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Repeating Earthquakes

Naoki Uchida[1] and Roland Bürgmann[2]

[1]Graduate School of Science and International Research Institute of Disaster Science, Tohoku University, Sendai 980-8578, Japan; email: naoki.uchida.b6@tohoku.ac.jp

[2]Berkeley Seismological Laboratory and Department of Earth and Planetary Science, University of California, Berkeley, California 94720, USA; email: burgmann@seismo.berkeley.edu

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Keywords

repeating earthquakes, fault creep, earthquake source mechanics, earthquake cycle, Earth structure changes

Abstract

Repeating earthquakes, or repeaters, are identical in location and geometry but occur at different times. They appear to represent recurring seismic energy release from distinct structures such as slip on a fault patch. Repeaters are most commonly found on creeping plate boundary faults, where seismic patches are loaded by surrounding slow slip, and they can be used to track fault creep at depth. Their hosting environments also include volcanoes, subducted slabs, mining-induced fault structures, glaciers, and landslides. While true repeaters should have identical seismic waveforms, small differences in their seismograms can be used to examine subtle changes in source properties or in material properties of the rocks through which the waves propagate. Source studies have documented the presence of smaller slip patches within the rupture areas of larger repeaters, illuminated earthquake triggering mechanisms, and revealed systematic changes in rupture characteristics as a function of loading rate.

- Repeating earthquakes are observed in diverse tectonic and nontectonic settings.
- Their occurrence patterns provide quantitative information about fault creep, earthquake cycle dynamics, triggering, and predictability.
- Their seismic waveform characteristics provide important insights on earthquake source variability and temporal Earth structure changes.

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1. INTRODUCTION

The existence of earthquakes with similar waveforms has been recognized since the early days of seismology, and such events were interpreted as earthquakes located close to one another (e.g., Omori 1905). The possibility of repeated stress release at the same location is suggested by seismicity in a confined region (Bufe et al. 1977) and by the consideration of waveform similarity in different frequency bands (Geller & Mueller 1980). Vidale et al. (1994), Nadeau et al. (1994), and Ellsworth (1995) identified earthquakes with nearly identical waveforms and locations along the San Andreas and Calaveras Faults in California and interpreted them as repeated rupture of a fault patch. These early studies suggested that the fault is creeping in the zone around the frictionally locked patch of the colocated events. Nadeau & McEvilly (1999) used repeating earthquakes, or repeaters, as indicators of spatial and temporal variations of slip rate on the San Andreas Fault. Thus, repeaters provide insight into the fault creep at depth, which is usually difficult to characterize from surface observations alone. Repeaters illuminate the spatiotemporal distribution of slow slip, including postseismic afterslip, spontaneous and periodic slow slip events, and the distribution of steady fault creep and interplate coupling.

Well-characterized repeaters are mostly small ($M < 4$) but can be larger than M6 (Murray & Langbein 2006, Yamanaka & Kikuchi 2004). The occurrence mechanisms of the small repeating sequences may be similar to those commonly associated with large characteristic earthquakes (Nishenko & Buland 1987, Schwartz & Coppersmith 1984) and may thus provide insights into the recurrence behavior and interactions of much larger earthquake ruptures, which are of interest because of their great damage potential.

The small temporal and spatial scale, relatively simple mechanism, well-understood boundary conditions, and frequent recurrence of repeaters also aid in the interpretation of laboratory experiments and numerical simulations and inform studies of earthquake predictability.

The repeated event occurrences can also be used as stable seismic energy sources to estimate temporal property changes of features of interest, including fault zones, volcanic systems, or Earth's core. This time-dependent imaging capability is complementary to active source methods, which use explosions and other controlled sources, or seismic interferometry, which uses natural noise sources.

In this review, we summarize our current understanding of repeaters, describe their diverse applications in the Earth sciences, and discuss what we have learned about the physics of faults and the varying properties of Earth materials in a wide range of settings.

2. TECHNICAL DEFINITION AND DETECTION OF REPEATING EARTHQUAKES

Ideal repeaters represent two or more events that have exactly the same fault area and slip and thus produce the same seismic signal or waveform. In reality, the fault area and slip are somewhat variable, and there is no standard definition of repeaters. For the practical detection of repeaters, we need a precise technical characterization. Proposed definitions mostly rely on the overlapping ratio of estimated earthquake source areas and/or the degree of waveform similarity. The similarity of magnitude is sometimes also considered.

2.1. Detection of Repeaters by Event Location

Accurate hypocenter determinations that can confirm the actual colocation of earthquakes represent a straightforward way to identify repeaters (Ellsworth 1995, Hatakeyama et al. 2017,

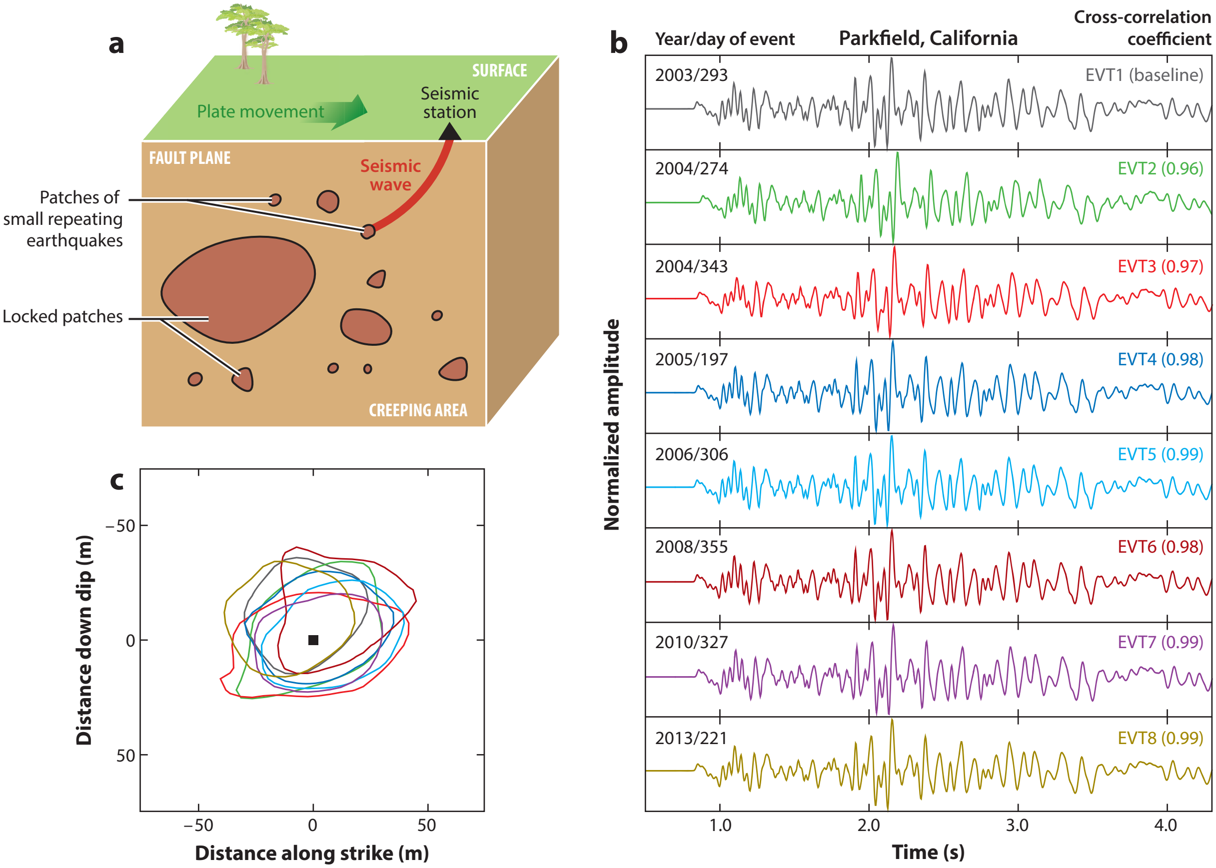

Figure 1

Characteristics of repeating earthquakes on creeping faults. (*a*) Schematic fault model of small locked patches driven by aseismic slip on the surrounding fault surface. The leftward-moving block that exists on the viewer side is not shown. (*b*) Highly similar waveforms of a sequence of eight ~Mw2.1 repeating earthquakes near Parkfield, California. The waveforms represent the vertical component of the recorded velocities with a 1-Hz high-pass filter. The event times (year/day of year) are shown in the top left corner, and the cross-correlation coefficients of the repeater waveforms with the first event are shown in the top right corner of each waveform. (*c*) Overlapping peak slip areas of the eight repeaters shown in panel *b* from finite slip modeling. Here, the slip areas are defined by the contour of half of the mean slip of each event and shown in the same color as in panel *b* (for details, see Kim et al. 2016). Panels *b* and *c* adapted from Kim et al. (2016).

Lengliné & Marsan 2009, Yu 2013) (**Figure 1*c***). Waveform-based differential time measurement of direct P and S waves is often used to assure location accuracy better than the source size of earthquakes (Waldhauser & Ellsworth 2000). The source sizes are usually determined by assuming a typical earthquake stress drop. The minimum overlapping areas commonly used to identify repeaters range from 50% to 70% (Lengliné & Marsan 2009, Waldhauser & Ellsworth 2002). However, sufficiently accurate hypocenter locations are not always available due to limited station coverage and/or timing accuracy.

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2.2. Detection by Waveform Cross-Correlation and Coherence

Fresnel zone: a prolate ellipsoidal volume between two points within which objects affect the point-to-point propagation of seismic waves

Cross-correlation coefficient: a measure of similarity of two time series as a function of lag time, $C(\tau) = \frac{1}{N}\sum_{t=1}^{N} f_x(t) f_y(t+\tau)$, where f_x and f_y are two time series (e.g., repeater waveforms) with N discrete samples, and τ is the lag time

Coherence: a measure of similarity of two time series as a function of frequency, $\mathrm{coh}(\omega) = \sqrt{\frac{|S_{xy}(\omega)|^2}{S_{xx}(\omega)S_{yy}(\omega)}}$, where $S_{xy}(\omega)$ is the cross spectrum between earthquakes x and y calculated from the Fourier transform of the original waveforms

Establishing waveform similarity is another way to select repeaters, even if their locations are uncertain. If the Earth structure and observation instrument did not change, a common travel path of the seismic wave from the earthquake source to the station is a precondition of highly similar waveforms (**Figure 1*a***). However, in reality, the path is not a line but a volume around the path. In other words, the detailed shape of a waveform is affected by a volume (the Fresnel zone) that is dependent on the wavelength of the wave. Geller & Mueller (1980) showed that, if the propagation path differs by more than one-quarter of a wavelength, then the waveform correlation substantially decreases. As a quantitative measure of similarity, the waveform cross-correlation coefficient and coherence are often used for nearby events from routine hypocenter locations. Many studies identify repeaters by using waveform correlation (e.g., Igarashi et al. 2003, Kimura et al. 2006, Matsubara et al. 2005, Meng et al. 2015, Nadeau & McEvilly 1999, Schmittbuhl et al. 2016, Taira et al. 2014, Yamashita et al. 2012). Commonly used cross-correlation coefficient thresholds range from 0.90 to 0.98. In the example of repeater waveforms in **Figure 1*b***, the cross-correlation coefficient with respect to the reference waveform is provided for each of the other waveforms. Waveform coherence is also used for the detection of repeaters (Lengliné & Marsan 2009, Materna et al. 2018, Taira et al. 2014, Uchida et al. 2009) and has a detection ability similar to that of cross-correlation. Coherence thresholds for repeater identification range from 0.95 to 0.98.

2.3. Challenges and Uncertainties in the Criteria for Repeater Detection

In the waveform-based determination of cross-correlation or coherence values, the repeater identification mainly depends on the frequency band and the length of the time window spanning the waveform of an event. The use of longer time windows, higher-frequency bands, and higher cross-correlation or coherence threshold values is meant to ensure that truly overlapping events are identified. In the hypocenter-based detection, large overlapping ratios of the estimated source area assure truly repeating events. However, too-strict criteria may miss events due to noise, change in rupture propagation, or location and source-area uncertainties, despite an otherwise identical slip patch (e.g., Lengliné & Marsan 2009). Insufficiently strict criteria sometimes associate events with very short time separation that are probably nearby triggered events rather than true repeaters (Lengliné & Marsan 2009, Nadeau et al. 1995, Nakajima et al. 2013, Rubin et al. 1999). For robust detection, multiple data constraints, including S-P differential time, overlapping source area, and waveform similarity, provide an independent check on the identification of repeating events (Chen et al. 2008, Lengliné & Marsan 2009). Examinations of the effect of noise on repeater identification (Materna et al. 2018) and discrimination of triggered burst-type repeaters (Igarashi et al. 2003, Lengliné & Marsan 2009, Templeton et al. 2008) are useful to more fully characterize the selected repeater candidates. Since there are inherent uncertainties in the selection of repeaters, it is important to understand the criteria and threshold values used for event identification in each repeater catalog.

3. GLOBAL OBSERVATIONS OF REPEATING EARTHQUAKES

3.1. Repeaters Along Plate Boundary Zones

Supplemental Material >

Repeaters are abundant along many plate boundary fault systems (**Figure 2*a***; **Supplemental Table 1**). Along the San Andreas Fault system, which represents a transform plate boundary between the Pacific and North American plates, many repeating earthquakes have been found along

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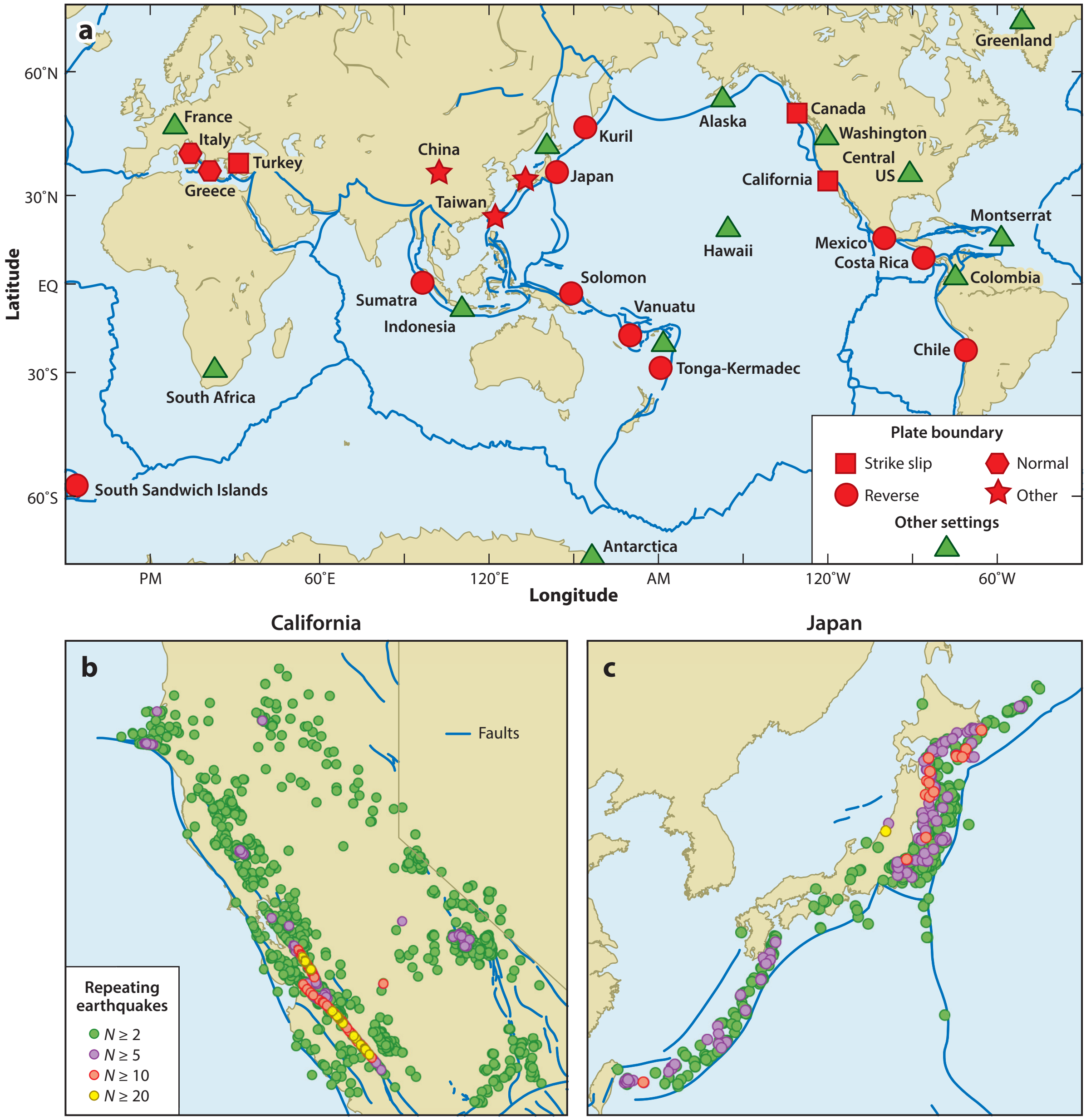

Figure 2

Distribution of observed repeating earthquakes. (*a*) Published examples of areas hosting repeating earthquakes around the world (see **Supplemental Tables 1** and **2** for more information and related publications). (*b*,*c*) Distribution of repeating earthquakes in (*b*) California and (*c*) Japan, color coded by the number of recurrences. Panel *b* adapted from Waldhauser & Schaff (2008); panel *c* adapted from Igarashi (2010).

Supplemental Material >

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sections where fault creep is also evident from geodetic and field observations (Bürgmann et al. 2000, Chaussard et al. 2015, Lengliné & Marsan 2009, Nadeau & McEvilly 2004, Templeton et al. 2008). Repeaters along the North Anatolian Fault (Turkey) (Bohnhoff et al. 2017, Peng & Ben-Zion 2005, Schmittbuhl et al. 2016) and the Queen Charlotte Fault (Canada) (Hayward & Bostock 2017) also fall into the strike-slip category. Materna et al. (2018) found repeaters along the Mendocino Transform Fault off California, suggesting that oceanic transform faults with low apparent seismic coupling ratios (Bird et al. 2002) likely accommodate much of their slip by fault creep. Along normal faults in central Italy (Valoroso et al. 2017, Vuan et al. 2017) and Greece (Duverger et al. 2018), repeaters have been recognized on deep shallow-dipping detachments. Repeaters also occur on the rapidly creeping, oblique reverse Longitudinal Valley Fault located in a continental collision zone in Taiwan (Chen et al. 2008, Rau et al. 2007).

Along subduction plate boundaries, repeaters are frequently found in locations with relatively abundant microseismicity and variable interplate coupling, as deduced from geodetic observations. These heterogeneously locked subduction thrusts are distributed around the Pacific and Indian Oceans, where repeaters often reveal large afterslip transients and spontaneous slow-slip events (e.g., Dominguez et al. 2016; Gardonio et al. 2015, 2018; Igarashi 2010; Kimura et al. 2006; Meng et al. 2015; Uchida et al. 2003; Yamashita et al. 2012; Yao et al. 2017; Yu 2013; Zhang et al. 2008).

Some seismic zones that are not on major interplate faults but instead in slowly deforming, distributed plate boundary zones also feature repeaters. In Japan, the aftershock sequences of the Noto Hanto earthquake (M6.9) (Hiramatsu et al. 2011) and the Western Tottori earthquake (Mw6.6) (Hayashi & Hiramatsu 2013) contained repeaters. Schaff & Richards (2004) reported repeaters over a wide area across China, Li et al. (2007) found them along the Tangshan Fault in eastern China, and Li et al. (2011) identified repeaters in the Longmen Shan Thrust Fault zone near the eventual rupture of the 2008 Wenchuan earthquake (Mw7.9).

3.2. Repeating Earthquakes in Other Settings

Far from plate boundary zones, repeaters have been found in intraplate seismic zones in the central United States (Bisrat et al. 2012) and among deep intraslab earthquakes in Tonga (Wiens & Snider 2001, Yu & Wen 2012) and Colombia (Prieto et al. 2012, Zhang et al. 2008) (**Figure 2*a***; **Supplemental Table 2**).

Supplemental Material >

Repeaters have also been found in more unusual, nontectonic settings. They are abundant in some active volcanoes (e.g., Battaglia et al. 2003, Hotovec-Ellis et al. 2015, Okada et al. 1981, Petersen 2007, Ratdomopurbo & Poupinet 1995, White et al. 1998). Repeaters have also been recognized in active landslides in Japan (Rausu) (Yamada et al. 2016), Colorado (Gomberg et al. 2011), and Greenland (Poli 2017); in glaciers in Antarctica (Danesi et al. 2007), the Alps (Helmstetter et al. 2015), and Washington (Thelen et al. 2013); during water injection in a geothermal field in France (Bourouis & Bernard 2007, Lengliné et al. 2014); among mining-induced microearthquakes in South Africa (Naoi et al. 2015); and even in clusters of 700–1,200-km-deep moonquakes (Frohlich & Nakamura 2009).

In addition to regular earthquakes, tremor and low-frequency events found in the deep roots of some plate boundary faults also appear to feature repeated source failures. Thousands of low-frequency earthquakes below the seismogenic zone of the San Andreas Fault near Parkfield have very similar waveforms and can be grouped into families that may represent frequent failure driven by surrounding fault creep (e.g., Shelly 2017). Thus, the rate of repeating low-frequency earthquakes appears to also be a direct measure of otherwise aseismic fault slip at depth (Thomas et al. 2018). Similar families of low-frequency earthquakes have been recognized in the Cascadia subduction zone (e.g., Bostock et al. 2015).

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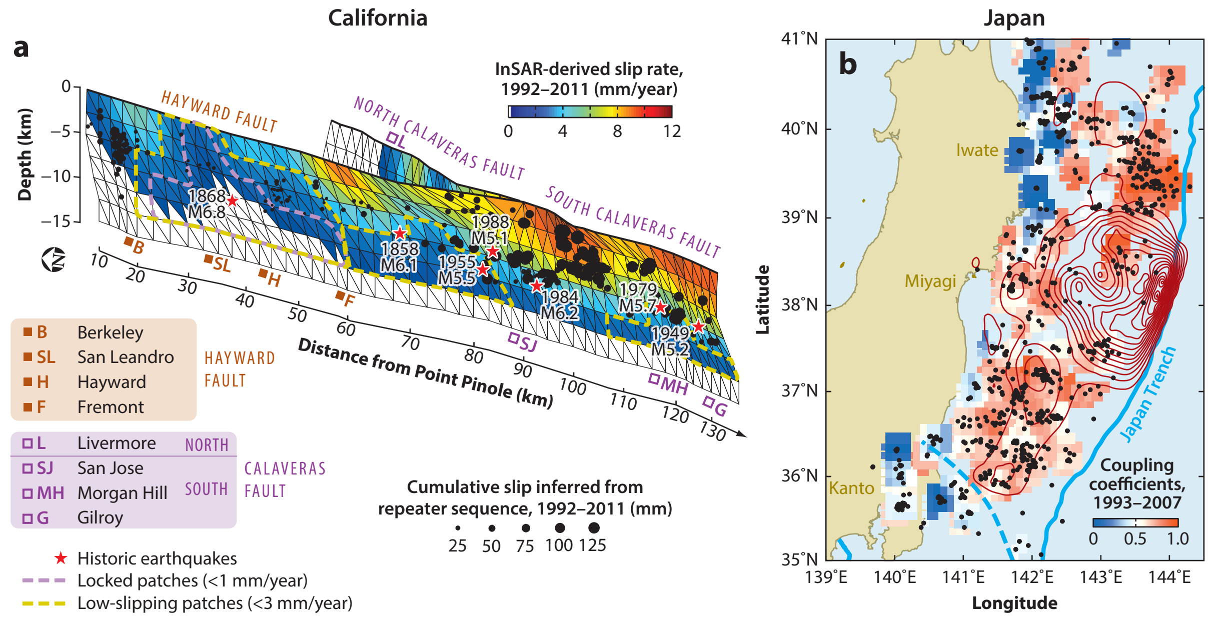

Figure 3

Slow fault slip inferred from repeating earthquakes. The spatial distribution of repeaters (*black circles*) is shown on (*a*) the Hayward and Calaveras Faults in California and (*b*) the subduction megathrust in northeastern Japan. In panel *a*, the symbol size is proportional to the 1992–2011 cumulative slip inferred from the repeater sequence. In panel *b*, the colors show coupling coefficients for the period 1993–2007, estimated from repeater-derived fault creep rates. Dark red contours indicate the coseismic slip distribution of the 2011 Tohoku-oki earthquake (M9.0) (Iinuma et al. 2012). The dashed blue line shows the northeastern limit of the Philippine Sea plate on the Pacific plate (Uchida et al. 2009). Panel *a* adapted from Chaussard et al. (2015); panel *b* adapted from Uchida & Matsuzawa (2011).

3.3. Spatial Distribution of Repeaters in California and Japan

Since there has been no global systematic search for repeaters, there are likely many more areas featuring repeaters than have been found to date (**Figure 2**). In California and Japan, however, more systematic searches have been carried out over relatively wide areas. In California, most repeater sequences with a large number of recurrences occur along the rapidly creeping sections of the San Andreas, Hayward, and Calaveras Faults (Waldhauser & Schaff 2008) (**Figures 2*b*** and **3*a***). Repeaters on these faults are found along zones of frequent and localized microseismicity, away from relatively quiescent, currently locked fault sections and historic earthquake rupture zones (e.g., Chaussard et al. 2015, Ryder & Bürgmann 2008). The area of greatest slip in the 1984 Morgan Hill earthquake (M6.2) coincides with a large hole, outlining the part of the fault that is locked between large earthquakes (Schaff et al. 2002). Repeaters that recurred more frequently following the 1984 mainshock are located around its periphery (Templeton et al. 2009). Other minor faults in the San Andreas Fault system on which more modest repeater activity is found are either known or suspected to creep at low (<5 mm/year) rates (e.g., Templeton et al. 2008, Turner et al. 2013, Xu et al. 2018).

In Japan, repeaters mostly occur along the Japan and Kuril subduction zones in northeastern Japan and along the Ryukyu trench (**Figure 2*c***). The repeaters are absent along the northern to central Nankai Trough. This distribution probably reflects the relatively strong locking along the Nankai subduction zone, where many historical ∼M8 earthquakes occurred. Along the Japan Trench, the M9 Tohoku-oki earthquake occurred where the density of repeaters is relatively low (**Figure 3*b***), and the main slip areas of the 1994 Tokachi-oki earthquake (M7.2) (Uchida et al. 2004) and the 2003 Tokachi-oki earthquake (M8.0) (Matsubara et al. 2005) also lack repeaters. Thus, repeater activity appears to be spatially anticorrelated with the locations of large earthquake rupture zones and concentrates in areas where geodetic models find lower coupling ratios.

Rate- and state-dependent friction: laboratory experiment-derived friction laws in which shear stress supported by a fault can be described as a logarithmic function of the fault slip rate and one or more variables that characterize the time-dependent state of fault zone materials

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4. MECHANICS OF REPEATING EARTHQUAKES

4.1. Nature and Scaling of Repeaters on Creeping Faults

The source characteristics of repeaters on plate-boundary faults, especially in relation to their recurrence intervals, were first examined based on elastic rebound theory for interplate earthquakes. Because crustal stress accumulation rates (1–50 kPa/year) in plate boundary zones are a small fraction of typical earthquake stress drops (1–10 MPa), repeaters featuring recurrence intervals of a few years or less must be driven by much faster loading. Locked patches distributed on an otherwise creeping fault zone experience such highly accelerated stressing rates (e.g., Bufe et al. 1977, Vidale et al. 1994).

Nadeau & Johnson (1998) took advantage of many repeater recurrences over a ∼10-year period on the San Andreas Fault near Parkfield and Stone Canyon to construct a scaling relationship between seismic moment, slip, stress drop, and recurrence time. They assumed that the slip areas are constant for each sequence and related the cumulative repeater slip to an average regional creep rate established from geodetic data. Their recurrence interval–seismic moment relationship appears to hold in many other regions once the difference in fault slip rates is taken into account (Chen et al. 2007, Dominguez et al. 2016, Igarashi et al. 2003, Yu 2013). This universality suggests that there is a common mechanism and scaling involved in repeaters on creeping faults. The recurrence interval–slip relationship is also generally consistent with rates inferred from surface geodetic measurements and plate convergence rates (Chen et al. 2008, Igarashi et al. 2003).

Nadeau & Johnson's (1998) scaling relationship also suggests that the stress drop increases with decreasing seismic moment. This is different from the typical observations for normal earthquakes with constant stress drop over a wide range of seismic moments (e.g., Abercrombie 1995). To describe the implied difference in source properties of repeating and nonrepeating events, Johnson & Nadeau (2002), Seno (2003), and Johnson (2010) proposed a heterogeneous fault patch model for repeaters to explain the seismic moment dependency of the stress drop. However, observations of repeaters revealed that there is no systematic pattern of stress drop that increases with decreasing seismic moment (Abercrombie 2014, Imanishi et al. 2004, Uchida et al. 2007, Urano et al. 2015).

To explain the discrepancy between the observations and magnitude-dependent stress drop changes that is expected from the empirical relation of Nadeau & Johnson (1998), Sammis & Rice (2001) considered repeating events to be concentrated along the border between locked and creeping sections on a fault. However, the wide spatial distribution of repeaters is not easily reconciled with such an edge model. Consideration of a magnitude-dependent contribution of aseismic slip during earthquake recurrences can also explain the empirical scaling relationship of repeaters and reconcile the apparent discrepancy (Beeler et al. 2001). Chen & Lapusta (2009) used earthquake simulations relying on laboratory-based rate- and state-dependent friction relations to study the moment–recurrence interval relationship. Their model of a small fault patch governed by steady-state velocity-weakening friction that is surrounded by a larger velocity-strengthening region can explain the relatively smaller fraction of seismic slip during the earthquake cycle of smaller events (**Figure 4**). In summary, individual repeaters on plate boundary faults probably have no special characteristics compared with ordinary earthquakes, but the observed scaling of magnitude,

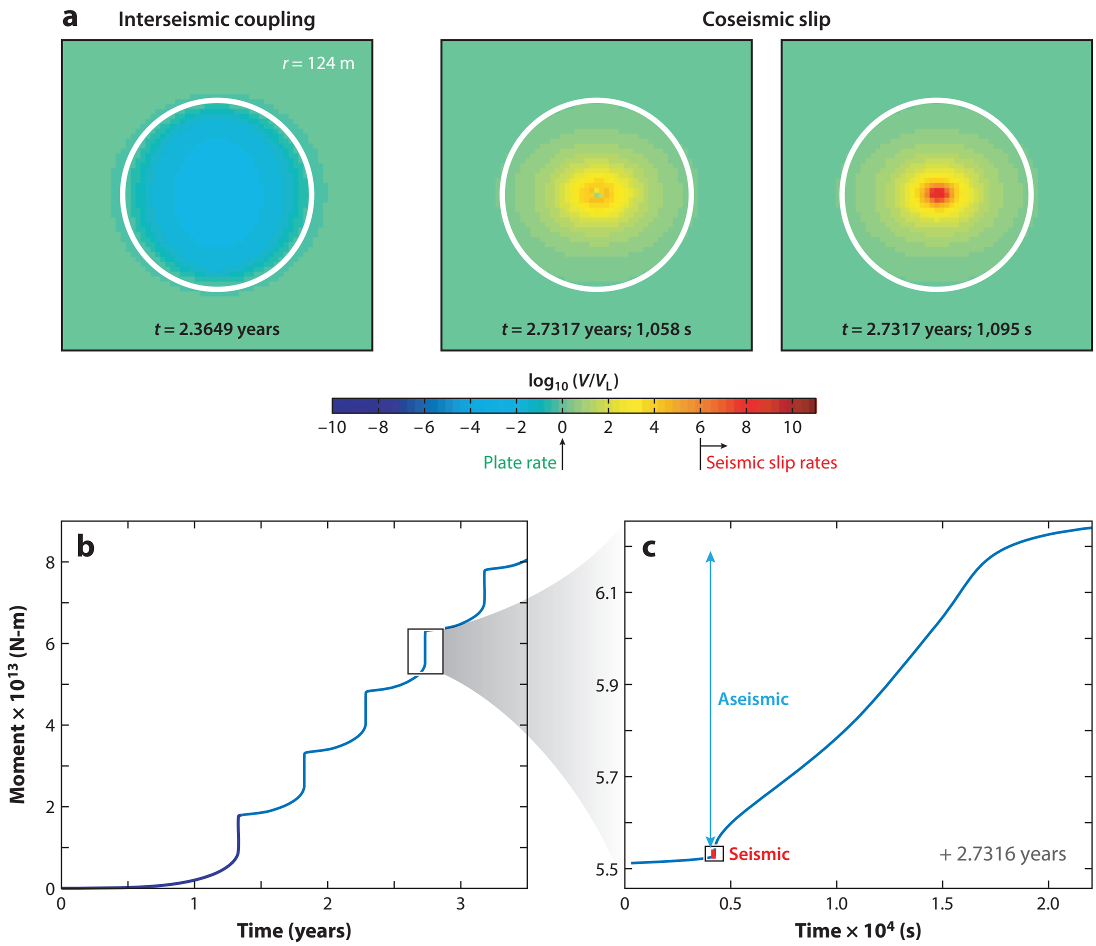

Figure 4

Seismic and aseismic slip during earthquake cycles of simulated repeating earthquakes governed by rate- and state-dependent friction. (*a*) Snapshots of slip rate. A velocity-weakening patch with a radius of 124 m is located at the center, surrounded by the creeping, velocity-strengthening fault surface. The left subpanel illustrates interseismic coupling of the patch, and the middle and right subpanels show times of coseismic slip near the center of the patch. (*b*,*c*) Cumulative moment release on the velocity-weakening patch (*b*) for multiple earthquake recurrences and (*c*) in close-up at the time of seismic slip. In this example, only a small fraction of the total moment of the patch slip is seismically released, and there is significant preseismic and postseismic slip. Figure adapted from Chen & Lapusta (2009).

recurrence interval, and coseismic slip suggests that they feature an increasing aseismic slip component with decreasing magnitude.

4.2. Source Processes of Repeaters in Other Settings

For repeaters that are far from plate boundary faults, different source models may be indicated. Some repeaters have been found in areas with little or no resolvable tectonic strain, mostly in the form of burst-type clusters. The inland earthquakes in China that have similar waveforms amount to nearly 10% of total seismicity, and most are doublets with repeat intervals of one month or less (Schaff & Richards 2004). Given the choice of a relatively low waveform cross-correlation

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coefficient threshold (0.8) used for selecting events, in this case, most of the events are probably not overlapping, and short-term triggering of immediately adjacent fault patches is indicated. Such burst-type repeaters are also found in Japan (Igarashi 2010, Igarashi et al. 2003) and California (Templeton et al. 2008). However, it is interesting that sequences of high-quality repeaters were found in the New Madrid seismic zone in the United States (Bisrat et al. 2012) and in the aftershock sequence of the 2000 Western Tottori earthquake (Mw6.6) (Hayashi & Hiramatsu 2013). Special conditions, such as loading by a large mainshock or high pore fluid pressure, may be necessary to produce repeaters on inland tectonic faults, which usually have extremely low loading rates.

For intermediate- and deep-focus events, some physical models of the source process of such events seem to preclude repeated fault failures (Houston 2015, Kelemen & Hirth 2007), but the generation mechanisms continue to be under discussion (Hasegawa & Nakajima 2017). Nonetheless, repeaters have been recognized among intraslab events. Yu & Wen (2012) identified a single sequence with overlapping earthquake sources in the Tonga–Fiji subduction zone, where 66% of the globally recorded deep seismicity occurs. Prieto et al. (2012) and Zhang et al. (2008) found very similar earthquakes in a dense cluster of events at 145–165-km depth in Colombia, including some with reversed polarity. Nakajima et al. (2013) examined earthquake clusters with similar waveforms at ∼150-km depth in the northeast Japan subduction zone and concluded that they have complementary rupture areas. These studies suggest that it is rare for stress to rapidly reaccumulate on exactly the same structure in deep subducted slabs; further study is necessary to examine whether true repeaters with overlapping source areas occur in intermediate- and very deep-focus earthquakes, and what processes might be responsible for generating repeaters there.

Repeaters in volcanoes are often observed preceding eruptions (Ketner & Power 2013, Thelen et al. 2011), during the growth of lava domes (Hotovec-Ellis et al. 2015, Okada et al. 1981, White et al. 1998), during basaltic eruptions (Battaglia et al. 2003, Saccorotti et al. 2007), and as volcano-tectonic earthquakes during noneruptive time periods. Various mechanisms have been proposed for repeaters in volcanoes, including stick-slip events along the edges of an extruding plug of solidifying magma (Thelen et al. 2011); slip along nearby cracks where gases escape from the conduit (Thelen et al. 2011); resonance of a magmatic conduit, cavity, or crack (Battaglia et al. 2003, Saccorotti et al. 2007); and rapid slip on brittle shear surfaces activated during magmatic transport. Petersen (2007) proposed that shock waves due to accelerations of fluid to supersonic speed prompted the occurrence of frequent repeating long-period earthquakes at Shishadin volcano. Thelen et al. (2011) observed a decrease in the fraction and lifespan of similar earthquakes to total seismicity before eruptions. They related the observation to a relatively unstable environment prior to explosions, characterized by large and variable stress gradients.

For repeaters found at mobile landslides and glaciers, stick slip of small patches on basal or lateral slip surfaces is the most likely mechanism (Danesi et al. 2007, Yamada et al. 2016). In geothermal areas, fluid pressure may reduce the normal stress on faults, leading to slow slip and repeated ruptures (Lengliné et al. 2014). For earthquakes in mining environments, loading can be extremely rapid due to the expansion of mined-out cavities, which can drive repeated failure (Naoi et al. 2015). It is important to note that the mining-induced microrepeaters ($-5.1 \leqq M_w \leqq -3.6$) yielded an impossibly large estimate of the driving creep when analyzed using Nadeau & Johnson's (1998) scaling relationship, and this relationship seems not to be applicable to these events. For the deep moonquakes, the periodic tides are considered the primary source of stress, but contributions from other tectonic processes are also possible (Frohlich & Nakamura 2009). Some of the lunar repeater clusters feature reversals in event polarity that seem indicative of periodically reversed tidal stress, but this is not always the case (Weber et al. 2009). It is important to resolve whether such reversed events share the same slip areas. In conclusion, the physical conditions allowing for repeated failures away from rapidly slipping plate boundary faults include transient elevation of loading rate (e.g., afterslip, stress perturbation, mining), increased pore pressure, fluid movements, and volcanic activities.

4.3. Source Structure of Tectonic Repeaters

The slip distribution, secondary microearthquakes in the source areas, and temporal changes of repeaters provide valuable information about their source structure. The slip distribution of an ∼Mw2.1 repeater sequence (**Figure 1*c***) in Parkfield, estimated using empirical Green's functions, suggests that there is a slip patch with high stress drop of 67–94 MPa, in contrast to the average stress drop, which is small (2.5−5.6 MPa) (Dreger et al. 2007). Such high-stress-drop patches suggest relatively isolated contact points where high-stress concentrations can develop and be released on a regular basis (Dreger et al. 2007). Subtle temporal changes in the Parkfield repeater waveforms suggest spatial variability in nucleation points, and the inferred peak slip and stress drops were systematically reduced following the nearby 2004 *M*6 Parkfield earthquake (Kim et al. 2016). Chen et al. (2016) and Hatakeyama et al. (2016) propose that inherent heterogeneity of stress and strength may be tied to the irregularity of repeating earthquake slip and recurrence.

The fine-scale structure of the repeater source can be studied through observations of microseismicity within and around repeater ruptures. Precise estimation of the source locations, together with the source dimensions, of Kamaishi-oki earthquake cluster events (Matsuzawa et al. 2001, 2002) suggests that the smaller earthquakes ($2 \leqq M \leqq 4$) are contained within the rupture area of the ∼*M*5 repeater sequence (**Figure 5*a***) (Uchida et al. 2007, 2012). This suggests that patches within the source area of repeaters with larger magnitude can be ruptured by smaller earthquakes (i.e., the earthquake source area can have a hierarchical structure). A similar hierarchical structure was also observed for smaller earthquakes, where ∼*M*1 events locate within the source areas of ∼*M*2 earthquakes (Dreger et al. 2007, Godano et al. 2015), and for the much larger Tohoku-oki earthquake, where earlier ∼*M*7 earthquakes occurred in the eventual coseismic slip area of the *M*9.0 rupture (Uchida & Matsuzawa 2011).

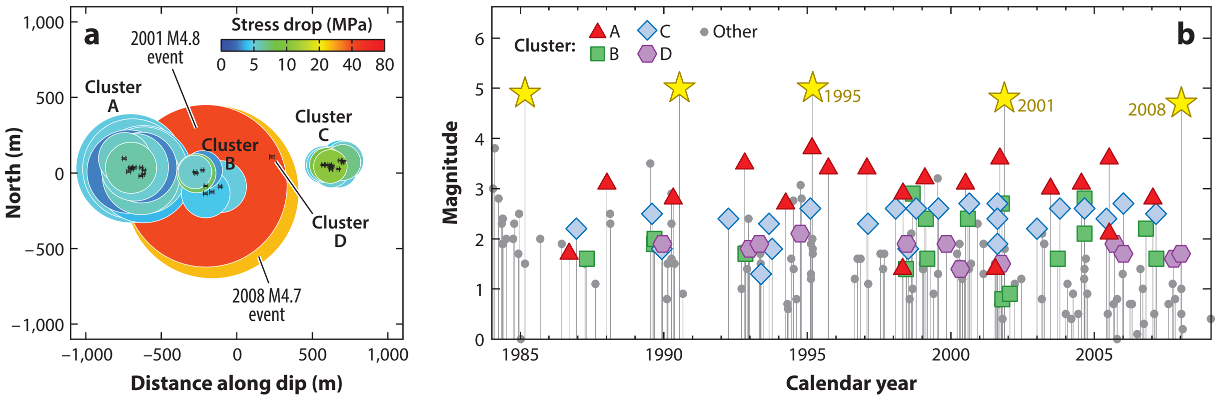

Figure 5

Hierarchical structure and temporal evolution of small and large repeater slip areas for the Kamaishi-oki earthquake cluster. (*a*) Spatial distribution of repeating earthquake patches on the subduction thrust. Colors represent stress drops of events during the period from 1995 to 2008. The source sizes are estimated from corner frequencies of the earthquake spectra. (*b*) Temporal distribution of the earthquakes in the area shown in panel *a*. The small earthquakes (clusters A–D with *colors* and other nearby earthquakes in *gray*) tend to occur more frequently later in the earthquake cycle of the ∼*M*5 mainshocks (*yellow stars*). Please note that this panel shows more earthquakes than those from 1995 to 2008 whose locations and stress drops are estimated in panel *a*. Figure adapted from Uchida et al. (2012).

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The stressing process on the repeater patch is illuminated by the nearby microseismicity spanning multiple cycles. A cluster of smaller repeaters within and very close to the repeating ∼*M*5 Kamaishi-oki earthquakes appears to be quiet immediately after each recurrence and then accelerates toward the eventual recurrence of the next ∼*M*5 mainshock (**Figure 5*b***) (Uchida et al. 2007). This pattern of temporal change of microseismicity during the Kamaishi-oki earthquake cycles did not change when the recurrence intervals of the ∼*M*5 sequence were reduced to as short as nine days due to postseismic stress changes from the 2011 Tohoku-oki earthquake (Okuda et al. 2018). A comparison of finite slip models of two successive occurrences of the Kamaishi-oki sequence suggests that differences in slip distribution lie in the region where the smaller earthquakes occur in the interseismic period (Shimamura et al. 2011). The spatiotemporal pattern of the microseismicity probably reflects the local stress loading and/or fault healing processes during the ∼*M*5 earthquake cycles. Such a multiscale structure is probably a fundamental aspect of earthquake sources that may determine the complex earthquake rupture process (Ide & Aochi 2005).

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4.4. Repeater Source Interactions

A large number of closely spaced repeaters and nearby background events provide a unique opportunity to assess the change in recurrence interval due to stress interactions. Examination of triggering effects of 112 ∼*M*0.4–3.0 sequences at Parkfield suggests that nearby seismicity can trigger repeater occurrences in a matter of several days or less, while spatially isolated repeaters tend to exhibit more regular recurrence intervals (Chen et al. 2013). Chen et al. also found that the distance over which short-term triggering is evident increases from <1 km to 4 km as the magnitude of the source event increases from *M*1 to *M*4. A static stress increase of ∼30 kPa can be enough to produce resolvable triggering. In addition to static stress triggering, Wu et al. (2014) proposed dynamic triggering of ∼*M*1–3 sequences along the San Andreas Fault by regional to global *M*4–9 earthquakes. They documented a weak correlation between dynamic perturbations in excess of ∼20 kPa and shortened recurrence intervals.

4.5. Repeater Source Variations

The source processes of repeaters can also change due to physical perturbation in the surrounding host rock. The waveform amplitudes of repeaters that occurred during a water circulation test in a geothermal reservoir in the Soultz-sous-Forêts in France suggests that the earthquake dimension estimated from the corner frequency did not change during the test but that the slip amplitude fluctuated (Lengliné et al. 2014). This indicates variations in the stress drop of the earthquakes, most likely due to changes in effective normal stress on the interface caused by varying fluid pressure. This is an important observation of source property changes related to a decrease in fault strength.

The effect of slow slip or loading rate on repeater source characteristics has also been examined in California and Japan. Laboratory studies predict fault strength recovery proportional to a power of the time of stationary contact (Dieterich & Kilgore 1994). Such behavior, predicting increasing seismic moment with increasing recurrence interval, was found on both the Calaveras and San Andreas Faults in California (Nadeau & McEvilly 1999, Taira et al. 2009, Vidale et al. 1994). However, Peng et al. (2005) found increased seismic moment with decreasing recurrence interval (faster loading rate) for deep (5.5 km) repeaters, although seismic moment decreased with decreasing recurrence interval (faster loading rate) at shallow depths (≦5.5 km). For the negative dependency on recurrence interval observed for deeper repeaters, Peng et al. (2005)

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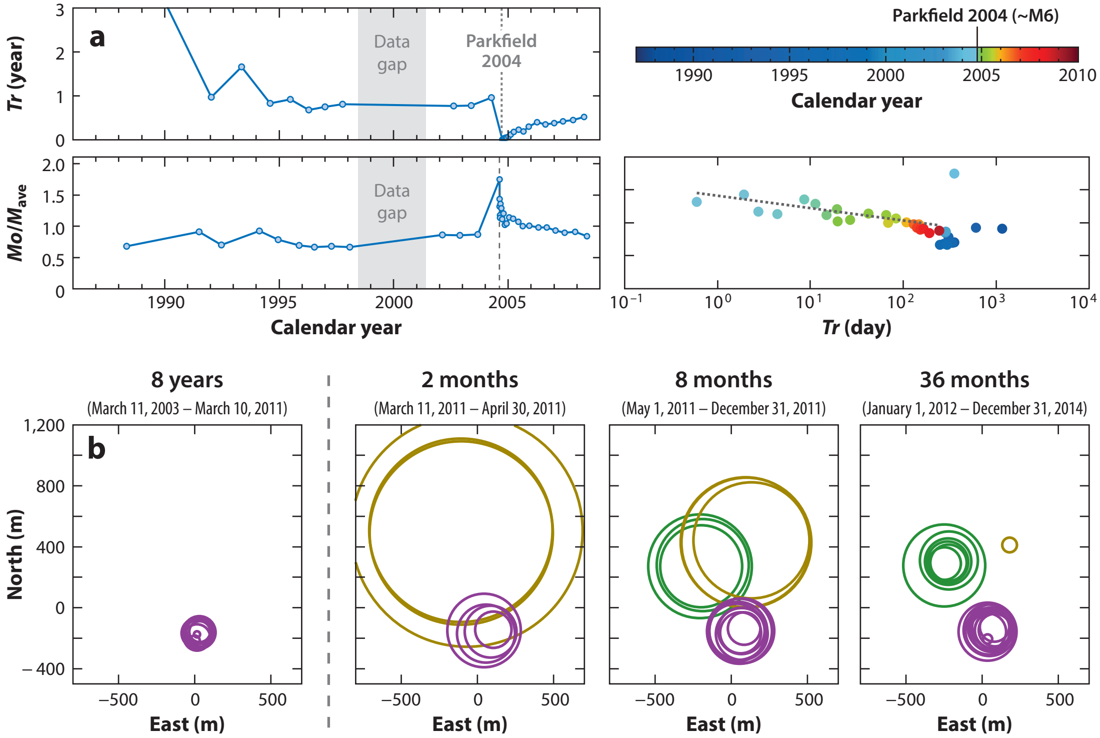

Figure 6

Temporal changes of source characteristics of a repeating earthquake sequence. (*a*) Scaled moment (Mo/M_{ave}; seismic moment divided by its average)–recurrence interval (*Tr*) relationship for a repeating earthquake sequence affected by large loading rate variations (*right*). The graphs on the left show temporal changes in *Tr* and Mo/M_{ave}. This ~M0.6 repeater sequence is located in a zone of rapid afterslip, updip of the coseismic rupture zone of the 2004 Parkfield earthquake. Panel adapted with permission from Chen et al. (2010). (*b*) Repeating earthquake activity in a small area on the northeastern Japan Megathrust (~39.75°N, 142.36°E) before and after the March 11, 2011, Tohoku-oki earthquake (M9.0). The observation time periods are shown above each panel. Circles representing each repeater location are scaled assuming a 10-MPa stress drop. Circles with the same color show the events whose centroid locations are very close. Panel adapted with permission from Hatakeyama et al. (2017).

speculated that high strain rate in the early postseismic period may cause transient embrittlement and strengthening of the deep repeater sources.

The many repeater sequences near Parkfield were also examined in terms of their variable seismic moments and recurrence intervals before and after the 2004 M6 earthquake (Chen et al. 2010, Taira et al. 2009). Chen et al. (2010) show that most small sequences demonstrate increased moment with decreasing recurrence interval (faster loading rate) (**Figure 6*a***), while some larger-magnitude sequences, such as the ~Mw2.1 sequence studied by Kim et al. (2016), show the opposite relationship. These observations are qualitatively consistent with earthquake simulations with rate- and state-dependent friction, where repeaters are produced on velocity-weakening patches surrounded by velocity-strengthening fault areas (Chen & Lapusta 2009). Similarly, the response of repeaters to afterslip of the 2011 Tohoku-oki earthquake showed that most repeaters shortened their recurrence intervals and increased in seismic moment under the faster loading rate (Uchida et al. 2015). The slip distributions estimated for the ~M5 Kamaishi-oki sequence show that not only the peak slip but also the source dimension became larger. This means that the area where aseismic slip (creep) was occurring under slow loading rates before the Tohoku-oki earthquake underwent seismic slip under faster loading rates. Hatakeyama et al. (2017) show that some repeater sequences actually emerged in the area where interplate seismicity was absent before the mainshock. While such emergence was observed after the 2004 Parkfield earthquake, and pre-earthquake quiescence was attributed to nearby interseismic locking of the fault (Lengliné & Marsan 2009), the geodetic and seismic data at Tohoku suggest that the source area was creeping before the onset of repeater activity (Hatakeyama et al. 2017). These M3–6 repeaters were only active during the postseismic slip acceleration and then disappeared again as afterslip slowed down (**Figure 6*b***). The apparent emergence and disappearance of the same sequence in Tohoku suggest that the temporal change in loading rate fully alternated the slip mode (seismic/aseismic) of repeater patches. This result indicates the importance of conditional stability of frictional fault surfaces (e.g., Bilek & Lay 2002) for the generation of these earthquakes. In summary, the variable seismic moment of repeaters seems not to be a simple function of contact time (recurrence interval) but rather to reflect more complex frictional properties near the transition from stable to unstable sliding.

Conditional stability: frictional fault behavior near the stable–unstable slip transition where both aseismic and seismic behavior can occur due to changes in loading rate, fluid pressure, and slip patch dimensions

Laboratory studies of repeaters suggest an increased high-frequency component of the lab-repeater waveforms with larger recurrence time (McLaskey et al. 2012). Such a change in high-frequency components with healing time is also observed in repeaters on the San Andreas Fault (McLaskey et al. 2012). These observations and experiments suggest that increased healing causes a disproportionately larger amount of high-frequency seismic radiation. This illuminates the importance of the fundamental fault loading conditions and time-dependent frictional fault properties that govern earthquake source characteristics.

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5. SCIENTIFIC USES OF REPEATER DATA IN GEOPHYSICS

5.1. Illuminating Subsurface Fault Structure

Accurate hypocenter determinations enable us to examine the structure of fault zones. Streaks of seismicity that include many repeaters aligned with the direction of fault slip are a common feature along creeping sections of the San Andreas Fault (Rubin et al. 1999, Waldhauser et al. 2004) and the Calaveras Fault (Schaff et al. 2002). The location of repeaters may reflect a locally irregular fault surface geometry (Hasegawa et al. 2007, Zhan et al. 2012). Intervening areas where earthquakes are absent (holes) can be interpreted as either locked or freely creeping. Therefore, the distribution of repeaters can tell us about both fault structure and coupling.

Another important feature of the data obtained from repeater hypocenter distributions is that repeater sequences are not always coplanar. On the San Andreas Fault near Parkfield, repeater-hosting faults are offset by a few hundred meters, suggesting that slow slip there is accommodated on multiple subparallel strands (Waldhauser et al. 2004). As markers to discriminate seismicity on the primary actively deforming interplate fault from seismicity on secondary structures, Kimura et al. (2006) and Hirose et al. (2008) used repeaters in Kanto, Japan, to determine the depth to the upper surface of the Philippine Sea plate.

Repeaters are also useful when trying to find the subset of earthquakes near a plate boundary that are true interplate events. About 38% of offshore seismicity in the Tohoku subduction zone does not have interplate-type focal mechanisms (Nakamura et al. 2016), suggesting that many earthquakes do not occur on the main plate boundary fault. Nakamura et al. (2016) used repeaters and earthquakes with focal mechanism data as templates to find the focal mechanism type of many more earthquakes off Tohoku, Japan. The results show clear changes in the distribution of interplate earthquakes before and after the Tohoku-oki earthquake.

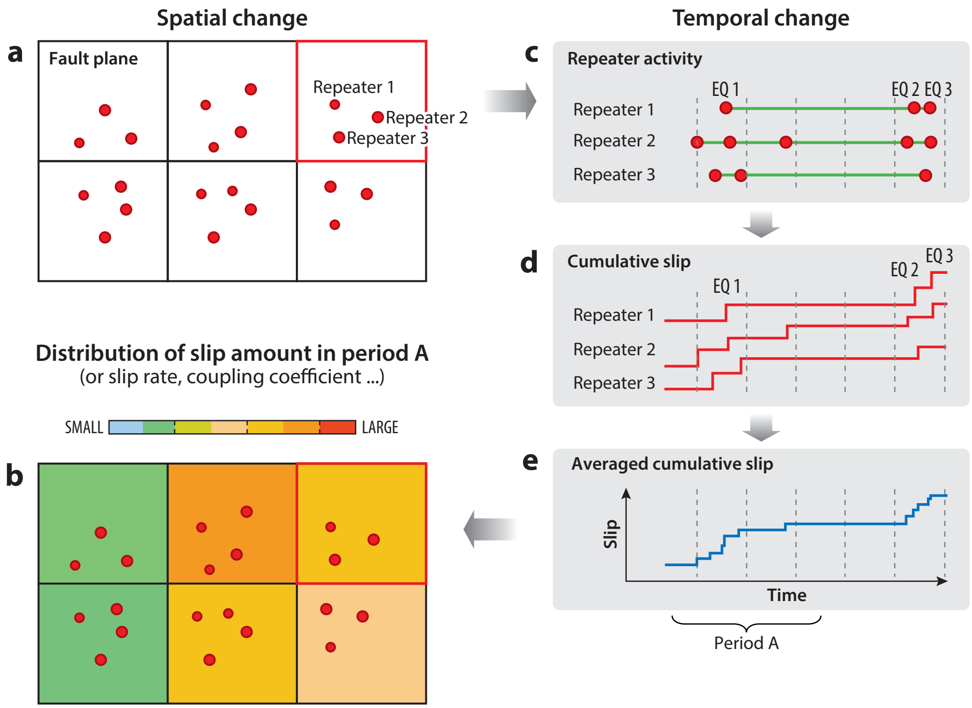

Figure 7

Example of an estimation method to determine the spatiotemporal variation of slow slip from sequences of multiple repeaters. (*a*) Spatial distribution of repeating earthquake sequences on a gridded fault surface. (*b*) Final slip distribution for an observation period A based on average slip or slip-rate estimates in each grid cell. (*c*) The temporal distribution of repeaters in each sequence in one of the grid cells. (*d*) Cumulative slip of earthquakes in each repeater sequence. (*e*) Averaged cumulative slip within the grid cell. The slip amount, slip rate, or coupling ratio during period A can be plotted as shown schematically in panel *b* and in the examples in **Figure 3**. Abbreviation: EQ, earthquake.

5.2. Spatiotemporal Estimation of Slow Fault Slip at Depth

Since the stress accumulation of the repeater patches is considered to be due to slow slip on the surrounding fault area, repeaters can be used to quantify the fault creep. The cumulative slip of repeaters is assumed to be equal to the fault creep because the stick-slipping fault patches keep up with the surrounding slow slip (**Figure 1*a***). The combination of many repeater sequences enables us to estimate variations of slip in space and time in which each repeater is used as a simple creep-meter embedded in the plate boundary. **Figure 7** demonstrates how slow slip is inferred from repeaters. There are several relationships relating seismic moment and repeater slip. A commonly used one is the Nadeau & Johnson (1998) model described in Section 4.1. Many studies successfully used this relationship to estimate interplate slip (e.g., Chen et al. 2007, Igarashi et al. 2003, Materna et al. 2018, Yu 2013). Other approaches include the Beeler et al. (2001) model, which considers the contribution of aseismic slip in the interseismic period (Mavrommatis et al. 2015), or a method using a crack model assuming constant stress drop or strain drop (Schmittbuhl et al. 2016, Yao et al. 2017).

Fault coupling: degree to which slip on a section of a fault is held back during the interseismic period

The mean slow-slip rate and associated fault coupling provide important information for evaluating earthquake potential. The interplate coupling ratio estimated from repeaters before the Tohoku-oki earthquake (**Figure 3*b***) is relatively large in the area where the coseismic slip was

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moderate to large (Uchida & Matsuzawa 2011). The repeaters located within the eventual rupture zone also indicate that parts of the slip area of the Tohoku-oki earthquake underwent some aseismic slip, suggesting heterogeneous coupling and a rupture breaking through creeping sections of the megathrust. **Figure 3*b*** also suggests that, in the southern part of the Tohoku area (Kanto), where the subducting Philippine Sea plate is overlying the subducting Pacific plate, the coupling coefficient is low over a wide depth range. This can be interpreted as being due to the existence of a serpentinized mantle wedge at the bottom of the Philippine Sea plate (Uchida et al. 2009). For the Hayward and Calaveras Faults, Chaussard et al. (2015) used InSAR data to compute an interplate coupling model and showed that the distribution is very consistent with repeater-derived slip rates (**Figure 3*a***). From the inferred coupling distribution, they estimated potential earthquake sizes along the fault zone consistent with the rupture zones of a number of historic large events.

The temporal changes of slow slip estimated from repeaters also provide important information on the nature of fault slip. Along much of a 175-km-long creeping segment of the central San Andreas Fault, the slow slip rate inferred from repeaters exhibits periodic changes (Nadeau & McEvilly 2004, Nadeau et al. 2005, Turner et al. 2015) (**Figure 8*a***). Similar periodic slip-rate pulses were also found in the Tohoku subduction zone (Uchida et al. 2016) (**Figure 8*b***). Surface creepmeters, GPS, and/or InSAR data lend support to the slip-rate variations inferred for the San Andreas Fault and Tohoku Megathrust (Khoshmanesh et al. 2015, Nadeau & McEvilly 2004, Uchida et al. 2016). It is important to note that the slow slip transients sometimes precede large earthquakes, suggesting a triggering relationship (Kato & Nakagawa 2014, Kato et al. 2012, Meng et al. 2015, Uchida et al. 2016). Temporally decaying afterslip following larger ruptures can also be estimated from repeaters (e.g., Matsubara et al. 2005, Meng et al. 2015, Shirzaei et al. 2014, Templeton et al. 2009, Uchida et al. 2003, Yao et al. 2017). In addition to these shorter-term slip rate variations, GPS and repeater data show that a long-term unfastening of the plate boundary occurred in the ~10 years before the Tohoku-oki earthquake, possibly as part of the final stage of the earthquake cycle of the impending *M*9 rupture (Mavrommatis et al. 2015). Slow slip is an important component of the earthquake cycle (Avouac 2015, Bürgmann 2018), and the study of repeaters contributes to a more comprehensive understanding of slow slip.

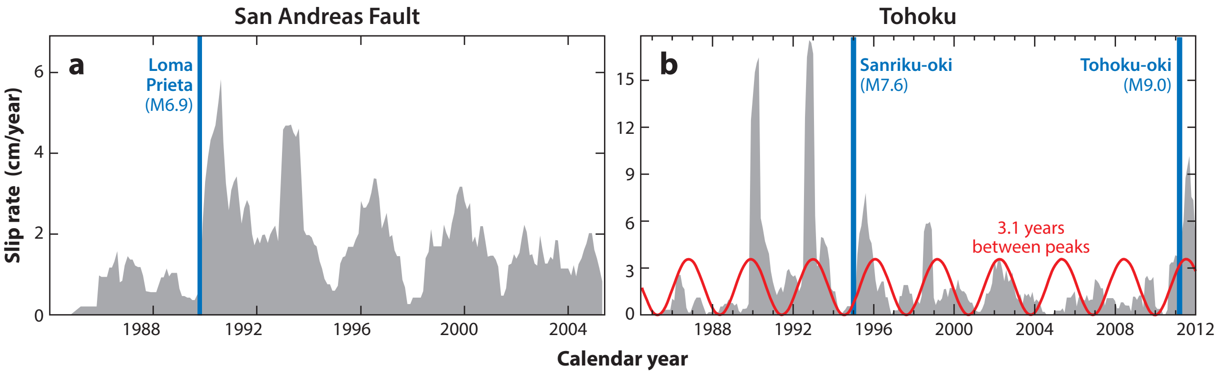

Figure 8

Periodic slip-rate changes found (*a*) on a creeping section of the San Andreas Fault located approximately 90 km northwest of Parkfield and (*b*) in the offshore Sanriku region of the Tohoku subduction zone. Gray shading shows temporal changes of the slip rate estimated from repeating earthquakes for the two target fault areas. Slip rates were estimated using moving 0.8-year and 0.5-year time windows for panels *a* and *b*, respectively. The red line in panel *b* is a sinusoidal curve (period of 3.1 years) fitted to the Tohoku data. Panel *a* adapted from Nadeau et al. (2005); panel *b* adapted from Uchida et al. (2016).

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5.3. Testing Earthquake Predictability

Small repeaters that have many complete earthquake cycles during the instrumental period provide a good opportunity to define the nature of earthquake recurrence and their predictability. Knowing the correct distribution of recurrence intervals is important for the calculation of earthquake probabilities. Using a large data set of repeaters, Ellsworth (1995) suggested that the probability distribution of recurrence intervals is a long tailed one, such as a log-normal or Gamma distribution. Nadeau et al. (1995) also showed that the recurrence intervals of a sequence ranging from 0.2 to 2.8 years fit a log-normal distribution. Relying on recurrence interval data from repeaters in Parkfield and northeastern Japan, Goltz et al. (2009) reached the conclusion that both the Weibull and log-normal distributions fit the data. Zechar & Nadeau (2012) used a sequence-specific, time-varying hazard function from several distributions and showed that its performance is better than that of a distribution relying on random guessing. Okada et al. (2007) estimated the prior distribution of parameters in an earthquake renewal model with log-normal distribution from the intervals of small repeaters in northeastern Japan. Okada et al. suggested larger variance in the recurrence intervals of small repeaters selected from waveform similarity ($M \leqq 5$) than in those of large and moderate earthquakes from individual studies of characteristic earthquakes ($M \geqq 5$), which can be interpreted as indicating that the smaller-event sequences were perturbed by the stress changes from nearby larger events. However, this difference may also reflect a selection bias in the identification of large-magnitude characteristic earthquake sequences. Tanaka et al. (2018) retrospectively examined the effect of the number of known recurrence intervals for the performance of a long-term forecast of earthquake timing and illustrated that, initially, the performance rapidly improved, reaching a plateau after approximately 10 known intervals. When there were only a few repeats available in the data set, the difference between different forecast models was largest, and the Bayesian statistics log-normal distribution model had the best performance.

In contrast to renewal models, which assume no memory of previous events, there are physical models that account for specifics of the sequence to date. Rubinstein et al. (2012) examined the time- and slip-predictable models (e.g., Shimazaki & Nakata 1980), in which recurrence time or slip amount depends on the time of the previous event, and found that fixed recurrence and slip models better predict earthquakes than do time- and slip-predictable models.

In another practical application, Yagoda-Biran et al. (2015) used repeaters to examine the event variance of ground shaking. They found that the variance of ground shaking between repeating events is smaller than the variance between earthquakes in multiple locations. At sites where the hazard is controlled by a single recurring source, one could potentially use between-event variance in seismic hazard calculations.

5.4. Temporal Changes in Earth Structure and Properties

Observing temporal changes in Earth structure is key to improving understanding of dynamic processes of Earth, including changes in fault zones related to earthquake faulting; the evolution of volcanic systems; the response of the shallow subsurface to seismic shaking, fluid flow, and other sources; and the rotation of Earth's core. Repeating earthquakes can provide a stable and strong seismic energy source to estimate temporal property changes in volumes of interest.

5.4.1. Structure change related to earthquakes.

Changes in wave speed in rock samples due to the formation of dilatant cracks or addition of water have been experimentally observed (e.g., Birch 1960, Simmons 1964), and the study of temporally changing seismic velocities and associated

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changes in Earth structure near seismogenic faults has long been a focus of research aimed at improved understanding of the earthquake process and earthquake prediction.

In an early study, Poupinet et al. (1984) used repeaters spanning an earthquake on the Calaveras Fault in California to estimate subtle temporal changes of crustal velocity, evident in a stretched waveform of the delayed arrival. By using the phase delay along the wave trace between events that occurred before and after the 1979 Coyote Lake earthquake (*M*5.9), they showed that the S-wave velocity decreased by 0.2% around the southern end of the aftershock zone. Coseismic velocity decreases and/or subsequent recovery in the shallow crust from repeaters have been reported for aftershock zones of the 1989 Loma Prieta (Mw6.9) and 1984 Morgan Hill (Mw6.2) earthquakes in California (Schaff & Beroza 2004), the 1999 Izumit (Mw7.4) and Duzce (Mw7.1) earthquakes (Peng & Ben-Zion 2006), the 2004 Sumatra–Andaman (Mw9.2) and 2005 Nias (Mw8.6) earthquakes (Yu et al. 2013), and the 2003 Tokachi-oki earthquake (*M*8.0) (Rubinstein et al. 2007).

However, there exists an argument about whether the velocity reduction is due only to near-surface damage. Rubinstein et al. (2007) suggested that the coseismic velocity reduction occurs both near the surface and deeper in the fault zone by using waveforms with various travel paths. Sawazaki et al. (2015) used repeating earthquake sources to reveal an apparent velocity reduction of 0.2% and 0.1% in P and S waves, respectively, after the 2011 Tohoku-oki earthquake (**Figure 9*a***). They suggest a 1% velocity reduction at 0–150-m depth and a 0.1% or smaller reduction down to 80-km depth from waveform simulation. They also show that the postseismic recovery of velocity in the deep zone is slower than that near the ground surface. Chen et al. (2015) also employed waveform simulation to estimate the location of velocity changes for the 1999 Chi-Chi earthquake and showed that stations in the footwall of the *M*7.7 rupture show the combined effect of near-surface and fault zone damage, where the velocity reduction (2–7%) is two to three times greater than at hanging wall stations.

Temporal changes of crustal properties other than seismic velocity have also been reported. Niu et al. (2003) found a systematic temporal variation in the seismograms of repeating microearthquakes that occurred on the Parkfield segment of the San Andreas Fault over the decade 1987–1997. Their results suggest the existence of a 10-m shift of scatterers during the period that may be due to stress-induced fluid migration associated with an aseismic slip transient in 1993. Taira et al. (2009) used the temporal changes of the repeater waveforms to characterize changes in fault strength. They suggest that the fault strength was affected by the teleseismic surface waves of the distant *M*9 2004 Sumatra–Andaman earthquake, suggesting a process that could explain global clustering of large earthquakes.

5.4.2. Structure change related to other processes. Improved knowledge of subsurface structure changes associated with magmatic intrusions and other volcanic processes is important for better understanding of volcanic systems and short-term eruption forecasting. Repeating earthquakes can provide important direct information about temporal changes of nearby subsurface volumes affected by magmatic processes. A velocity increase inside Merapi volcano has been inferred from the coda wave time delay between repeaters (Poupinet et al. 1996, Ratdomopurbo & Poupinet 1995). The velocity increase started 10 months before the eruption and was interpreted as a consequence of pressure increase in the magma chamber or in the conduits that resulted in closure of nearby cracks. The seismic velocity changes monitored by repeaters at Mount St. Helens show fluctuating velocity, and the magnitude of changes was largest near the newly extruding dome (Hotovec-Ellis et al. 2015). The velocity fluctuations correlate with seismicity rates, reflecting fluctuations of pressure in the shallow subsurface in the period of active volcanism.

Repeaters have even proven useful for detecting changes in Earth's inner core. Larger repeaters provide a powerful and stable source whose seismic waves repeatedly travel through Earth's inner

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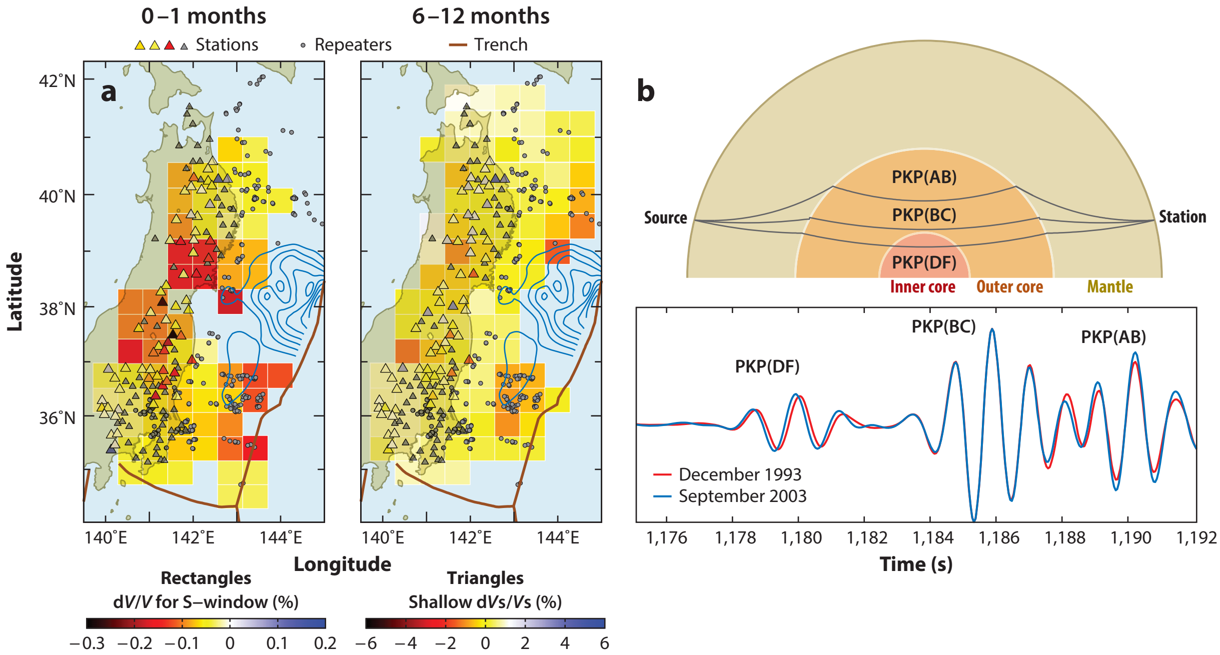

Figure 9

Imaging of changes in Earth structure from changing seismic velocities along the path of repeater seismic waves. (*a*) The distribution of the apparent S-wave velocity change (dV/V) after the 2011 Tohoku-oki earthquake estimated from a linear fit to the phase shift between waveforms of 218 repeating earthquake sequences (*circles*) observed at Hi-net seismic stations (*triangles*). The colors of the triangles show shallow (depth $\leqq$ 150 m) S-wave velocity changes (dVs/Vs) estimated from borehole data (Sawazaki & Snieder 2013). The colored squares in the two panels show the velocity changes from before the Tohoku-oki earthquake until 0–1 and 6–12 months after the earthquake. The velocity reduction along the path from the interplate repeaters is relatively small, but the spatial distribution is consistent with the stress change by the Tohoku-oki earthquake and is decaying with time. Panel *a* adapted from Sawazaki et al. (2015). (*b*) An example of waveform of earthquake doublets (repeaters) at the South Sandwich Islands region recorded at Alaska and illustration of how doublets are used to detect inner-core travel time change. (*Top*) The ray paths of PKP waves that travel in Earth's core. (*Bottom*) The wave that travels through the inner core [PKP(DF)], showing a shift between two repeating earthquakes in December 1993 (*red*) and September 2003 (*blue*). Waves that travel along other paths [PKP(AB) and PKP(BC)] do not show a phase shift. Panel *b* adapted from Zhang et al. (2005).

core and can thus provide an accurate measurement of its rotation rate relative to the mantle (super-rotation) (**Figure 9*b***). Poupinet et al. (2000) used repeaters to test the existence of super-rotation and concluded that the relative rotation speed is smaller than ∼0.2° per year. Zhang et al. (2005) found waveform shifts between phases that traversed the inner core and those that did not (**Figure 9*b***), showing that the inner core is rotating faster than the mantle and crust by approximately 0.3–0.5° per year. Zhang et al. (2008) utilized a larger number of global ≥M4 repeaters to find more complex variations in changing travel times that have been interpreted as reflecting both the rotation and the heterogeneous structure of the inner core.

SUMMARY POINTS

1. Repeating earthquakes have nearly identical waveforms and locations. Repeaters that slip identical rupture patches allow for one to estimate the surrounding fault creep and are useful sources of seismic waves for detecting temporal changes in Earth structure.

2. Repeating earthquakes are not fundamentally different from other earthquakes. A single empirical scaling relationship between slip and seismic moment appears to apply in many places with repeaters driven by fault creep. Large changes in loading rate can lead to changes in repeater magnitude that reflect varying contributions of slow slip.
3. The repeater source characteristics illuminate the fundamental structure of earthquake faults, including a hierarchical (multiscale) structure of the earthquake source area that enables partial ruptures of the slip area of larger earthquakes by smaller earthquakes.
4. The activity of smaller earthquakes in the rupture areas of larger repeaters sometimes shows temporal change related to the earthquake cycle of the largest repeaters. The behavior of such repeaters may provide a tool to monitor the evolution of fault stress and strength during the earthquake cycle.
5. Repeaters illuminate dynamic and static earthquake triggering processes.
6. Having recurrence-interval data for many events is important for establishing the appropriate probability distribution model to underlie earthquake forecasting. Repeating earthquake data also inform efforts to incorporate physical earthquake cycle models to improve earthquake forecasting.
7. The distribution of repeating earthquakes and their cumulative slip provide information on spatially variable interplate coupling. Temporal changes of repeater rates reveal the nature of afterslip, preseismic slip, and spontaneous and periodic slow-slip events.
8. Volcanoes host abundant repeating earthquakes produced by a variety of processes and structures. Glaciers and landslides also feature repeating earthquakes that are interpreted as reflecting stick slip at their base and lateral margins.
9. Repeating earthquakes provide stable seismic sources to monitor temporal changes of subsurface structure associated with earthquakes, volcanoes, inner core rotation, and other processes affecting the velocity and scattering of seismic waves.

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FUTURE ISSUES

1. Technical difficulties in discriminating repeaters with actual overlapping slip areas exists due to the uncertainty in location, slip area, and the degree of waveform similarity chosen to select repeaters. Ensuring stable long-term earthquake observations and improvements in selection methods will be important for future repeating earthquake analyses.
2. Although empirical scaling relationships between seismic moment and slip of repeating earthquakes provide consistent results in many plate boundaries, there are reports that they may not be applicable in some environments. Further efforts to examine scaling relationships in different environments may provide more appropriate slow slip estimations.
3. The interactions between slow slip and large earthquakes are key targets for improved understanding of the earthquake preparation process. The mechanisms determining the recurrence interval and loading rate dependence of a repeater's seismic moment need further explorations in natural settings, the laboratory, and mechanical modeling.

4. The combination of repeating earthquake data with complementary geodetic and seismic data is important for better scientific utilization of repeaters. This applies to the examination of both slow slip and temporal changes in Earth structure.

DISCLOSURE STATEMENT

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