

## SEISMOLOGY

# Searching for hidden earthquakes in Southern California

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Earthquakes follow a well-known power-law size relation, with smaller events occurring much more often than larger events. Earthquake catalogs are thus dominated by small earthquakes yet are still missing a much larger number of even smaller events because of signal fidelity issues. To overcome these limitations, we applied a template-matching detection technique to the entire waveform archive of the regional seismic network in Southern California. This effort resulted in a catalog with 1.81 million earthquakes, a 10-fold increase, which provides important insights into the geometry of fault zones at depth, foreshock behavior and nucleation processes, and earthquake-triggering mechanisms. The rich detail resolved in this type of catalog will facilitate the next generation of analyses of earthquakes and faults.

Earthquake catalogs have formed the basis for many investigations of earthquakes and faults since the dawn of the era of seismic instrumentation (1). With the development of the local magnitude scale, earthquake sizes could be quantitatively compared for the first time (2), which led directly to the establishment of one of the first power-law size relationships in earth science, the Gutenberg-Richter law (3). This empirical relationship states that for a unit decrease in magnitude ( $M$ ), earthquakes are approximately ten times more frequent. The implications of this relation are profound: earthquake catalogs are all inherently incomplete because there are always many more small earthquakes below a detectability threshold. These hidden events fill in the gaps in the earth-

quake record and are the key to a better understanding of the geometry of faults at depth (4–6), foreshock and swarm processes (7, 8), and the triggering and nucleation of earthquakes (9–11). However, extending this magnitude scale to increasingly smaller events is hampered by signal-to-noise issues and the need to unscramble overlapping seismograms from near-simultaneous earthquakes.

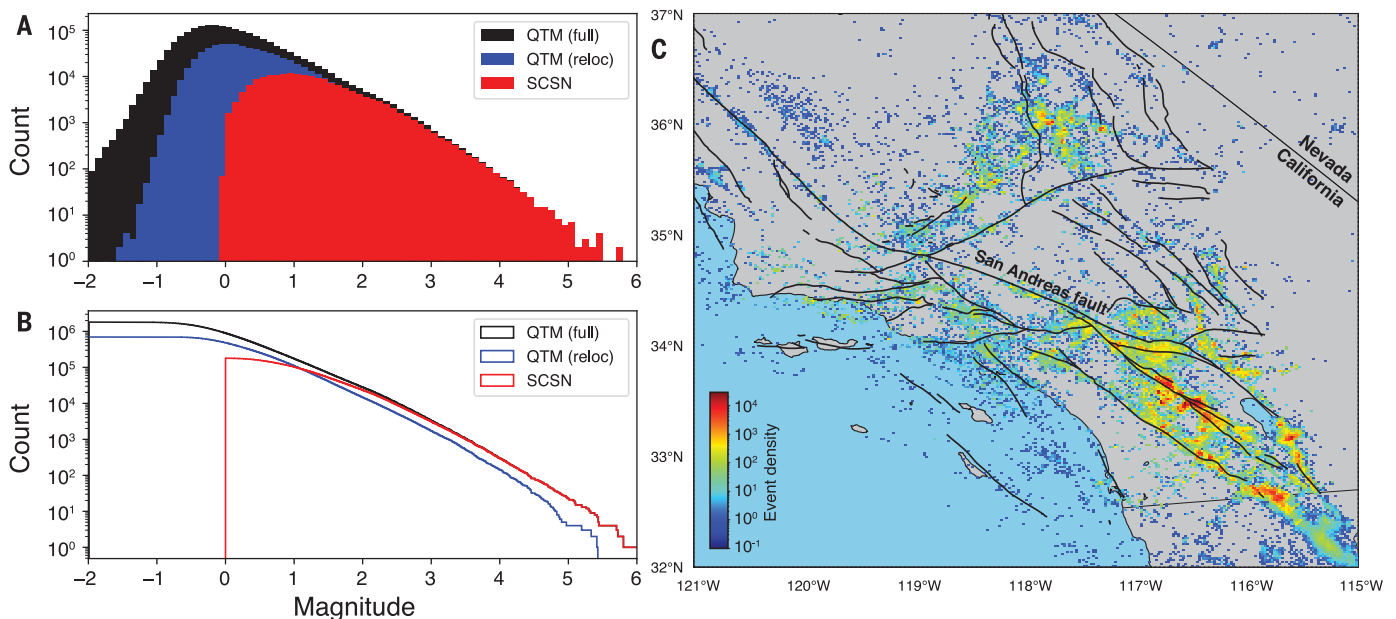
A technique called template matching successfully detects, across a wide range of scenarios, the small earthquakes missed by conventional techniques. Template matching exploits the similarity of earthquake waveforms between nearby events by using the seismograms of previously identified earthquakes as templates, which are then cross-correlated against continuous waveform data.

Typical applications of this technique expand the number of detected earthquakes by a factor of 10 (12–15). However, its heavy computational demands have limited its usage to smaller seismic networks and datasets spanning only days to weeks. As a result, template matching is typically used for studying the most active earthquake sequences rather than being leveraged as a method to dig into the substantially larger datasets collected by regional seismic networks. To overcome these limitations, we used an array of 200 NVIDIA P100 graphics processing units to perform template matching on the continuous waveform archive (2008–2017) of the Southern California Seismic Network (SCSN) and produced an earthquake catalog for the entire Southern California region. During the course of these calculations, nearly 284,000 earthquakes listed in the SCSN catalog over the period 2000–2017 were used as template events. The resulting detections were then relocated with a cluster-based double-difference algorithm (16) to obtain precise relative hypocenters.

Our catalog, which we designate QTM (for quake template matching), exhibits the expected power-law size relationships (Fig. 1). For the 10-year study period, the original SCSN catalog had nearly 180,000 earthquakes, whereas the QTM catalog contains 1.81 million earthquakes (a 10-fold increase). The QTM catalog is nearly complete for earthquakes of  $M > 0.3$ , compared with earthquakes of only  $M > 1.7$  for the SCSN

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**Fig. 1. Summary information for QTM catalog.** (A) Frequency-magnitude distribution of earthquakes listed in the SCSN catalog, the full QTM catalog, and the relocated subset (reloc) of the QTM catalog. (B) Corresponding cumulative frequency-magnitude distributions. (C) Map of earthquake density in the QTM catalog (bins: 2 km by 2 km). The station distribution that was used is shown in fig. S4.

catalog. The systematic improvement in the detection rate results in identification of about 495 earthquakes per day across Southern California, with an average time of just 174 s between events. In contrast, for the SCSN catalog, earthquakes are spaced ~1753 s apart, on average, demonstrating that the newly detected events in the QTM catalog provide a far more detailed picture of how seismicity evolves in time.

The relocated hypocenters in the QTM catalog provide insights into the geometry of fault zones at seismogenic depths. For example, we compare the best relocated version of the SCSN catalog (17) with the QTM relocated hypocenters for a segment of the San Jacinto fault zone known as the trifurcation area (Fig. 2), a complex zone of deformation where the main fault splits into three subparallel strands (6). The internal structure of the fault zone is markedly clearer in the QTM catalog, with pronounced asymmetric damage zones, many sharp lineations of seismicity with frequent crosscutting structures, and evidence for additional, previously unmapped strands of the fault. The southwest fault strand, Coyote Creek, is clearly delineated, including the point at which it merges with the central Clark fault; the geometry of the Coyote Creek fault appears to be highly curved at depth. Such resolution improvements are present in most of the Southern California plate boundary area and will ultimately lead to improved fault maps, a better understanding of the three-dimensional geometries of fault zones, and more realistic modeling of earthquake and fault processes.

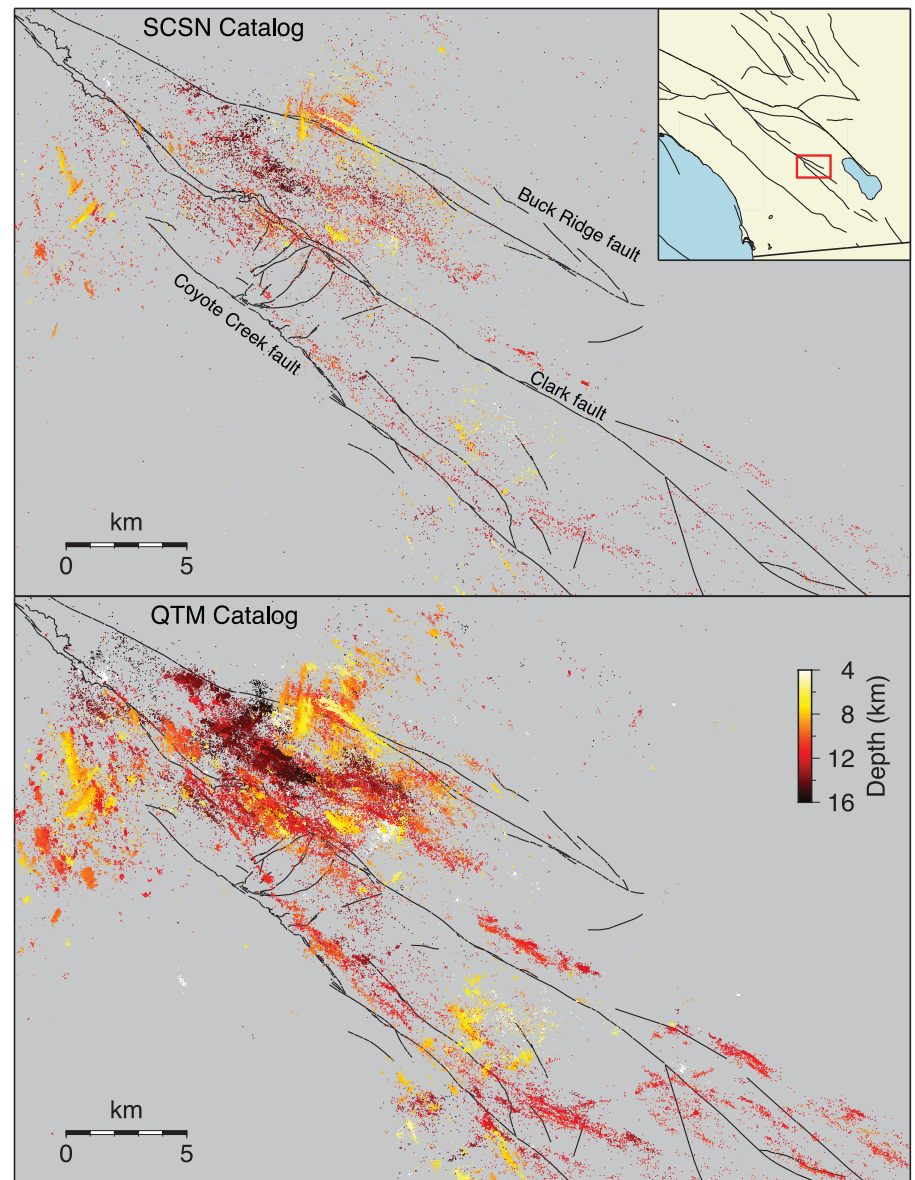
How earthquake sequences initiate is one of the most fundamental outstanding questions in earthquake science. In typical earthquake sequences, mainshocks are occasionally preceded by smaller magnitude foreshocks, whereas earthquake swarms may be driven by external factors such as fluids or aseismic slip and have complex temporal patterns without a clear mainshock. Detailed observations on the initiation of sequences are critical because they can provide insight into earthquake-triggering mechanisms and constrain the physics of earthquake nucleation (18). Having resolved many more small earthquakes, the QTM catalog provides an opportunity to revisit these important questions. As an example, we show the magnitude-time distribution of the seismicity during the onset of the 2012 Brawley, California, swarm (Fig. 3), which consisted of 10 earthquakes of  $M > 4$  over a span of 3 days and an abundance of smaller events (19). In the QTM catalog, the time at which the sequence appears to start is nearly 10 hours earlier than what is visible in the SCSN catalog, and 36 additional earthquakes of  $M \sim 0.5$  are observed during this period. In the SCSN catalog, the swarm appears to initiate quite rapidly, whereas the onset is more gradual in the QTM catalog. Nearby injection activity induced aseismic slip that preceded this swarm (20), which may be related to the low-magnitude seismicity we discovered. Improving our understanding of these processes is aided by the ability to better resolve the spatial-temporal evolution of the

onset of swarms and aftershock sequences using template-matching catalogs.

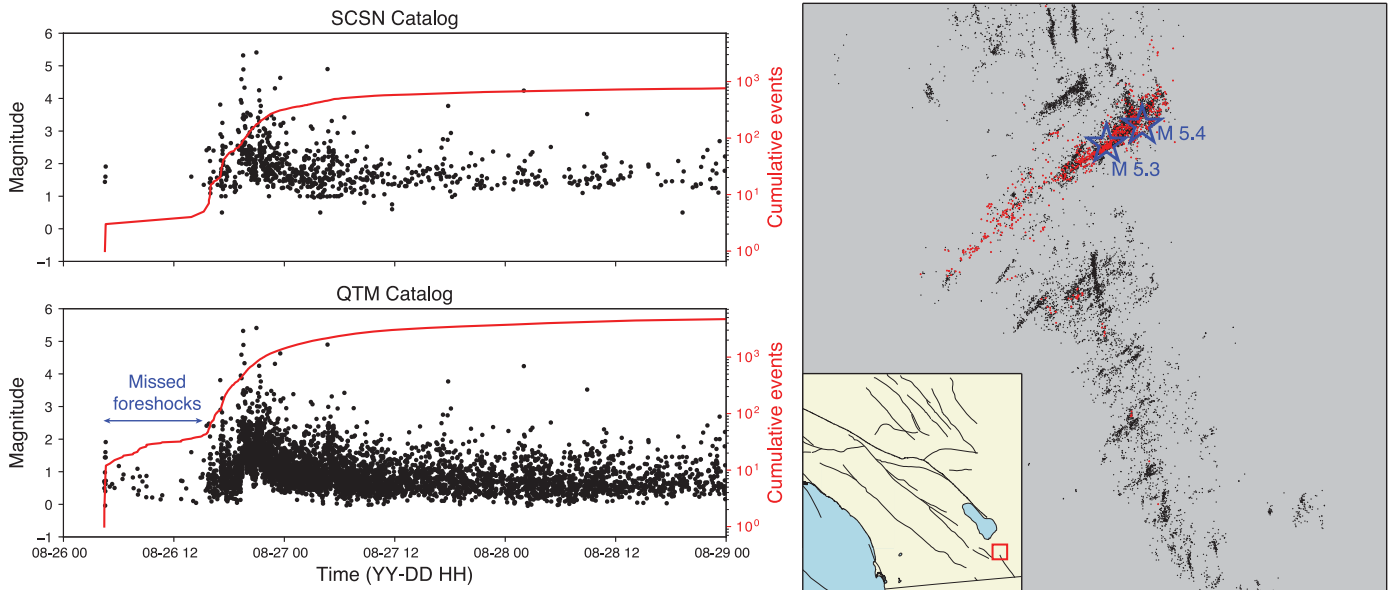
More broadly, the physical mechanisms by which earthquakes communicate with and trigger each other are not yet well understood. The most common explanations for earthquake triggering invoke either static stress changes imparted by fault displacements (21) or dynamic stress changes induced by the passage of seismic waves (22). These physical processes make specific predictions about the expected spatial decay of the stress changes with distance  $r$ , with static stress changes decaying as  $r^{-3}$  and dynamic stress changes decaying as  $r^{-2}$ . Large earthquakes are known to be capable of triggering small earthquakes at large hypocentral distances (23–26),

but detailed analyses of the spatial signature of earthquake triggering after large earthquakes have suffered from a lack of data.

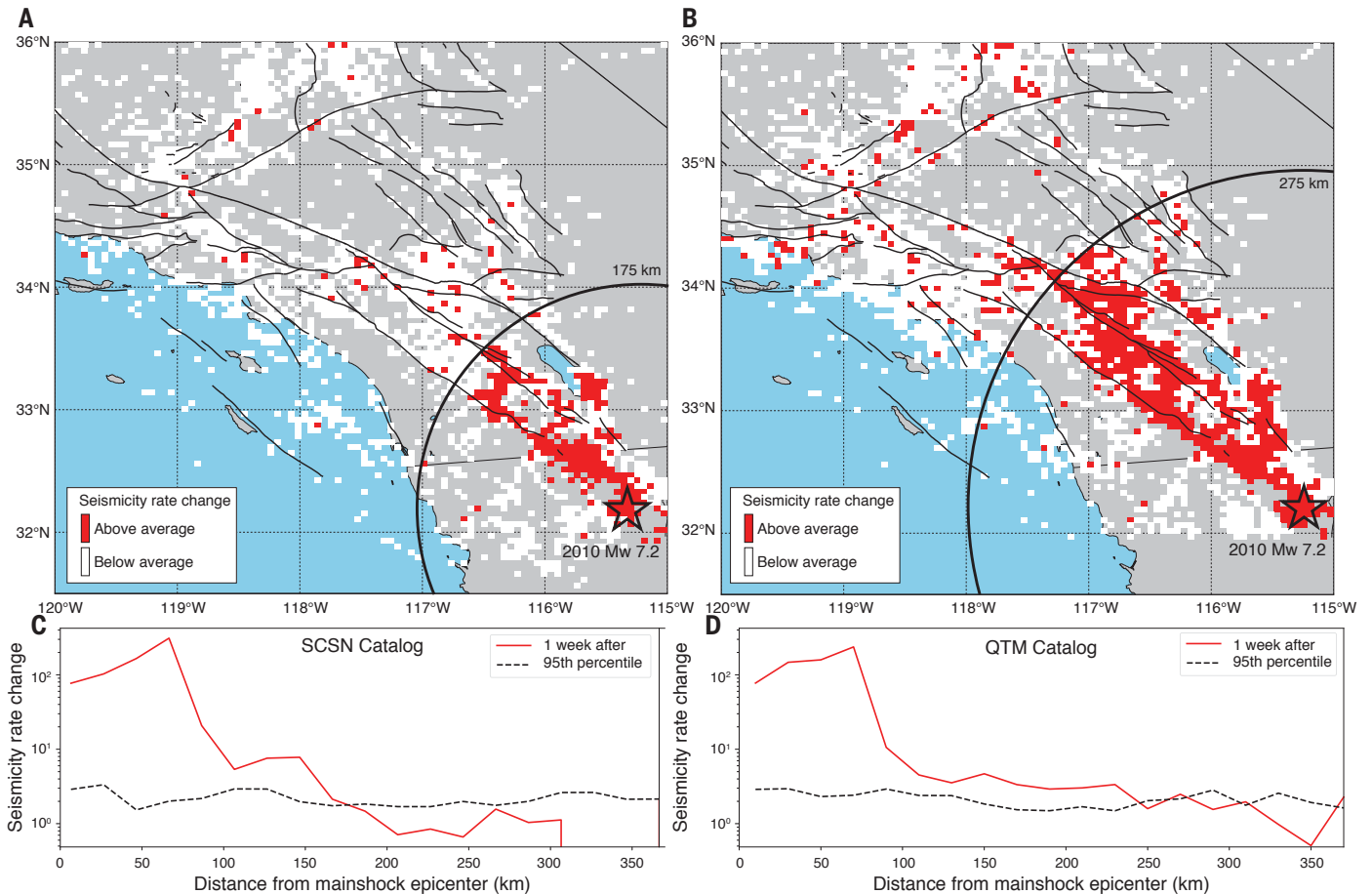
The largest earthquake near the seismic network during our study period was the 2010 moment magnitude ( $M_w$ ) 7.2 El Mayor–Cucapah earthquake, which occurred in Baja California, close to the United States–Mexico border (27) (Fig. 4A). The larger number of events in the QTM catalog provides improved constraints on earthquake-triggering rates, for example, by allowing for the examination of how the El Mayor–Cucapah earthquake affected seismicity rates across all of Southern California in the week after the mainshock. We show the seismicity rate change across the region relative to the



**Fig. 2. Mapped seismicity in the San Jacinto fault zone.** Black lines indicate mapped late Quaternary faults. The structural complexities of the fault zone are imaged with much higher resolution in the QTM catalog (bottom panel) than in the SCSN catalog (top panel). The inset map shows the location of the study area.



**Fig. 3. Seismicity during the 2012 Brawley, California, swarm.** Left panels show magnitude-versus-time plots of the swarm onset. In the SCSN catalog, the swarm is preceded by three events 10 hours before, which appear unrelated given the large time gap. In the QTM catalog, this 10-hour period contains 36 events leading up to the eventual surge in activity. Right panel shows a map of seismicity in the area, with background seismicity in black and events during the swarm in red. Blue stars indicate the epicenters of the largest events. The inset map shows the location of the swarm.



**Fig. 4. Analysis of earthquake triggering after the 2010  $M_w$  7.2 El Mayor–Cucapah earthquake.** (A) Earthquakes are triggered out to a 175-km distance in the SCSN catalog. (B) Earthquakes are triggered out to a 275-km distance in the QTM catalog, likely by the passage of seismic waves from the mainshock (indicated with a star). There are 142% more red tiles within 275 km in the QTM catalog than in the SCSN catalog. (C and D) Seismicity rate change versus distance from the mainshock epicenter (red curve). 95th percentile of the weekly background rate is calculated over the period 2008–2009 (dashed black curve).

average weekly seismicity rate during the 2 years preceding the earthquake (Fig. 4, A and B). A substantial fraction of the Southern California plate boundary exhibited an above-average seismicity rate that correlated strongly with the major faults. Using a nonparametric test, we also show the seismicity rate change as a function of distance, alongside the 95th percentile of the weekly rate change during the same 2-year period (Fig. 4, C and D). For the SCSN catalog, a significant increase in the seismicity rate can only be resolved out to ~175 km. This is the approximate distance at which static stress changes from the mainshock reach levels comparable to those of the solid Earth tides (~2 kPa) (28); therefore, static-triggering effects cannot be ruled out as the exclusive triggering mechanism. However, in the QTM catalog, there is a significant increase in the seismicity rate well beyond this point, extending to 275 km. This indicates that the El Mayor–Cucapah earthquake triggered low-magnitude seismicity across most of Southern California that was unresolvable in the standard catalog. Because these more-distant events were triggered at hypocentral distances for which the static stress changes are negligible (<1 kPa), these observations suggest the occurrence of widespread dynamic triggering of earthquakes that is not limited to a few particularly sensitive locations. Similar observations were made for the San Jacinto fault zone and Salton Sea geothermal area (29), which are included in our analysis. These results imply that a single physical mechanism is unlikely to be responsible for earthquake triggering, and, in the case of the El Mayor–Cucapah earthquake, the list of mechanisms may also include processes like aseismic afterslip and postseismic diffusion of fluid pressure near the rupture terminus (30). Thus, the complex spatiotemporal patterns commonly observed for aftershocks may result in part from the presence of multiple driving mechanisms.

Although template matching can produce extremely detailed seismicity catalogs, the results are limited to source regions with known earthquakes. Template events generally only cross-correlate well with other earthquakes within a radius of ~100 to 200 m, implying that some events will remain undetected in regions for which templates are unavailable. However, because we have used a starting catalog spanning 17 years that is complete for earthquakes of  $M > 1.7$ , it is likely that the total number of small events missed because of limitations in the template catalog is negligible. Future improvements in template availability may result from the ap-

plication of deep-learning techniques, which have recently shown great promise in automated event detection and characterization of seismograms (31, 32).

In the QTM catalog, the nominal temporal resolution of the inter-event spacing is 2.0 s, a limit that was imposed to minimize the likelihood of duplicate detections between different template events. Because the seismic wave train is generally longer than this for most recordings, the catalog will resolve many events that at least partially overlap with others. However, events that occur nearly simultaneously in time, but in slightly different locations, will not be resolved.

It would be beneficial for future comprehensive analyses of seismicity and associated hazards to construct a similar template-matching catalog for other regions. This would require a reliable catalog of template events and high quality three-component continuous waveform datasets.

As seismologists detect increasingly smaller earthquakes, the average time between observed events will continue to decrease, revealing more-complex dynamical behavior. These rich spatiotemporal patterns provide valuable constraints on the physics of earthquakes and faults—reflecting properties of the underlying fault structure and the various mechanisms and external loadings that can trigger earthquakes—and may also provide additional information on the rupture process of individual events. By extending the minimum magnitude of completeness down by more than a full magnitude unit over a decadal time period, the earthquake catalog produced in this study is the most comprehensive to date, and going forward, such catalogs will facilitate the next generation of analyses of earthquakes and faults.

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34. The Southern California Earthquake Data Center (<https://doi.org/10.7909/C3WD3xH1>) is the archive of the Southern California Seismic Network.

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**Competing interests:** The authors declare no competing interests. **Data and materials availability:** The QTM catalog will be publicly available from the Southern California Earthquake Data Center ([scedc.caltech.edu](https://scedc.caltech.edu)). All waveform and parametric data are available from the Caltech/USGS Southern California Seismic Network (33) and stored at the Southern California Earthquake Data Center (34). All other data are available in the main text or the supplementary materials.

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Materials and Methods  
Supplementary Text  
Figs. S1 to S9  
References (35–42)

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### Using earthquakes to find earthquakes

Earthquake catalogs elucidate the behavior of faults and allow for rough estimates of when large earthquakes might occur. Cataloging small earthquakes is challenging because the small signal is often indistinguishable from noise. Ross *et al.* used a template-matching algorithm to find almost two million tiny earthquakes previously missed by other earthquake-logging techniques in Southern California (see the Perspective by Brodsky). This more-complete catalog can be used to better understand faults, earthquake reoccurrence, and other geophysical processes.

*Science*, this issue p. 767; see also p. 736

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