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Key Points:
- Earthquakes cluster in time according to an event characteristic timescale, renewal interval
- Emergent organization of earthquake timing without direct triggering is consistent with nonlinear interactions among earthquakes
- Time-dependent probability related to such clustering could improve forecasting skill

Supporting Information:
- Supporting Information S1
- Data Set S1

Correspondence to:
R. Bendick,
bendick@mso.umt.edu

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Evidence for Synchronization in the Global Earthquake Catalog

R. Bendick[1] and D. Mencin[2]

[1]Department of Geosciences, University of Montana, Missoula, MT, USA, [2]CIRES, University of Colorado Boulder, Boulder, CO, USA

Abstract Phase alignment (synchronization) is a generalized property of interacting oscillators. If such interactions apply to earthquakes, they should manifest as time-dependent variations in earthquake productivity organized according to a characteristic elastic loading period. Defining this period as renewal interval, the time required to accumulate the elastic potential energy released in a rupture, gives a consistent scaling property that can be used to search for temporal organization. We test for the expected structure in earthquake productivity using three different statistical tools optimized for different temporal sensitivities: Schuster spectra for events with short renewal intervals (0–25 years), Fourier power spectra for events with short and intermediate renewal intervals (0–100 years), and topological data analysis (TDA) for events with long renewal intervals (>100 years). All three indicate that earthquakes are organized in time according to renewal interval. Accounting for such unsteady temporal organization may improve forecasting skill by providing time-dependent event probabilities.

Plain Language Summary Earthquakes can be thought of as elastic objects that store potential energy as they are loaded over time by tectonics and then release that stored energy during rupture. This loading and unloading cycle defines a characteristic timescale for an earthquake, its renewal interval. Generalized systems of many objects of this type are known to have nonlinear interactions over many cycles of loading and unloading that lead to patterns of events in time, such that events with similar natural periods become synchronized. We test for these interactions in earthquakes by sorting the global earthquake catalog by renewal interval and then testing whether events with similar renewal intervals tend to occur closer together in time than would be expected for independent event occurrence.

1. Introduction

Numerous investigators have drawn attention to quasiperiodic temporal structure in earthquake catalogs and the possibility of event triggering by time-dependent loading processes, from seasonal hydrologic loading (Ader & Avouac, 2013; Bettinelli et al., 2008; Bollinger et al., 2007; Johnson et al., 2017) to changes in Earth's rotation rate (Anderson, 1974; B. Levin et al., 2017; Levin & Sasarova, 2015a, 2015b, 2017) or solid earth tides (e.g., Bodri & Iizuka, 1989; Cochran et al., 2004; Ide et al., 2016; Métivier et al., 2009). More broadly, quasiperiodic decadal fluctuations in global seismicity have been reported in many studies without a specific physical mechanism (Kanamori, 1977; Liritzis & Tsapanos, 1993; Milne, 1881; Pines & Shaham, 1973; Press & Briggs, 1975; Riguzzi et al., 2010; Shanker et al., 2001). Simulated earthquake catalogs also demonstrate emergent periodicity (Ader et al., 2014; Richards-Dinger & Dieterich, 2012; Sammis & Smith, 2013; Zahn & Shearer, 2015). This work builds on a hypothesis of nonlinear interactions proposed in Bendick and Bilham (2017) to show that temporal structure related to a characteristic earthquake timescale (renewal interval) occurs over a wide range of moment magnitudes.

Highly nonlinear systems of many mechanically coupled elements are responsive to extremely small time-dependent stress variations especially if they are repeating or quasiperiodic (e.g., Abrams & Strogatz, 2006; Kuramoto & Battogtokh, 2002; Mertens & Weaver, 2011). Considering earthquakes to be analogous to integrate-and-fire units, such that fault patches are "loaded" or "charged" with elastic potential energy over some finite time and then "discharge" that energy in an earthquake, we hypothesize time-dependent earthquake productivity arising either from self-organization or nonlinear sensitivity to entrainment by an external force (Corral et al., 1995; Ritt, 2003). In this manuscript, we define a loading timescale as *renewal interval*, the time required to store the elastic potential energy released as finite strain in an event of a given magnitude. Elsewhere this is called the minimum time between [full] ruptures (Cattania, 2019; Hawthorne & Rubin, 2013) and defines a characteristic temporal scaling of earthquake "cycles" that has a clear physical basis and is less sensitive to sampling bias than recurrence interval. We test for patterns in the global earthquake catalog consistent with interactions by looking for temporal variations in productivity (manifest as number of events in a given year, preferred interevent intervals, or clustering in time) that depends on renewal interval. The period of cycles in productivity should then be proportional to renewal interval, such that event productivity period is longer for events with longer renewal intervals. Tests of this relationship are complicated by limitations on completeness and duration of the global instrumental earthquake catalog, requiring different statistical approaches for different renewal intervals.

2. Methods

In order to look for synchronization, we require information about both the absolute timing and the renewal interval of individual earthquakes, for as many events over the longest sampling duration possible. Thus, we seek the most comprehensive, longest available earthquake catalog and apply consistent methods for estimating renewal interval to all events over a magnitude threshold. We apply three different numerical techniques to test for temporal structure dependent on renewal interval, specifically time-dependent variations in the number of events, overrepresented interevent intervals, or clustering of events in absolute time. The techniques differ in their resolution and spectral sensitivity, such that in the aggregate they provide complementary information with high precision at short periods as well as sensitivity to periods much longer than the catalog duration.

2.1. Catalog Considerations and Timing

We use the 2018 ISC-GEM release (Di Giacomo et al., 2018; Storchak et al., 2013). To test the completeness of the catalog, we plot the annual earthquake count for different magnitudes in 0.2 Mw increments on a log linear graph for the period 1905–2017 (Figure S1 in the supporting information). If the catalog were complete, and a Gutenberg-Richter relationship prevailed, the resulting time series should have similar peaks and troughs separated by a factor of two on the seismicity rate axis. Annual counts track each other well for magnitudes $6.6 < Mw < 7.2$, but the range of self-similarity is substantially impaired before the introduction of the worldwide standard seismic network (WWSSN) in the 1960s. Several other artifacts in the data are obvious: $Mw \leq 6.5$ earthquakes increasingly escape detection early in the catalog, and WW2 resulted in a reduction in the detection of $Mw < 6.2$ earthquakes. In contrast, the catalog is mostly complete for $Mw > 7$ earthquakes (Michael, 2014). The ISC-GEM event count increases monotonically with time ($\approx +5$ earthquakes per century) probably as a result of changes in the assignment of magnitudes. Aftershock sequences also strongly influence observed annual global seismicity rates (Shearer & Stark, 2011) and therefore produce highly significant clustering and periodicity in the raw catalogs (Figure S7). There is no clear consensus on the best algorithm for removing sets of aftershocks (e.g., Hainzl et al., 2006; Zaliapin & Ben-Zion, 2013; Zhuang et al., 2002); we use Reasenberg's (1985) declustering algorithm on the global ISC-GEM $Mw \geq 5.5$ data. This approach simply replaces sets of events within a specified time and space window with a single event. The resulting catalog (18,660 events) contains absolute timing information and other event characteristics and is provided as supporting information.

2.2. Renewal Interval

In order to convert event moment magnitudes to renewal interval, we follow the process in Bendick and Bilham (2017) with some additional assumptions for smaller events. For each catalog event, we use the scaling rule from Leonard (2010) to estimate mean slip from magnitude. We then use the event location to estimate the maximum tectonic loading rate based on the GSRM2.1 plate motion model. We apply a coupling coefficient (i.e., the proportion of the tectonic loading rate that is accommodated seismically) using estimates from Berryman et al. (2015) where available and the regional tectonic literature where Berryman et al. do not provide an estimate. For events that do not fall on a well-established tectonic boundary (e.g., 636 events in the Asian interior), we use a default loading rate of 5 mm/yr and complete coupling (coupling coefficient = 1.0). These events constitute less than 5% of the catalog and have very long renewal intervals because of their low loading rate. Finally, we calculate the nominal renewal interval as the mean event slip divided by the loading rate times the coupling coefficient, $R = \frac{D}{cv}$. This approach, especially for the smaller events, gives

10.1029/2020GL087129

an imperfect approximation of the renewal interval because it makes two major assumptions about the seismicity: that plates are perfectly rigid away from a rupturing fault and that all of the relative tectonic velocity is accommodated on the rupturing fault patch. Neither of these assumptions is completely true, and relaxing either would increase the renewal interval, sometimes by as much as 2 orders of magnitude. In addition, uncertainty or time dependence of the coupling coefficient could change renewal interval by as much as an order of magnitude. However, there is no other obvious systematic way to estimate renewal interval for events down to *Mw* 5.5, and such estimates are likely to be correct relative to one another (longer vs. shorter) even if the absolute renewal interval is underestimated. The algorithm allows each event in the catalog to be assigned a renewal interval, which we interpret as a characteristic timescale for that event, analogous to the period of a standard oscillator. The method allows us to maximize the event data available for statistical analyses, and we complement it by choosing analysis methods assuming that the individual renewal intervals have high uncertainties and that many events may be missing. Finally, we sort events according to their calculated renewal intervals and create subcatalogs of events with renewal intervals in four ranges: short renewal (1–25 years), intermediate renewal (25–50 years), long renewal (50–100 years), and very long renewal (>100 years).

2.3. Schuster Spectra

We calculate Schuster spectra using the approach of Ader and Avouac (2013) for each renewal interval subcatalog. The Schuster approach is designed to quantify the statistical significance of periodicity in catalogs with a lot of temporal variability and, for such catalogs, the full Schuster spectrum is preferable to a Schuster test (Ader & Avouac, 2013). The approach compares the observed interevent times for every pair of events to a bootstrapped probability distribution of interevent times derived from a random walk. With a sufficiently large catalog, the Schuster spectrum can differentiate among periodic terms with very similar periods and provides rigorous confidence intervals for spectral peaks. However, because it bootstraps the p values compared to a null hypothesis derived from the input catalog, power at longer periods cannot be accurately resolved. Based on tests using synthetic series with specific spectral content (e.g., Figure S7), on tests of decimated catalogs (Figure S9), and on the theoretical limit of resolution given the catalog duration, that Schuster spectra do not reliably resolve periods longer than ~(1/4) of the total time series length and the shortest resolvable period is sensitive to the total number of events in the catalog. The Schuster spectra therefore have high resolution in the binned event catalogs, but only for interevent periods ≤25 years.

2.4. Fourier Spectra

Fourier power spectra, the most traditional means of identifying periodic terms in time series, are calculated for the time series of event productivity of each subcatalog. These time series are generated by calculating the number of events in each subcatalog in each calendar year. Fourier spectral methods deconvolve discrete time series into a sum of periodic terms (sines and cosines) and use the amplitude of each term to determine the power at each frequency. These methods can resolve periods up to the length of the event catalog and are less sensitive to the number of events in each bin but are much less precise than the Schuster analyses for noisy or partially incomplete series. Furthermore, Fourier methods do not formally propagate uncertainties (although they can be bootstrapped), so there is no formal confidence interval. We calculate Fourier spectra for time series of the number of events in each year in subcatalogs as for the Schuster spectra (1–25, 25–50, 50–100, and >100 years) (Figure S4). Prior to transformation, the series are detrended by subtracting a linear term calculated using least squares, in order to remove power introduced by time-dependent catalog completeness.

2.5. Topological Data Analysis

Finally, since neither of the spectral methods can resolve periods longer than the duration of the earthquake catalog, we use a topological method to identify and characterize temporal clustering of events by renewal intervals. This approach calculates an N-dimensional shape, or topology, in which distances and connections between sets of events quantify the similarity of their observational properties and the persistence of similarity within groups. Such methods are highly effective at identifying groups of events that share many characteristics or have unique properties, even if other measured properties are not sorted in the same way or are distributed stochastically (Carlsson, 2009). The topological data analysis (TDA) simultaneously assesses absolute timing and renewal interval of events, hence directly quantifies whether events whose

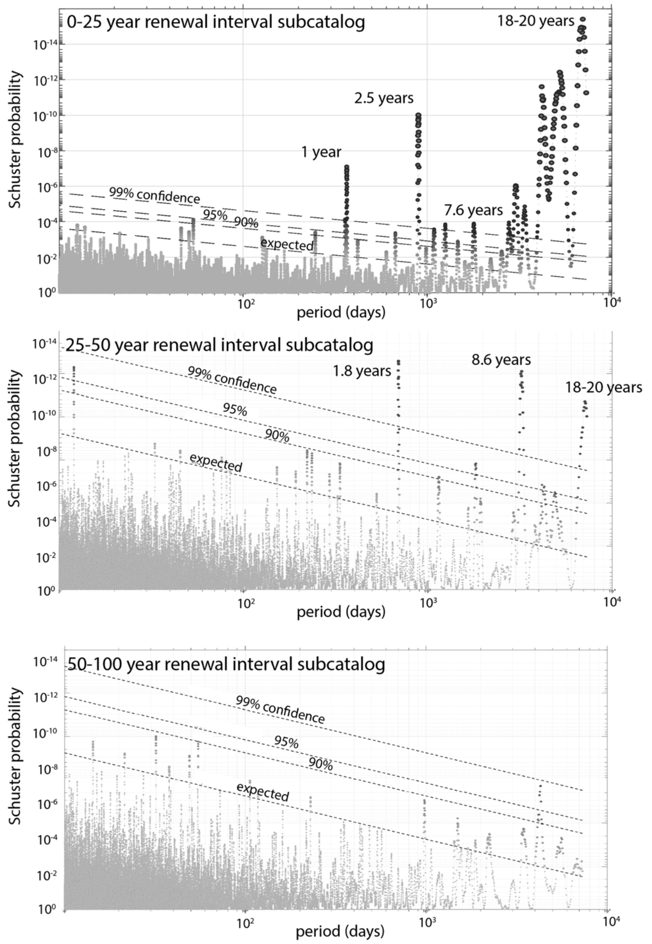

Figure 1. Schuster spectra for subcatalogs of events by nominal renewal interval. The shortest renewal interval events show large numbers of events separated from each other by a year as well as several other statistically significant interevent intervals matching renewal intervals (top), intermediate renewal events have fewer and longer significant interevent intervals (middle), and the longest renewal events have no significant interevent interval bias within the resolution band of the method (bottom).

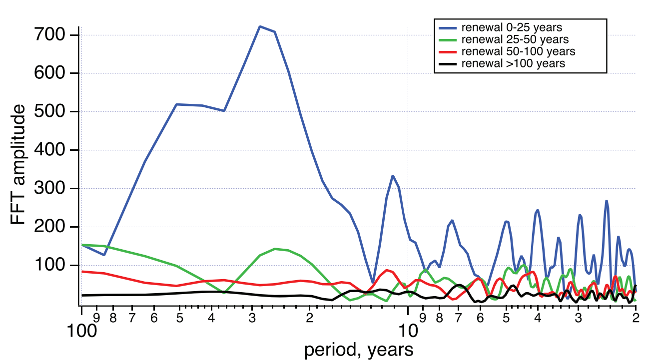

Figure 2. Power spectra of the detrended event counts by year for four earthquake subcatalogs by renewal interval.

renewal intervals are similar also occur more closely together in time than expected for stochastic or Poisson event occurrence but the method does not calculate a time-dependent productivity period. The statistical significance of topological distance is reported as *p* values and Kolmogorov-Smirnov values (a nonparametric measure of likelihood). The longest interval events, if they have renewal dependent productivity as hypothesized, should appear as distinct temporal clusters of events with similar renewal interval. We implement the cluster analysis using the SymphonyAyasdiAI computing environment. As with the Schuster method, the topological analysis is optimized for noisy and incomplete data.

3. Results

We observe statistically significant time dependence of earthquake productivity depending on renewal interval for events over 3 orders of magnitude in renewal interval, although doing so requires the variety of statistical methods described above because of differences in resolution and sensitivity of the various approaches. Some of the significant periods recur across methods of analysis (Table S1).

3.1. Schuster Spectra

The Schuster spectra demonstrate statistically significant periodicity of interevent interval for events with renewal intervals from 0–50 years. This means that many more events have the significant interevent times than expected for random walk event occurrence. The number of significant periods and the shortest significant period varies with renewal interval (Figure 1). Specifically, the subcatalog containing the shortest renewal events (renewal <25 years), has at least 10 different periods with confidence >99%, including an annual component, (more events are separated by a year than in the null case), one at ~2.5 years, and several more at periods between 8 and 20 years. This is consistent with our hypothesis that events with renewal intervals of 0–25 years should have periodic variations in productivity with periods of 0–25 years leading to systematic patterns in interevent intervals if they are either entrained by external forcing, such as seasonal hydrologic loading or orbital loading in the case of the annual cycle, or self-organized into sets of events with similar renewal interval. It is possible that some of the power at the shortest periods in the Schuster spectra also represents some sets of aftershocks incompletely removed by the choice of declustering algorithm. Intermediate renewal events (25–50 year renewals) still display three statistically significant (>99% confidence) peaks in the Schuster spectrum, with the shortest period approximately twice as long as observed for the shortest renewal events and a well-resolved peak at 20 years. Finally, for events with renewal intervals greater than 50 years, we observe no statistically significant interevent periodicity within the window of resolution of the method (≤25 years).

3.2. Fourier Spectra

The Fourier results are complementary to the Schuster spectra. The time series of annual event productivity for the short renewal interval (1–25 years) subcatalog indicates power at frequencies also identified in the Schuster spectrum (2.5, 7.2, 11, and around 20 years) with additional resolved peaks at 3, 4, 5, and 28 years (Figure 2). The modal renewal interval in the bin is 4.2 years. Annual event productivity of intermediate

10.1029/2020GL087129

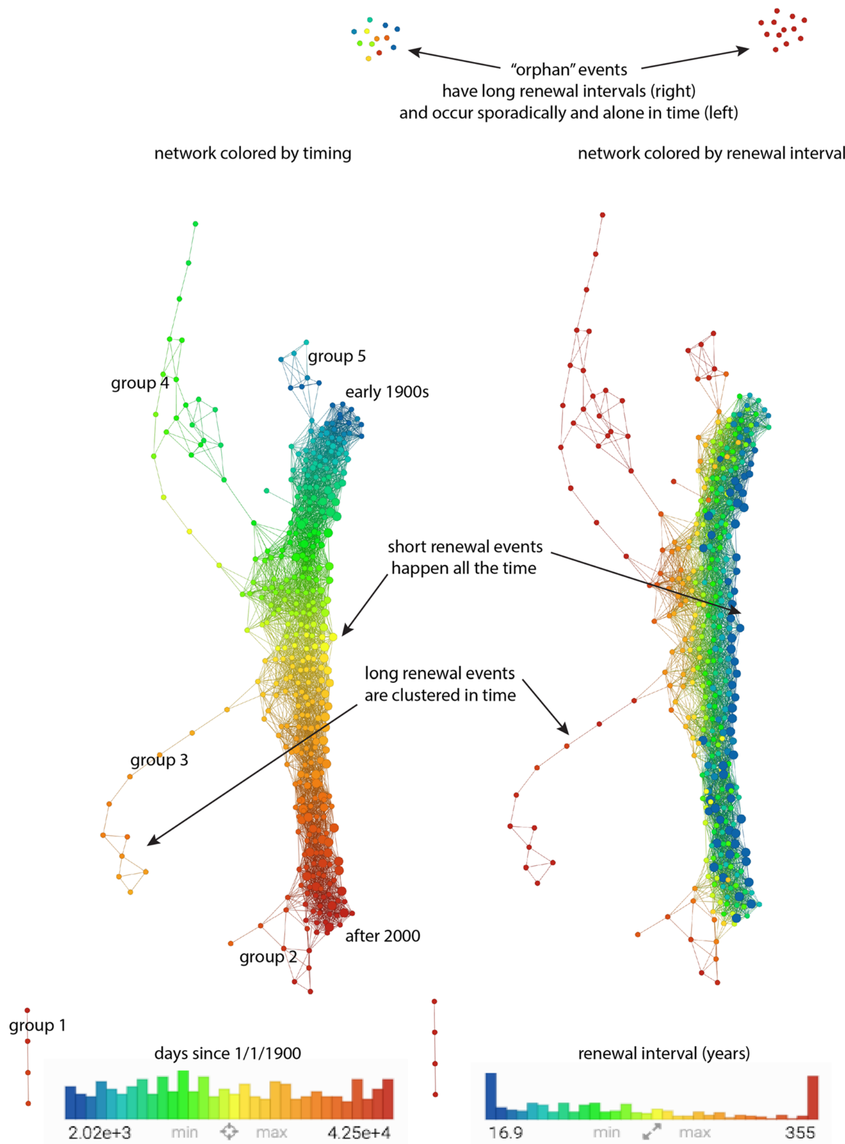

Figure 3. Topological network of the whole catalog using a variance normalized Euclidean metric operating on the L-infinity centrality, which calculates the maximum distance between each event and the most distant event in the catalog, and on the Gaussian density, which applies a Gaussian density estimator kernel over the distribution of all event characteristics. The longest renewal interval events are strongly clustered, with many events of similar renewal interval occurring at discrete short time intervals and strongly separated from the rest of the catalog with respect to their properties. Labeled groups correspond to the statistics listed in Tables 1 and S2. "Orphan" events are single long renewal events that occur alone in time in the catalog. Note that short renewal events occur at all times in the catalog, hence are not temporally clustered, although some organization of similar renewal events in time is revealed in the higher resolution topological networks for subsets of the catalog sampled by renewal.

renewal interval events (25–50 years) has peaks in power at 3.2, 4.5, 9, and 25 years; the latter two correspond to peaks in the Schuster analysis within uncertainties. The power spectrum for productivity of the longest renewal interval events has no significant power within the resolution of the technique. Table S1 compares productivity periods identified using different techniques.

3.3. Topological Analyses

The topological data analyses show a systematic trend of increasingly strong event clustering in time for longer renewal interval events. Specifically, the shortest renewal interval events (0–25 years) occur at all

Table 1
Basic Metrics for Event Clusters in Figure 3

	Average *R*	Median date	Number of events	K-S for t	K-S for R	*p* value for *t*	*p* value for *R*
					versus rest of catalog		
Group 1	518.9	2006	5	0.795	0.998	3.54E−03	8.80E−05
Group 2	215.8	2010	56	0.724	0.975	5.37E−13	5.40E−13
Group 3	400.9	1978	14	0.444	0.996	7.56E−03	1.65E−12
Group 4	454.3	1938	35	0.665	0.995	2.68E−13	5.37E−13
Group 5	320.8	1911	17	0.961	0.99	3.79E−13	5.37E−13

Note. K-S is the Kolmogorov-Smirnov score for the events in the cluster compared to the remainder of the earthquake catalog for timing (t) or renewal interval (R). P values are the probability of the group being randomly drawn from the entirety of the catalog.

times in the catalog. A topological network of these events based on a variance normalized Euclidean metric (N-dimensional Euclidean distance) on parameters derived from event timing and renewal interval is nearly homogeneous, showing nearly steady event productivity in time (although the Schuster spectra show significant biases in interevent intervals) (Figure S10). In contrast, subcatalogs of longer renewal interval events (25–50, 50–100, and >100 years) with the same analysis metric and parameters show more and more distinct temporal clustering with lengthening renewal, with the longest renewal interval events organized into five distinct sets: 17 events with average renewal interval of 321 years centered on 1911, 35 events with average renewal interval of 454 years centered on 1938, 15 events with average renewal interval of 401 years centered on 1978, 5 events with average renewal interval of 519 years centered on 2006, and 55 events with average renewal interval of 216 years centered on 2010 (Figure 3), including the Sumatra, Japan, and Chile megaquakes. These clusters differ statistically from one another at extremely high levels of confidence (Tables 1 and S2) and are separated from one another by long time spans with few or no such long renewal interval events. They consist of sets of events with similar renewal intervals that happen very close together in time, with the stated year the year of the middle event in the set.

4. Conclusions

Sets of integrate-and-fire oscillators are expected to have quasiperiodic fluctuations in productivity that arise either as a consequence of self-organization or response to external forcing. Specifically, sets of oscillators with similar charging intervals fire together, and do so at periods similar to the length of the charging interval. This synchronization is intrinsic to how emergent systems such as brains and lasers work. The presence of time-dependent event productivity in earthquakes organized by renewal interval is consistent with such organization. The salient observations are that the shortest renewal interval events have statistically significant periodic fluctuations in occurrence, with preferred interevent intervals similar to renewal intervals. The longest renewal interval events are strongly clustered in time, consistent with time-dependent cycles longer than the catalog duration. Evaluating the whole catalog without segregation by renewal interval would show little or no temporal clustering (e.g., Michael, 2011a, 2011b) because all of these sets of events are stacked with arbitrary phase.

The presence of multiple significant variations in productivity in the short and intermediate renewal interval subcatalogs reflects the fact that even the subsampled bins of events include sets of events with many different characteristic renewal intervals. Furthermore, our estimates of renewal interval are imprecise, especially for smaller-magnitude events that may occur on faults with unknown slip rates and coupling coefficients. The three different statistical approaches have different sensitivity to variable productivity: Schuster spectra appear to have the highest resolution but detect only periods of 1/4 of the catalog duration or less, Fourier spectra have lower resolution but can detect periods up to the catalog length, and topological analyses are insensitive to stacked periodicity but reveal temporal clustering of events with renewal intervals longer than the catalog duration. Some of the observed productivity structure at the shortest periods for the shortest renewal events may arise from incompletely removed aftershock sequences (e.g., Figure S8), as aftershock sequences consist of large numbers of events separated by little elapsed time. However, many significant intervals identified in both the Schuster and Fourier spectra (Figures 1 and 2) are longer than expected for aftershock sequences. For the TDA results, the temporal structure suggests time-dependent grouping of events at intervals of hundreds of years, much longer than aftershock sequences. We interpret these results to indicate that time-dependent and renewal-dependent earthquake productivity does not arise solely from aftershock sequences.

The overall structure of unsteady event occurrence in time dependent on renewal interval is as expected for synchronized or entrained quasiperiodic oscillators with many different natural periods. This means that the global catalog is consistent with nonlinear interactions among earthquakes, not that unsteady event occurrence definitively proves synchronization. Regardless of a causative mechanism, the result offers potential improvements in empirical earthquake forecasting skill through three pathways that leverage the temporal structure. First, small events and events in highly active tectonic regions may have directly measurable periodicity or regularized interevent intervals, so that the probability of events varies in a quantifiable way in time. That is, the probability of events with a given renewal interval can be considered quasiperiodic, and peaks and troughs in earthquake productivity can therefore be forecast from dominant interevent intervals and phase alignment. Second, the likelihood of large and rare events, those with the longest renewal intervals, appears to increase following an initial event of the given renewal interval, although single "orphan" events also occur in the catalog. Temporal clusters of long renewal events imply that the probability of similar events should increase following an initial large rare event, a useful relationship for risk forecasting. The most notable shortcoming of this outcome is that the empirical synchronization approach provides no useful constraints on the location of events in a developing cluster; they occur globally (Bendick & Bilham, 2017). Synchronization finally implies that small-magnitude events in areas of high tectonic velocities should be particularly sensitive to annual hydrologic and tidal loading, such as is observed for microseismicity in the Himalaya, Southern California, and Cascadia; that regions with faster relative plate velocities, hence shorter renewal intervals for a given magnitude event, have systematically shorter period clustering than those with slower relative plate velocities (Figure S6) and that very large and rare events occur more closely together in time than expected from random walk or Poisson event distributions.

Data Availability Statement

The earthquake catalog used for this analysis is available from ISC-GEM (at http://www.isc.ac.uk/iscgem/). The reduced declustered catalog with calculated renewal intervals is provided as supporting information.

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