multistation z-scores

Figure 10: Summary of TAMC observables for the 24-hour pre-event window of the 2011 Lorca (Spain) earthquake. (a) Distribution of detected extreme excursions. (b) Aggregate TAMC activity metrics and external forcing proxy. (c) Temporal segmentation of collective activity/susceptibility phases. (d) Fraction of simultaneously active stations highlighting intermittent multistation synchronization episodes. (e) Station-resolved standardized activity (z-scores) showing heterogeneous yet coordinated bursts. All panels are generated using the same fixed parameters and standardized processing conditions as in the main cases, and should be interpreted jointly as complementary projections of the collective state.

The 2011 Lorca earthquake (Mw 5.1) was deliberately selected as a challenging test case for the TAMC–FRANJAMAR framework. Unlike the large subduction and intraplate earthquakes analyzed elsewhere in this study, Lorca represents a moderate-magnitude, shallow, and spatially localized event occurring within a relatively dense regional seismic network. From a methodological standpoint, this type of event was initially expected to provide an example in which no meaningful multistation synchronization would emerge.

The motivation for including Lorca was therefore explicitly conservative. Given its limited rupture size, short preparation time, and strong local character, the event appeared well suited to illustrate a scenario in which the framework would fail to detect collective organization, thereby reinforcing its non-universal and non-predictive nature.

Contrary to this expectation, the analysis reveals the presence of nontrivial collective behavior in the 24 hours preceding the mainshock. While the overall level of synchronization is weaker and less persistent than in large megathrust events such as Tohoku or Maule, the network exhibits clear episodes of coordinated extreme activity involving multiple stations. These episodes are temporally structured and cannot be reduced to isolated single-station anomalies.

The synchronization phases observed for Lorca are characterized by short-lived but recurrent bursts of coherence, interspersed with relaxation intervals. This pattern differs markedly from the sustained synchronization–relaxation cycles seen in Tohoku, as well as from the largely incoherent behavior observed in the Wharton Basin case. Instead, Lorca appears to occupy an intermediate regime, in which collective effects are present but constrained by spatial scale and event magnitude.

Importantly, the detection of collective organization in this case should not be interpreted as evidence of a precursor in the classical sense, nor as an indication of predictive capability. Rather, it demonstrates that the emergence of multistation coherence is not restricted to great earthquakes, and that even moderate events may involve system-level reorganization detectable at the network scale.

From a broader perspective, the Lorca case highlights a central strength of the TAMC–FRANJAMAR framework: its ability to falsify expectations. The framework does not assume that synchronization must be present, nor does it privilege positive detections. Instead, it provides a unified statistical language in which both the absence and the unexpected presence of collective behavior carry interpretive value.

Including Lorca therefore serves a dual purpose. Methodologically, it reduces selection bias by incorporating an event chosen precisely because it was expected to “fail.” Substantively, it suggests that collective dynamics may play a role across a wider range of earthquake sizes and tectonic settings than commonly assumed, albeit with distinct signatures and limitations.

As in all cases presented in this work, the Lorca results are interpreted strictly in a retrospective and statistical sense. They illustrate how the framework responds to real data under fixed parameters, without implying universality, causality, or forecasting relevance.