Pervasive foreshock activity across southern California

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Abstract

Foreshocks have been documented as preceding less than half of all mainshock earthquakes. These observations are difficult to reconcile with laboratory earthquake experiments and theoretical models of earthquake nucleation, which both suggest that foreshock activity should be nearly ubiquitous. Here we use a state-of-the-art, high-resolution earthquake catalog to study foreshock sequences of magnitude M4 and greater mainshocks in southern California from 2008-2017. This highly complete catalog provides a new opportunity to examine smaller magnitude precursory seismicity. Seventy percent of mainshocks within this catalog are preceded by foreshock activity that is significantly elevated compared to the local background seismicity rate. Foreshock sequences vary in duration from several days to weeks, with a median of 16.6 days. The results suggest that foreshock occurrence in nature is more prevalent than previously thought, and that our understanding of earthquake nucleation may improve in tandem with advances in our ability to detect small earthquakes.

1 Introduction

There has long been an underlying tension between two competing observations of earthquake occurrence. From one perspective, the occurrence of large earthquakes within a fault zone appears random in time, and indeed classical models of earthquake hazard are based on a Poisson process that encodes this random, memoryless behavior by assumption (Baker, 2013). In contrast, one of the most striking characteristics of earthquakes is that they tend to cluster in space and time, with the triggering of aftershocks following larger, mainshock earthquakes being the best-studied example. The physical mechanisms driving aftershock occurrence are reasonably well-understood, at least a high level: slip on the mainshock fault interface imparts both static (King et al., 1994; Lin & Stein, 2004; Stein, 1999) and dynamic (Brodsky, 2006; Gomberg & Davis, 1996; Kilb et al., 2000; Velasco et al., 2008) stress changes in Earth's crust that trigger aftershock activity. Postseismic fault slip, subcrustal viscoelastic relaxation, and poroelastic stress transfer may also play an important role in certain circumstances (Freed, 2005; Freed & Lin, 2001; Koper et al., 2018; Ross et al., 2017).

Foreshocks – earthquake occurrences preceding mainshocks – are less well understood. While it is unambiguous that foreshocks do occasionally occur, both their physical significance and their relative prevalence are subject to vigorous debate (Ellsworth & Bulut, 2018; Seif et al., 2019; Shearer & Lin, 2009; Tape et al., 2018). In laboratory earthquake experiments, precursory slip events analogous to foreshocks are observed in nearly all instances (Bolton et al., 2019; Johnson et al., 2013; Rouet-Leduc et al., 2017; W. Goebel et al., 2013). Likewise, theoretical models of fault friction, including the widely used rate-and-state framework, typically require a seismic nucleation phase preceding dynamic rupture (Ampuero & Rubin, 2008; Dieterich, 1994; Marone, 1998). These facets of laboratory and theoretical earthquake behavior suggest that foreshock occurrence may be a natural manifestation of a nucleation or preslip process preceding rupture (Bouchon et al., 2013; Dodge et al., 1996). This interpretation if correct would have important scientific and practical consequences, and would intimate that foreshocks could potentially be used to forecast characteristics of eventual mainshock occurrence.

One problem with this interpretation is that foreshock activity in nature is not observed as frequently as it should be if it were a universal feature of earthquake nucleation. While it is notoriously difficult to compare different foreshock studies due to different magnitude thresholds or space-time selection windows (Reasenberg, 1999), foreshocks have previously been observed to precede 10-50% of mainshocks (Abercrombie & Mori, 1996; Chen & Shearer, 2016; Jones & Molnar, 1976; Marsan et al., 2014; Reasenberg, 1999). Taking these observations at face value, what happens during the nucleation process of the other 50 to 90% of earthquakes? Are there really no foreshocks, or are we simply not listening closely enough to detect them? The notion that there exists undetected but substantial foreshock activity is supported by a recent meta-analysis of 37 different studies of foreshocks (Mignan, 2014), which revealed systematic differences in the outcome depending on the minimum magnitude of foreshock detected. A similar effect can be seen in laboratory experiments, as the ability to forecast imminent laboratory earthquakes depends fundamentally on the magnitude of completion of precursory slip events (Lubbers et al., 2018).

In this study, we measure foreshock activity using a powerful new tool: a state-of-the-art earthquake catalog (Ross et al., 2019) of more than 1.81 million earthquakes that occurred in southern California from 2008 through 2017. The extraordinary detail of this catalog, which is complete regionally down to M0.3 and locally down M0.0 or less, allows us to examine precursory seismicity at the smallest of scales, in direct analog to well-recorded laboratory experiments. We find that elevated foreshock activity is pervasive in southern California, with 70% of earthquake sequences exhibiting a significant, local increase in seismicity rate preceding the mainshock event. The spatiotemporal evolution of these sequences is diverse in character, a fact which may preclude real-time forecasting based on foreshock activity. Nevertheless, these results help bridge the gap in our understanding of precursory activity from laboratory to Earth scales.

2 Earthquake Catalog Data

We analyze earthquake sequences in southern California derived from the Quake Template Matching (QTM) earthquake catalog(Ross et al., 2019). This recently released catalog of southern California seismicity from 2008 – 2017 was compiled using approximately 284,000 earthquakes listed in the Southern California Seismic Network (SCSN) catalog (Hutton et al., 2010) as templates for network-wide waveform cross-correlation (Gibbons & Ringdal, 2006; Shelly et al., 2007), yielding more than 1.81 million detected earthquakes. The vast majority of these newly detected earthquakes are small in magnitude ($-2 < M < 0$), well beneath the M1.7 completeness threshold of the original SCSN catalog. The QTM catalog, by contrast, is more than an order of magnitude more complete, with consistent detection at M0.0 and below in regions of dense station coverage.

We examine foreshock activity for magnitude M4 and greater mainshocks located within the latitude and longitude ranges of [32.68°, 36.20°] and [-118.80°, -115.40°]. This spatial boundary was guided by the density of the SCSN station coverage and the local magnitude of completeness (Figure S1), since in more remote locations the template matching detection threshold is poorer. The lower latitude boundary of 32.68° is set to approximate the California/Mexico border, so the study region only contains events within southern California.

Within this study region, we select a total of 43 mainshocks that are relatively isolated in space and time from other larger events, to ensure that the selected events are indeed mainshocks as traditionally defined, and that the seismicity rate during the pre-event window is not biased high due to aftershock triggering from unrelated events. To do this, we use a magnitude-dependent windowing criterion to exclude events within (i) 40 days and 40 km another M4 event, (ii) 80 km, 80 days of an M5 event, (iii) 160 km, 160 days of an M6 event, or (iv) 240 km, 240 days of an M7 event. We note that this criteria removes a large number of potential mainshocks occurring in the months following the 2010 M7.2 El Mayor-Cucapah earthquake, when the high triggered seismicity rate (Hauksson et al., 2011; Meng & Peng, 2014) renders foreshock analyses problematic. The El Mayor-Cucapah event is not considered in this study due to its location in Baja California, to south of our study region, though it was itself preceded by a notable foreshock sequence (Chen & Shearer, 2013).

3 Methods

For each selected mainshock, we measure the local background rate of seismicity within 10 km epicentral distance of the mainshock using the interevent time method (Hainzl et al., 2006). In this technique, the set of observed interevent time differences $\boldsymbol{\tau}$ between subsequent events, are modeled as gamma distribution:

$$\boldsymbol{p(\tau) = C \cdot \tau^{\gamma-1} \cdot e^{-\mu\,\tau}}. \qquad (1)$$

Here, μ is the background rate, γ is the fraction of the total events that are background events, and $\boldsymbol{C = \mu^{\gamma}/\Gamma}(\gamma)$ is a normalizing constant. The appeal of the interevent time method is that it can be used to extract a background rate from temporally clustered earthquake catalog data without assuming an explicit functional form for triggered, non-background seismicity as in the popular epidemic type aftershock sequence (ETAS) model (Ogata, 1988). For each earthquake, we solve for μ using a maximum likelihood approach (van Stiphout et al., 2012), and estimate uncertainties using a log-transformed jackknife procedure (Efron & Stein, 1981).

Having established the local background rate, we consider potential foreshocks within this same 10 km distance range from the mainshock. While most previous studies neglect the local background rate and consider any earthquake sufficiently close in space and time to the mainshock to be a foreshock (Abercrombie & Mori, 1996; Chen & Shearer, 2016), this assumption is clearly problematic for the QTM catalog due to its high spatiotemporal event density. Thus, to measure the statistical significance of foreshock activity, we count the observed number of earthquakes N in the 20 days preceding the mainshock, and use Monte Carlo simulations to compute the probability p of observing at least N events during the 20-day / 10-km window, given the background rate $\boldsymbol{\mu}$ and its uncertainty. Low p-values are indicative of foreshock activity rates in excess of the background rate, and we consider $p < 0.01$ to be statistically significant evidence for elevated foreshock activity.

These background rate estimates, when combined with the relative completeness of the QTM catalog, enable measurement of the duration of significant foreshock activity, a subject that has not been carefully studied to date. To do this, we calculate the event rate within 5-day moving windows (and the same 10 km spatial windows). We work backwards in time from the mainshock origin time $T = 0$, in steps of 0.1 days, until the observed event rate falls to within one standard deviation of the background rate $\boldsymbol{\mu}$, and take the window end time to be the duration estimate. We use a 5-day window (rather than, for example, 10 days or 20 days), as we found it to be the best compromise between precision in defining the onset of foreshock sequences, and robustness to short-duration gaps in seismicity. Measurement uncertainties in the duration estimates are of order 1 day, controlled primarily by the uncertainty in the background rate and the temporal averaging (5 days) used to compute the observed event rates.

It is also important to understand how improved catalog completeness augments our understanding of foreshock sequences. This issue is pertinent both within and beyond the study region of California, as future studies in regions across the globe will provide new high-resolution catalogs by applying advanced event detection techniques (Kong et al., 2019; Yoon et al., 2015). To address this question in southern California, we repeat our analysis of the 43 foreshock sequences using the SCSN catalog instead of the QTM catalog, using an identical procedure to calculate background rates and compute the *p*-value of the observed foreshock count within 20 days and 10 km (Figure S2).

4 Results

In total, 30 out 43 mainshocks in southern California have a statistically significant increase in foreshock activity relative to the background seismicity rate (Figure 1 and Table S1). This 70% fraction suggests that precursory seismicity is more ubiquitous than previously understood, and that the discrepancy between the prevalence of foreshocks in laboratory and real Earth studies may in part be explained by observation limitations. This hypothesis is supported through direct comparison with the SCSN catalog, in which only 21 of the 43 sequences exhibit significant foreshock activity. This fraction is consistent with recent studies of foreshocks in California (Chen & Shearer, 2016), which helps validate our methodology.

The improvement in the resolution of foreshock sequences using the QTM catalog is particularly notable given that the SCSN catalog with a nominal magnitude of completeness of M1.7, is among the highest quality network-based catalogs currently available. Despite this, there are numerous cases in which the SCSN catalog misses foreshock sequences entirely (Figures 2 and 3). In other instances where foreshock activity is apparent in both catalogs, the QTM catalog provides improved detail of the low-magnitude foreshock events that provide a more complete perspective of the nucleation process. For example, in the earthquake sequences depicted in Figure 4, the precise timing of the onset of each foreshock sequence is readily apparent using the QTM catalog, but is impossible to discern using the SCSN catalog alone.

The QTM catalog also provides a unique opportunity to examine the spatial and temporal characteristics of foreshock sequences in southern California. We can, for example, estimate the duration of foreshock activity by measuring the timespan preceding the mainshock for which the pre-event seismicity rate significantly exceeds the background rate (Figures 2-4, see Methods). Estimated foreshock durations for the 30 sequences range in length from 3 to 35 days, with a median of 16.6 days (Table S1). The duration estimates are limited in their precision by the uncertainty in the background rate and the temporal averaging required to compute the observed event rate. However, with nominal uncertainties of order 1 day, they still provide a useful measure of the temporal extent of elevated foreshock activity.

The foreshock sequences are diverse in their spatiotemporal evolution. Many of the longer-duration sequences are earthquake swarms that have been previously documented in select regions of southern California (Zhang & Shearer, 2016). A number of mainshocks are preceded by burst-like foreshock sequences near the mainshock hypocenter in the days and hours leading up to the event, while still others have a more diffuse and widespread elevation in seismicity rate (Figure 4 and Figure S3). Likewise, there are some notable instances of systematic linear migration in foreshocks toward the mainshock hypocenter, but this behavior is not universally observed. Indeed, these sequences exemplify the diverse characteristics one might anticipate in complex natural fault systems.

We do not observe variations in foreshock behavior related to mainshock magnitude or focal mechanism type, and the slight trend for shallow mainshocks to have more intense foreshock activity is not statistically significant given our relatively small sample size of candidate mainshocks (Figure S4). These findings may in part be attributed to the relative homogeneity in tectonic regime of the study region of southern California (Reasenberg, 1999). There are, however, subtle regional differences in foreshock activity. For example, the earthquake sequences nearest the Salton Sea and Coso geothermal field all feature extensive foreshock activity, while several well-recorded sequences near coastal Los Angeles do not (Figure 1). We note that at least two of the sequences without significant foreshock activity are within a remote part of the Eastern California Shear Zone with relatively sparse station coverage, so it is possible that smaller magnitude foreshocks in those particular sequences went undetected. Further, our significance criterion of $p < 0.01$ is conservative by design, and thus selects only the most robustly observed foreshock sequences. There are six additional sequences with $0.01 < p < 0.1$ in which the observed seismicity rates exceed the inferred background rate, but not to the extent where the physical significance of this rate increase is unambiguous.

5 Conclusions

We use a detailed new earthquake catalog to demonstrate that elevated foreshock activity is much more common than previously understood. The details of these foreshock sequences have to date been obscured by limitations in catalog completeness, even in southern California, where the SCSN maintains one of the most complete regional earthquake catalogs in the world. The prevalence of measurable foreshock activity we observe is reminiscent of laboratory experiments, where low-amplitude precursory slip events are ubiquitously observed preceding failure. In the laboratory, the statistical characteristics of these slip events can be used to predict the properties of imminent mainshocks, including their timing and slip amplitudes (Hulbert et al., 2019; Rouet-Leduc et al., 2017).

Despite the notable similarities with laboratory studies, the complexity observed in the real Earth will likely preclude hazard monitoring based on foreshock activity for the foreseeable future. Even within the limited study region of southern California, foreshock sequences vary substantially in duration and spatiotemporal evolution. Likewise, in real fault systems, precursory activity is not a unique cause of elevated seismicity rates, which are more commonly observed in association with aftershock triggering. While foreshock activity may be apparent in retrospect after careful statistical analyses, identifying foreshocks in real time presents a whole new set of challenges that we do not attempt to address in this work. It is also important to note that there are several instances of well-recorded mainshock events within our catalog that occur without detectable foreshocks, a fact which suggests that the nucleation processes of individual earthquakes are diverse rather than universal in character. Nevertheless, by examining the details of earthquake activity at the finest of scales, we will improve our understanding of the physical mechanisms underlying how earthquakes get started.

Acknowledgments

The two earthquake catalogs analyzed in the manuscript are publicly available online. The QTM catalog and the SCSN catalog are both archived by the Southern California Earthquake Data Center (scedc.caltech.edu/). The workflow and statistical analysis described in the Methods section was performed using open source python software packages. D. Trugman acknowledges institutional support from the Laboratory Directed Research and Development (LDRD) program of Los Alamos National Laboratory under project number 20180700PRD1. We are grateful to P. Johnson, I. McBrearty, and N. Lubbers for their helpful advice that improved the manuscript.

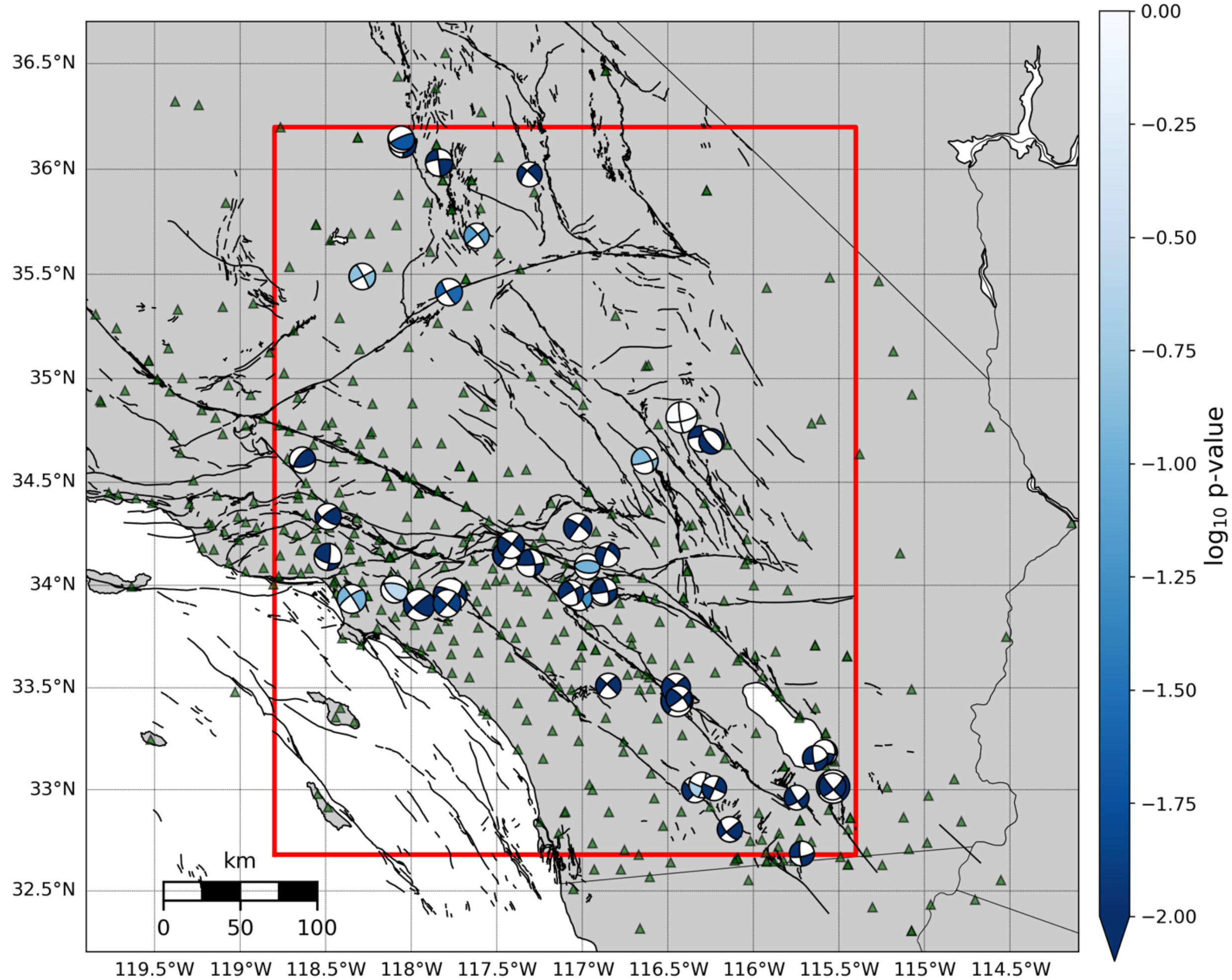

Figure 1. Foreshock sequences of 43 M4 and M5 earthquakes in southern California. The study region outlined in red – [32.68°, 36.20°] latitude and [-118.80°, -115.40°] longitude – was selected to ensure a sufficiently low magnitude of completion for detection (Figure S1). Each event is color-coded by the *p*-value measurement of foreshock activity described in the text, with lower *p*-values (darker colors) indicating more significant activity.

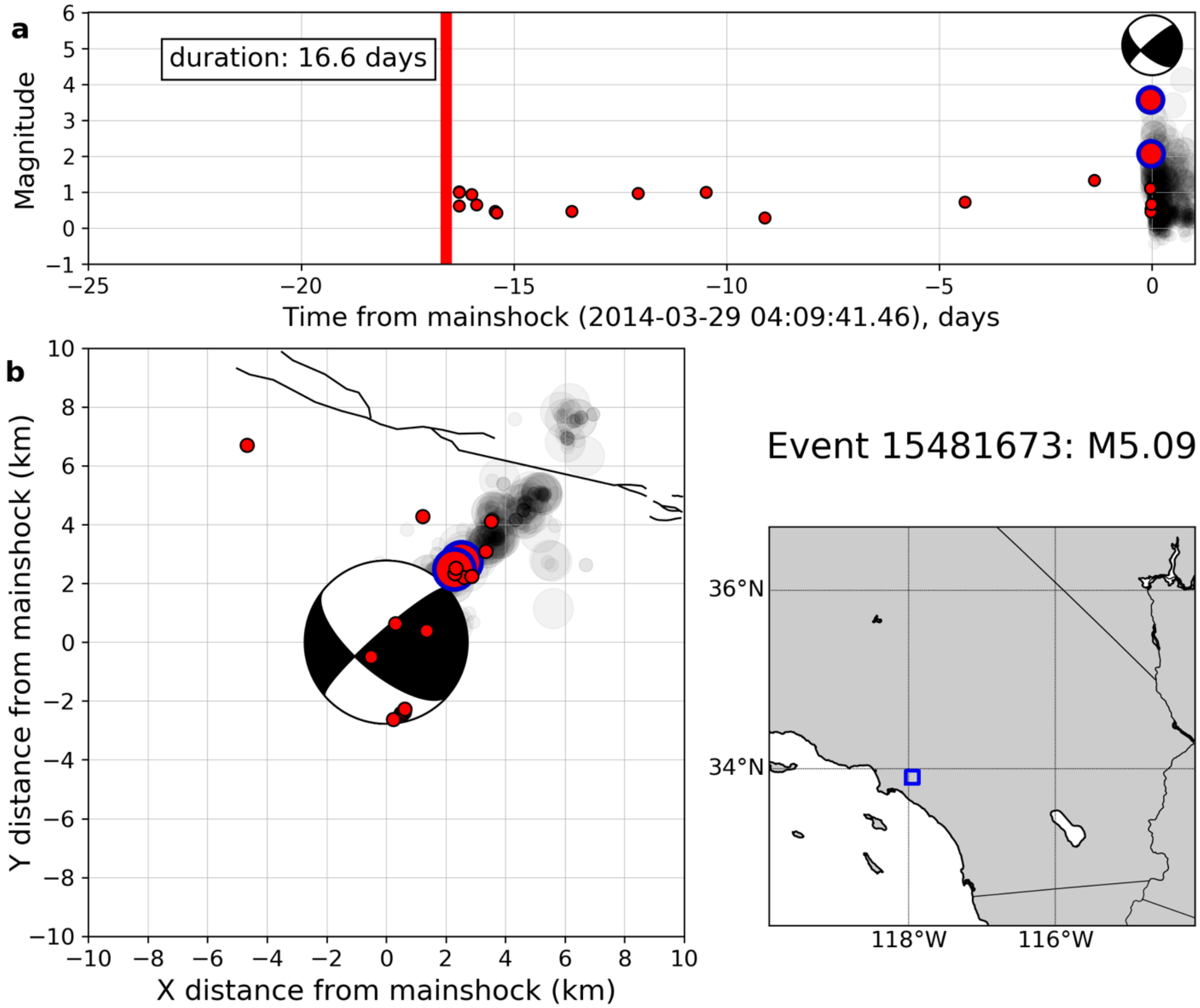

Figure 2. Example foreshock sequence for a M5.09 earthquake occurring during January 2016 (Event 15481673). (a) Earthquake magnitude versus time for events within a 10km region of the mainshock. Large circles with solid blue lines denote events listed within the SCSN catalog, while small circles denote newly detected events listed by the QTM catalog. The inferred foreshock duration of 16.6 days is denoted with a vertical red line. (b) Map view of the foreshock sequence and its location within southern California.

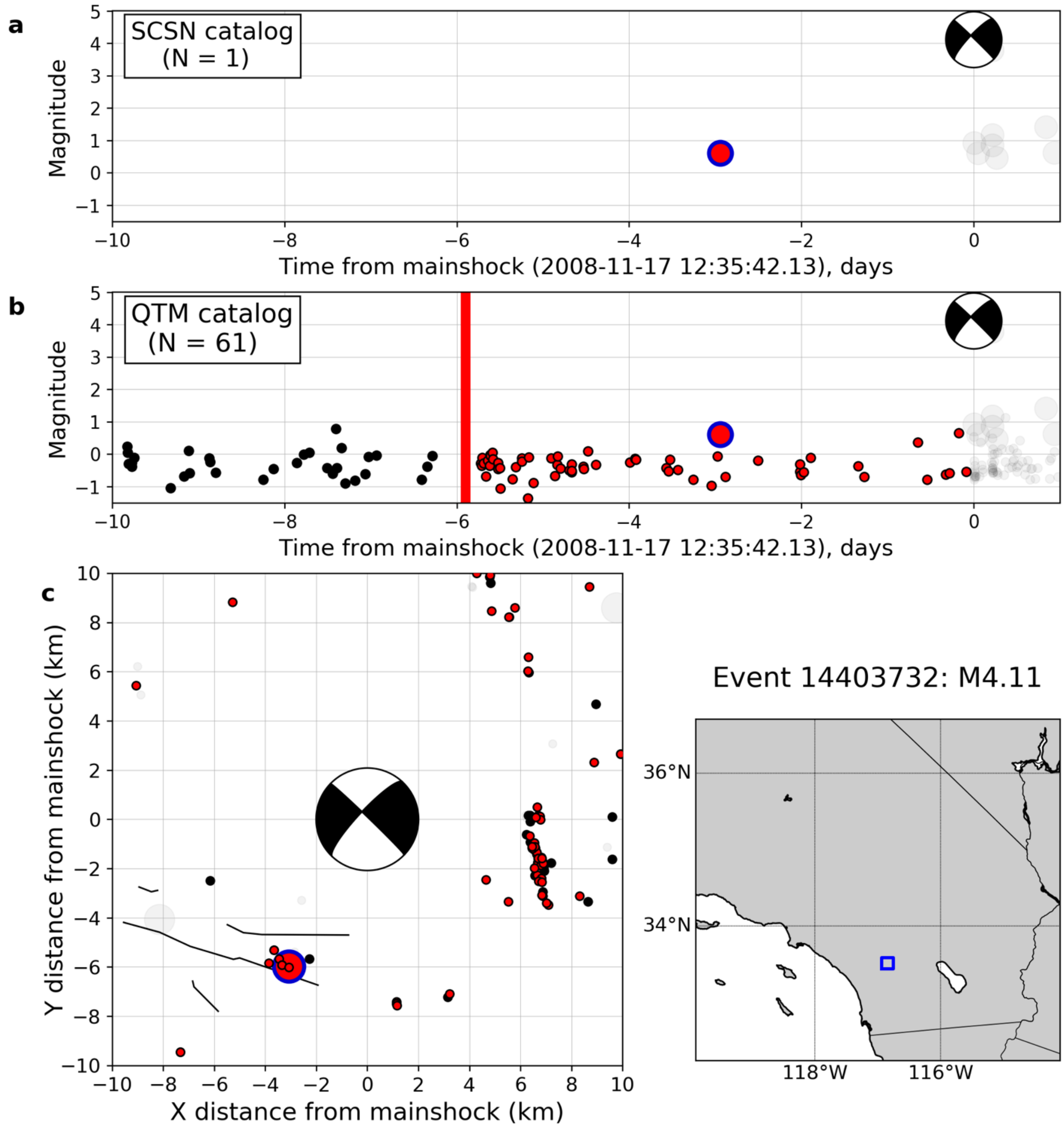

Figure 3. Hidden foreshocks revealed by the improved detection capability of the QTM catalog. Panels (a) and (b) compare the magnitude-time evolution of the foreshock sequence for an example earthquake (Event 14403732) from the perspective of (a) the SCSN catalog (b) the QTM catalog. In the 6 days preceding this event, only one SCSN earthquake was recorded, compared to 61 in the QTM catalog. Red circles denote events following the estimated foreshock duration (red line), while black circles denote events preceding this. (c) Map view of the foreshock sequence and its location within southern California.

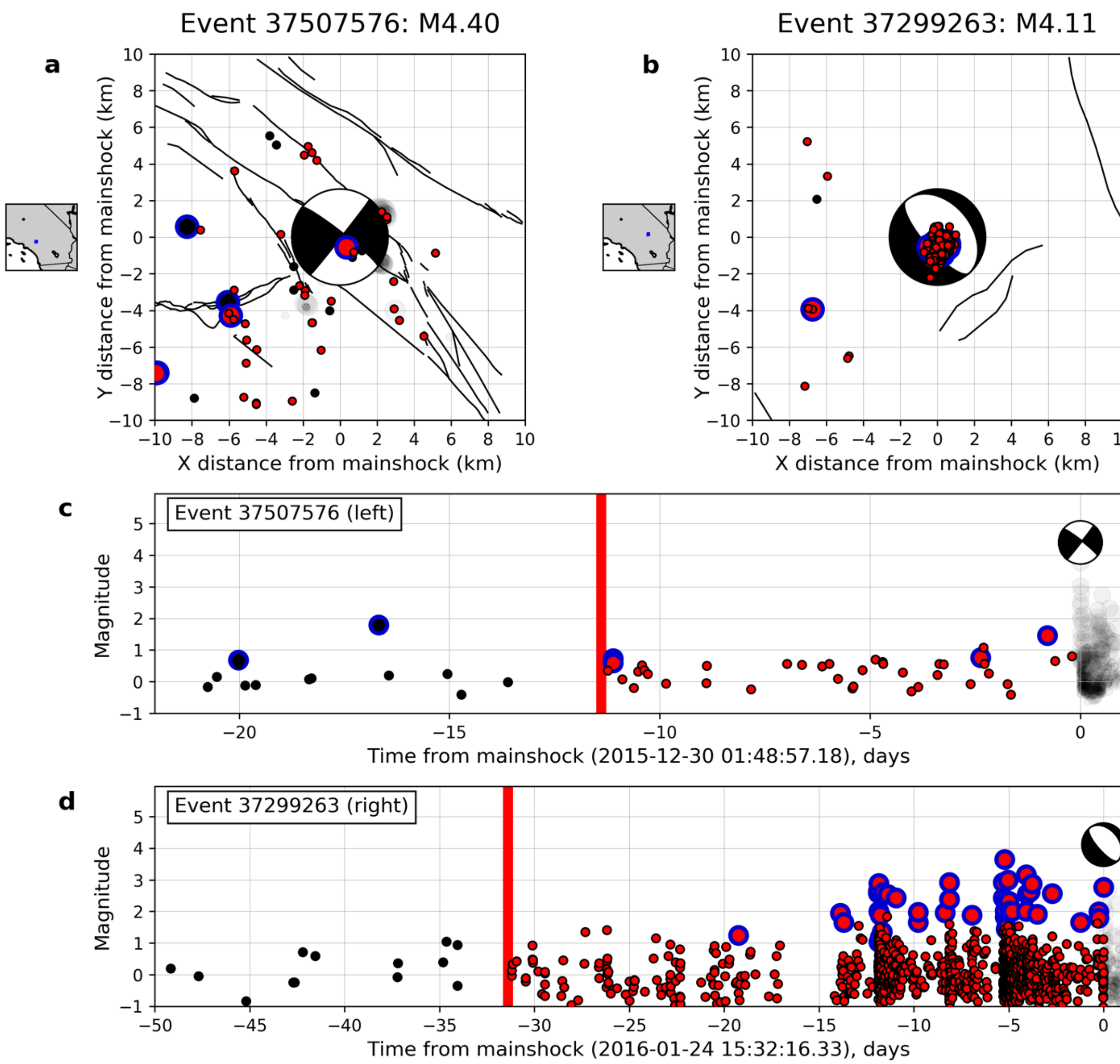

Figure 4. Diverse patterns of foreshock occurrence in southern California. Panels (a) and (b) show map view representations of two distinct foreshock sequences, one (a) with an extended period of elevated seismicity rate surrounding the mainshock hypocenter, and the other (b) with several highly localized bursts of seismicity preceding the mainshock. Red circles denote events following the estimated foreshock duration (red line), while black circles denote events preceding this. Large circles with solid blue lines denote events listed within the SCSN catalog, while small circles denote newly detected events listed by the QTM catalog. (c) and (d) Event magnitude versus time for the sequences shown in panels a and b, respectively.

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