https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Rethinking Earthquakes

Satoshi Ide[1]

[1]Department and Earth and Planetary Science, The University of Tokyo, Tokyo, 113-0033, Japan

Correspondence to: Satoshi Ide (ide@eps.s.u-tokyo.ac.jp)

Abstract. Earthquake science has progressed through major paradigm shifts regarding how we measure and conceptualize the size and physics of earthquakes. While seismology prior to the 1950s viewed earthquakes as dynamic, wave-dominated processes quantified by radiated energy, the establishment of plate tectonics in the 1960s shifted the focus entirely to macroscopic fault motions measured by the seismic moment. This fault-centric view, combined with laboratory-derived rate- and state-dependent friction (RSF) laws, fostered an optimism during the late 20th century that the entire earthquake process—including deterministic nucleation and precursors—could be comprehensively explained by continuum mechanics. However, the 21st-century discovery of slow earthquakes has fundamentally challenged this unified picture. This review rethinks the governing physics of both fast and slow earthquakes by contrasting their dynamic behaviours. Slow earthquakes, characterized by a linear moment–duration scaling, scale-dependent migration velocities, and Brownian fluctuations, are fundamentally governed by diffusion processes rather than the wave equation. Conversely, fast earthquakes represent a scale-free, stochastic cascade-up process on hierarchical fault structures. Decades of high-resolution observations indicate that macroscopic, deterministic nucleation phases are practically negligible, and that the earthquake growth process is well-approximated by a single, universal moment growth curve. Within this framework, the Gutenberg–Richter law can be reinterpreted not merely as a regional statistic, but as the conditional probability of a cascading rupture continuing or terminating, which is modulated by local environmental conditions such as stress and fault geometry. Ultimately, shifting our perspective to this stochastic, dual-mode nature of fault motion—powered by modern dense networks, Artificial Intelligence, and high-performance computing—provides a new foundation to unlock the remaining mysteries of fault mechanics and earthquake predictability in the coming decades.

1 Introduction: Earthquakes and Fault Motion

People have been afraid of earthquakes since ancient times. For the general public, even today, an earthquake is simply ground shaking that causes disasters. In an academic context, however, it is more precisely understood as a unified physical process: from elastic energy release at the source, through seismic wave propagation in the underground structure, to ground shaking at the surface. To measure the size of this process, seismologists introduced the concept of magnitude, beginning

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

with the local magnitude M_L by Richter (1935). Later, Gutenberg and Richter (1942, 1956) connected seismic wave energy E_s with magnitude M through the empirical relationship:

$$\log_{10} E_s(J) = 11.8 + 1.5M. \quad (1)$$

Therefore, at least until the 1950s, or before Gutenberg passed away in 1960, seismologists, much like the general public, considered earthquakes as a dynamic wave-dominated process and measured their size based on wave energy.

In the 1960s, in parallel with the development of plate tectonics theory, earthquake sources were clearly recognized as fault motions. The theoretical foundations of quantitative seismology, including the concepts of equivalent body force, double couple, and seismic moment M_0, were firmly established during this decade (Backus and Mulcahy, 1976; Burridge and Knopoff, 1964; Maruyama, 1963). Consequently, the size of earthquakes began to be measured using M_0 (Aki, 1966; Aki and Richards, 2002). Since the seismic moment is defined as the product of rigidity, fault area, and average slip, it represents the size of the static fault motion, not the radiated seismic energy. Strictly speaking, M_0 is not related to the amount of wave energy. However, after Kanamori (1977) introduced the moment magnitude M_W, it became the new standard to measure earthquake size using M_0 and M_W, despite this conceptual gap. This widespread adoption obscured the fundamental physical difference between fault slip and wave energy. Through the 1970s, representing an earthquake source using a single or a few rectangular faults was highly successful, enabling the modeling of many real earthquakes and establishing basic scaling relationships among fault parameters (Kanamori and Anderson, 1975).

In the 1980s and 1990s, owing to the increasing quality and quantity of available data, the research focus shifted toward resolving the details of fault motion and complex slip processes, while keeping the basic idea of rectangular fault planes. Various inversion methods were developed to estimate the slip distribution on finite faults (e.g., Hartzell and Heaton, 1983; Olson and Apsel, 1982) and applied to many large earthquakes (e.g., Beroza and Spudich, 1988; Fukuyama and Irikura, 1986; Takeo et al., 1993; Wald and Heaton, 1994). These models are often called kinematic slip models, but they also constrain dynamic stress changes during slip evolution. Consequently, they were utilized to estimate friction laws on actual fault planes (Bouchon, 1997; Guatteri and Spudich, 2000; Ide and Takeo, 1997). Conversely, we can simulate a kinematic fault model by assuming specific friction laws and stress conditions on fault planes in elastic media. This approach led to the development of dynamic rupture models starting in the 1990s (Miyatake, 1992; Olsen et al., 1997; Quin, 1990). These successes strengthened the view that earthquakes are simply fault slip motions, yielding a kind of optimism: we believed we could physically explain the entire process of earthquakes by combining friction laws with the theory of elastic media.

This optimism was further supported by the success of the rate- and state-dependent friction (RSF) law (Dieterich, 1979; Marone, 1998; Ruina, 1983), which was also developed during the 1980s and 1990s based on various laboratory experiments. By the 1990s, numerical simulations adopting the RSF law had successfully reproduced a wide range of fault behaviors, such as nucleation (pre-slip) (Dieterich, 1992), afterslip (Marone et al., 1991), and seismicity changes including aftershocks

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

(Dieterich, 1994). It even reproduced the entire earthquake cycle with four distinct periods: interseismic, preseismic, coseismic, and postseismic (Scholz, 1998; Tse and Rice, 1986). A critical contribution of the RSF law was its ability to model the earthquake preparation process. The nucleation or pre-slip occurring in the preseismic period attracted a lot of attention, not only within seismology but also in society, because it provided a theoretical basis for the existence of earthquake precursors.

Thus, by the end of the 20th century, the view that an earthquake is a frictional fault slip on a fault plane had become the central idea for understanding earthquakes. This idea remains valid today. However, it might be a mistake to assume that all frictional fault slips are earthquakes. This is exactly what we need to rethink now. In the 21st century, we discovered that different types of frictional fault slip events, collectively called slow earthquakes, occur frequently.

2 Slow and Fast Earthquakes

2.1 Location and Types of Slow Earthquakes

Slow earthquakes are also understood as frictional fault slips, but these slow movements radiate very little or no seismic waves (e.g., Beroza and Ide, 2011; Nishikawa et al., 2023; Obara and Kato, 2016). They have been discovered in various regions worldwide (Fig. 1). In subduction zones, they occur in areas such as Japan (around the Japan Trench (Nishikawa et al., 2019), the Nankai Trough (Hirose et al., 1999; Ito and Obara, 2006; Obara, 2002), and the Ryukyu Trench (Heki and Kataoka, 2008)), New Zealand (Hikurangi (Douglas et al., 2005) and Puysegur (Romanet and Ide, 2019)), the US and Canada (from Aleutian Islands, Alaska (Ohta et al., 2006; Peterson et al., 2011), to Cascadia (Dragert et al., 2001; Rogers and Dragert, 2003)), Mexico (Graham et al., 2014; Ide, 2012; Lowry et al., 2001), Costa Rica (Brown et al., 2009; Outerbridge et al., 2010), Ecuador (Vallée et al., 2013), Peru (Jara et al., 2024), and Chile (Azúa et al., 2025, 2026; Ide, 2012). They also occur along major strike-slip faults, such as the San Andreas Fault in the US (Lu and Ide, 2026; Nadeau and Dolenc, 2005) and the Alpine Fault in New Zealand (Wech et al., 2012), as well as along the collision zone in Taiwan (Ide and Chen, 2024; Peng and Chao, 2008).

Most of these regions also experience large regular (or fast) earthquakes. At first glance, slow earthquakes seem to happen in the same areas as fast earthquakes. However, a closer look reveals that slow and fast earthquakes are generally separated in space (Fig. 2). Around Japan, for example, deep and shallow slow earthquakes delineate the rupture areas of the 1944 Tonankai and 1946 Nankaido earthquakes along both the shallow and deep edges in the Nankai region. In contrast, along-strike segmentation between slow and fast earthquakes is more evident along the Japan Trench (Nishikawa et al., 2023). Such close spatial proximity strongly suggests a certain physical interaction between slow and fast events.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

In fact, "slow earthquakes" is a general term for underground shear deformation with a wide range of time constants. They are observed as low-frequency earthquakes (LFEs) or tectonic tremors in seismological observations above 1 Hz, as very low-frequency earthquakes (VLFEs) in the 0.02–0.05 Hz band, and as geodetically observed slow slip events (SSEs) lasting from a few days to several years. Their deformation mechanism is consistent with large-scale tectonic deformation in each region (Ide et al., 2007b; Ito et al., 2007; Royer and Bostock, 2014). These apparently different phenomena frequently occur simultaneously in the same region, although their spatio-temporal correlation is not always perfect (Bartlow et al., 2011; Kostoglodov et al., 2010; Yoshioka et al., 2015).

We can represent the size of these events using the seismic moment M_0, ranging roughly from M_W 1 to 7. Because all these events are characterized by long durations T a comparison between seismic moment and duration clearly distinguishes them from the group of fast earthquakes (Ide et al., 2007a; Ide and Beroza, 2023) (Fig. 3). Fig. 3 shows that the seismic moment M_0 of slow earthquakes scales almost linearly with duration T as:

$$\log_{10} T(s) = \log_{10} M_0(Nm) - 12.5. \quad (2)$$

while the moment of fast earthquakes scales with T^3. Along this linear relation, the gap between LFEs and VLFEs is bridged by continuous broadband signals, which can be observed when the background noise level is sufficiently low (Kaneko et al., 2018; Masuda et al., 2020). The gap between VLFEs and SSEs is also largely filled by clusters of tectonic tremors (Aiken and Obara, 2021; Bletery et al., 2017; Gomberg et al., 2016).

There are two key points to note in this diagram. First, the gap between fast and slow earthquakes is real. Any event located slightly above the fast earthquake line, for example, an M_W 6 earthquake with a duration of 100 seconds, would be easy to detect using modern global seismic networks. Nearly two decades after this gap was proposed, no such events have been detected. Second, the vast area to the upper left of the slow earthquake line is a hidden zone, where high observational noise prevents the detection of any events, even if they occur. While we might find some phenomena in regions with extremely low noise levels, it is natural to expect that many processes continue to occur without our detection. The linear scaling law for slow earthquakes (Eq. 2) implies that their maximum moment rate is bounded by a constant value around $10^{12.5}$ Nm.

2.2 Diffusional Aspect of Slow Earthquakes

The high-frequency group of slow earthquakes, such as LFEs and tectonic tremors, can be monitored with high precision using dense seismic networks. Consequently, long-duration catalogs have been constructed in several well-observed regions (Bostock et al., 2012; Chamberlain et al., 2014; Kato and Nakagawa, 2020; Mizuno and Ide, 2019; Sagae et al., 2025; Shelly, 2017; Wech, 2021). Tremors and LFEs occur as spatially and temporally clustered groups, repeatedly at almost the same locations separated by quiescence periods ranging from hours to months (Ide, 2010; Rubin and Armbruster, 2013). Within each cluster, various migration phenomena are frequently observed.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Large-scale tremor/LFE migrations propagate over long distances, sometimes exceeding 100 km within 1–2 weeks, mainly in the horizontal direction perpendicular to the slip motion (Dragert et al., 2004; Nishikawa et al., 2019; Obara, 2002). The propagation velocity of these migrations is around 10 km/day (approximately 0.1 m/s). Migration also occurs over shorter distances of up to 20–30 km within 10–20 minutes, with a velocity of about 1 km/min (approximately 10 m/s), primarily along the slip direction (Ghosh et al., 2010; Shelly et al., 2007). Even this higher speed is significantly slower than the rupture velocity of regular earthquakes, which is typically about 3 km/s. Furthermore, migration can spread diffusively—fast at the beginning and slower in the later stages—which can be approximated using parabolic curves in space and time with a diffusivity around 10^3 m^2/s (Ando et al., 2012; Ide, 2010). More generally, the migration velocity systematically decreases as the event duration increases (Gombert and Hawthorne, 2023; Danré et al., 2024). These behaviours strongly suggest that slow earthquakes are phenomena governed by a diffusion equation with a scale-dependent migration velocity.

In fact, the characteristics of observed slow earthquake signals can be explained using Brownian motion, which is a discrete representation of the diffusion equation (Ide, 2008; Ide and Yabe, 2019). For example, if we approximate the expanding area of tremors as a circle, we can derive a stochastic differential equation for its radius r as:

$$dr = -\alpha r dt + \sigma dB, \tag{3}$$

where α and σ are constants, and dt and dB represent the time increment and Brownian walk (Wiener process), respectively. The square of this radius r^2 with a constant slip rate corresponds to the moment rate function. This remarkably simple model can yield a whole suite of slow earthquake phenomena: high-frequency tectonic tremors, very low-frequency fluctuations like VLFEs, and SSE-like slow motions after time integration (Fig. 4). A two-dimensional version of this Brownian slow earthquake model, implemented using a probabilistic cellular automaton, also produces similar broadband moment rate functions (Ide and Yabe, 2019).

2.3 Comparison between Slow and Fast Earthquakes

In summary, while both slow and fast earthquakes share the same fundamental mechanism as fault motions, they are entirely different in almost all other physical aspects (Table 1). Slow earthquakes are known by various names depending on their observation methods, such as LFEs, tectonic tremors, VLFEs, and SSEs. Similarly, fast earthquakes may be called differently depending on their scales, ranging from laboratory acoustic emissions and rock bursts in mines to micro- and large earthquakes; however, they are essentially the same shear rupture process involving expanding rock fractures with slip. While the rupture velocity of fast earthquakes is nearly constant and close to the S-wave velocity, a scale-dependent rupture (or expansion) velocity is a prominent characteristic of slow earthquakes.

In addition to the moment-duration scaling, clear differences exist in stress drop and the ratio of seismic wave energy to

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

seismic moment, known as scaled energy. The stress drop of fast earthquakes typically ranges from 1 to 10 MPa (Kanamori and Anderson, 1975), whereas that of slow earthquakes (SSEs) is only about 1 to 100 kPa (Gao et al., 2012), which is smaller by about two orders of magnitude. Furthermore, the scaled energy of fast earthquakes is around 10^{-5} (Ide and Beroza, 2001), while that of slow earthquakes is around 10^{-9} (Ide and Maury, 2018). This massive four-order-of-magnitude difference in scaled energy strongly suggests that the dynamic processes governing these two phenomena are profoundly different. Thus, the close relationship between energy-based size and moment-based size, which we have long taken for granted for fast earthquakes, completely breaks down for slow earthquakes.

The root of this dynamic difference lies in the underlying governing physics. Fast earthquakes clearly obey the wave equation, with boundary conditions determined by friction laws or fracture criteria. In contrast, as suggested by their diffusional migration and Brownian models, the governing law of slow earthquakes must be a diffusion equation. In this sense, we might even call slow earthquakes "diffusional earthquakes," which was, in fact, the original title of the manuscript by Ide et al. (2007a). Diffusion and wave propagation are both fundamental physical processes described by similar differential equations. Therefore, it is not surprising that these two distinct deformation modes coexist within the Earth's interior.

3 Rethinking Fast Earthquakes

3.1 Scale Free Earthquake Growth

Fast earthquakes are a scale-free rupture process covering a wide range of scales, from micro-earthquakes to megathrust events, characterized by various scale-independent parameters such as the stress drop and scaled energy summarized above. However, most previous studies have measured these parameters as single, static values for each event. For example, the stress drop of an earthquake is typically estimated from the final slip area and total slip amount after the termination of the rupture. In reality, any earthquake starts as a very tiny fracture and can grow into a large event. It is not self-evident from a simple macroscopic comparison of final stress drops whether this scale-free nature is maintained throughout the entire rupture process, from its very beginning to its end.

A classic question along this line is whether all earthquakes start in a similar manner, or whether the final size of an earthquake is predictable at its beginning. This issue has been intensely debated in earthquake science since the 1990s (Ellsworth and Beroza, 1995; Iio, 1992; Mori and Kanamori, 1996), stimulated by the modelling of the nucleation process using the RSF law (Dieterich, 1992). Initially, various observational studies were presented to support both sides of the debate. However, papers supporting clear predictability have become rare in recent years. For example, although Olson and

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Allen（2005) concluded that earthquakes have a deterministic nature that allows for the prediction of their final size, their results were soon disproved by several groups (Rydelek and Horiuchi, 2006; Yamada and Ide, 2008).

Recent observational evidence further supports nearly identical initial phases between earthquakes of different sizes (Meier et al., 2016; Noda and Ellsworth, 2016), as long as we compare only the earliest part of the seismic waveforms. Reports of slowly accelerating initial phases remain rare. Two earthquakes (M_W 3.7 and 3.8) in Alaska are exceptional examples that exhibited a distinct slow phase immediately before the abrupt onset (Tape et al., 2018). Given the vast number of such medium-sized earthquakes globally, these two examples rather highlight the extreme difficulty of finding such phases. Therefore, although there might be a very subtle difference between the initial onsets of large and small earthquakes (e.g., Ide and Yoshida, 2026), it is a good time to admit that such differences are extremely difficult to detect. Instead, the earthquake growth process is well-approximated by a single, universal growth curve of seismic moment from a negligible nucleus (e.g., Uchide and Ide, 2010).

3.2 Hierarchical Earthquake Model

The problem of self-similar crack evolution was solved analytically in linear elastic fracture mechanics in the 1960s (Kostrov, 1964). Seismic wave radiation from such a crack after an abrupt stop was also provided by the Sato and Hirasawa (1973) model. In these classical models, the moment rate function and far-field P-wave displacement increase smoothly in proportion to the square of time t^2, which is different from actual observed waveforms. Real observations usually contain multiple bumps and complex fluctuations, making the estimation of the power exponent for time dependency less straightforward. The stacked growth curves of P-wave onsets (Meier et al., 2016; Noda and Ellsworth, 2016) are not exactly quadratic. Furthermore, estimates of the power exponent for the SCARDEC source time function database (Vallée et al., 2011) vary widely, ranging from 1–1.5 (Denolle, 2019) to 2.7 (Renou et al., 2019) depending on the measurement methodology.

To model such complex rupture processes while remaining consistent with modern friction laws, Ide and Aochi (2005; hereafter referred to as IA05) developed a hierarchical circular patch model (Fig. 5). In this model, numerous circular patches of various sizes are distributed on a planar fault, and their dynamic rupture processes are numerically calculated. These patches follow a fractal size distribution, and a slip-weakening friction law is applied to each patch. A key assumption of the IA05 model is that the critical slip-weakening distance, D_c, is proportional to the patch radius. Under a homogeneous initial stress condition, the fracture energy, G_c, is also proportional to the radius. Each rupture initiates from one of the smallest patches and stops immediately in most cases. Only when nearby patches are of similar or slightly larger sizes can the rupture continue to propagate and grow into a larger event. Consequently, the size-frequency statistics of the simulated

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

events naturally obey the Gutenberg–Richter law (Gutenberg and Richter, 1944).

While the IA05 model generates numerous small earthquakes and only a few large ones, the initial moment-rate growth of their source time functions is, by definition, indistinguishable. Yamada and Ide (2008) utilized these simulated source time functions to disprove the apparent size-dependence reported by Olson and Allen (2005), and Renou et al. (2022) later demonstrated the similarity between these synthetic source time functions and those in the SCARDEC database. Another important feature of the IA05 model is that the macroscopic rupture velocity is, on average, significantly slower than the shear wave speed, despite occasional brief periods of supershear acceleration. This is because the rupture in this model is almost always on the verge of stopping, only occasionally cascading into a slightly larger patch. Inside that larger patch, the rupture front accelerates but is soon decelerated at the patch boundary.

The IA05 model successfully explains the complex rupture processes observed in real earthquakes. For instance, the delayed large slip in the shallow portion of the fault during the 2011 Tohoku-Oki earthquake (e.g., Ide et al., 2011; Suzuki et al., 2011; Yokota et al., 2011) was explained by a time-consuming, multiple cascade-up process, assuming a circular patch distribution based on historical seismicity (Ide and Aochi, 2013). The observations of identical onsets between small and large earthquakes (Ide, 2019; Lu et al., 2025) are entirely consistent with this cascade-up mechanism. Furthermore, multiscale patch distributions have been suggested around repeating earthquake sequences (Chang and Ide, 2021; Gao and Ide, 2026; Uchida et al., 2012). Recent earthquake cycle simulations incorporating the RSF law have also demonstrated complex interactions between different-sized patches, confirming that very large earthquakes invariably start as a cascade-up process from a tiny patch (Nakata et al., 2026).

3.3 Negligible Nucleation Process

The success of the IA05 model was unexpected in 2005, when most researchers, including myself, believed that earthquakes—especially large ones—must have a distinct, slow initial process related to nucleation and preslip. At that time, the cascade-up model was considered just an extreme counterpart to the nucleation model, and it was widely thought that real earthquakes might lie somewhere between these two extremes. However, two decades of observations have revealed that reality is very close to the predictions of the IA05 model, and there are few intermediate phenomena between the two extremes. This conclusion implies that the slow, macroscopically deterministic nucleation process predicted by the RSF law is unnecessary to explain the observations of fast earthquakes. Does this mean that the RSF law is irrelevant to earthquakes?

Actually, it is remarkable that despite the countless numerical models computed using the RSF law, no model has successfully reproduced a realistic, sharp onset of a P-wave. In observational seismology, picking P-wave arrivals is one of the most fundamental tasks. It is also so straightforward that even a beginner can easily identify the precise onset time with a

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

resolution of a single time sample (i.e., 0.01 s). Recently, this task has been handled by Artificial Intelligence with accuracy comparable to or better than humans (Mousavi et al., 2020; Zhu and Beroza, 2019). Therefore, the critical question is: could an RSF simulation generate a P-wave that an AI could actually detect? The answer remains unknown, but previously simulated seismic waveforms based on the RSF law exhibit a beginning that is far too smooth to be detected at a 0.01 s resolution.

One might argue that the characteristic slip distance, L, of the RSF law was too large in most previous simulation studies, and that a smaller L would produce a sharper P-wave onset. While this is theoretically possible, it should be noted that the RSF law is physically valid only at low slip rates during the initial acceleration phase. Experimental evidence demonstrates that the standard RSF law does not hold at high slip velocities, such as 1 cm/s or faster, where dynamic weakening mechanisms dominate (Di Toro et al., 2011). Once the slip rate accelerates, the rupture is driven more by energy balance than by the details of the friction law, and rupture propagation is largely determined by the spatial distribution of G_c (Guatteri et al., 2004; Guatteri and Spudich, 2000). At this dynamic stage, simpler friction laws, including the slip-weakening law, are sufficient to describe the process.

Some may still argue that the RSF law is indispensable because the slip-weakening law alone cannot initiate spontaneous rupture. It is true that the RSF framework is a highly convenient tool within a deterministic, continuum mechanics approach. However, in discrete media, such as a spring-slider model (e.g., Burridge and Knopoff, 1967), spontaneous rupture naturally occurs simply through tectonic loading. Furthermore, real physical processes are not merely simple frictional slips on quasi-planar faults; they involve various complex styles of deformation and fracture. It is impossible to treat these processes completely deterministically. Instead, a more stochastic approach is required. The RSF law is undoubtedly the governing physics for slow deformation and remains crucial for understanding slow earthquakes. It likely explains an even wider variety of slow deformations than what we can currently observe.

4 From Deterministic Rupture to Stochastic Modelling

Unlike the nearly deterministic nature of slow rupture processes, fast earthquakes require an inherently stochastic approach. In this context, another of Beno Gutenberg's monumental achievements, the Gutenberg–Richter (GR) law, forms the fundamental backbone. Conventionally, this law has been viewed as a statistical frequency–size distribution of earthquakes that occur within a specific region and period. However, if we accept that an earthquake grows in a complex but statistically self-similar manner, we can reinterpret the GR law as a descriptor of the growth probability of an earthquake at any given size. In this probabilistic framework, the b-value is a physical parameter directly correlated with the probability of a rupture terminating. It is mathematically obvious from the GR law with $b = 1$ that 90% of earthquakes stop growing before their

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

magnitude increases by one unit (or, equivalently, before expanding by a factor of about three in length). Therefore, the long-distance rupture propagation of giant earthquakes is the result of an exceptionally rare chance, and attempting to model it in an entirely deterministic way may be inappropriate.

Recent observational and experimental studies have demonstrated that the b-value changes systematically depending on local environmental conditions, particularly on the stress state (Goebel et al., 2013; Scholz, 2015; Schorlemmer et al., 2005), fault roughness (Goebel et al., 2017), and the geometric consistency between the regional stress field and fault plane orientations (Ide et al., 2026; Matsumoto et al., 2024). Temporal variations in the b-value observed before (Nanjo et al., 2012) and after (Gulia and Wiemer, 2019) large earthquakes may also reflect these varying environmental conditions. Furthermore, although the effect of tidal stress is generally minor for ordinary earthquakes, recent statistical analyses have successfully detected subtle modulations of the b-value due to tidal loading (Ide et al., 2016). Moving forward, we need a much deeper physical understanding of exactly what environmental conditions control the spatial and temporal variations of the b-value.

Theoretical understanding of such growth processes in relation to the b-value remains limited, largely due to the scarcity of numerical modeling studies focused on multiscale cascade-up processes like IA05. Recently, Palgunadi et al. (2024) advanced this direction by developing a multiscale numerical simulation that incorporates a more realistic, three-dimensional distribution of small patches. Although computationally expensive, such models are essentially important and will be highly valuable for exploring more realistic fast earthquake processes that explicitly include seismic wave radiation. However, in addition to these spatially heterogeneous but perfectly deterministic continuum models, we likely need to simulate random, inelastic sub-grid processes that are practically impossible to model deterministically. As a pioneering attempt in this direction, Aso et al. (2019) introduced stochastic fluctuation terms directly into the elastodynamic equations, demonstrating that the progress of slow slip can be fundamentally aided by such random fluctuations.

5 Conclusions

The discovery of slow earthquakes has significantly changed our understanding of fault dynamics. The wide variety of slow earthquakes with different time constants may not be unified into a single, simple diffusional process, because actual physical diffusion in the Earth involves various driving mechanisms with different characteristic scales, such as changes in stress, fluid migration, heat, and chemical reactions. Consequently, we will likely never be able to detect all sorts of slow deformation inside the Earth. Deterministic modelling of fault slip using the RSF law and various diffusion equations remains critical to understanding these undetected, hidden processes. Crucially, we must recognize that the fast earthquake rupture process is entirely different from such diffusional processes; it is governed simply by fracture mechanics and

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

elastodynamic wave equations. Earthquakes are, fundamentally, processes of seismic wave radiation. Therefore, their size should be measured using radiated seismic energy, as originally proposed by Beno Gutenberg, and not just by the static size of fault slip measured by the seismic moment.

The discovery of slow earthquakes also highlights the almost complete absence of macroscopically observable slow processes immediately before the abrupt onset of fast ruptures. It is time to accept that the deterministic earthquake nucleation process is practically negligible for fast earthquakes. Although fracture mechanics requires some subcritical preparation processes, and small-scale nucleation or pre-slips similar to laboratory observations likely occur around natural faults, they cannot be resolved using our current observation systems. Furthermore, differences in the rupture onset between large and small earthquakes are almost negligible. Accepting these views naturally leads to the multiscale cascade-up view of earthquake rupture, as proposed by the IA05 model two decades ago. Within this framework, the growth probability of a cascading rupture is directly related to the b-value of the GR law, and a deeper physical understanding of the environmental factors controlling the b-value is fundamental.

While there is no accelerating slow slip immediately before an abrupt onset, broader, large-scale slow slip events have been frequently suggested prior to many large earthquakes (e.g., Kato et al., 2012; Ruiz et al., 2014). These broad processes certainly change the physical conditions around fault zones, thereby modulating the growth probability and local b-values of fast earthquakes. Therefore, the long-term interaction between slow and fast processes needs to be quantified much more accurately. Strong, direct interactions may occur at very small scales where fast and slow earthquakes become physically indistinguishable. This slow–fast bifurcation point is of great scientific interest and needs to be identified through advanced laboratory experiments and ultra-near-fault geophysical observations.

Ultimately, rethinking earthquakes through recent understanding of both fast and slow processes allows us to transcend the 20th-century view that treated all fault slips as identical macroscopic earthquakes. Earthquake science in the 21st century is now ready to advance to a much deeper level of understanding, powered by novel instrumentation, ultra-dense observation networks, high-quality catalogues aided by Artificial Intelligence, and high-performance computing that incorporates multiple physical processes. Embracing this stochastic and dual-mode nature of fault motion will be the key to unlocking the remaining mysteries of earthquake predictability and fault mechanics over the next decades.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

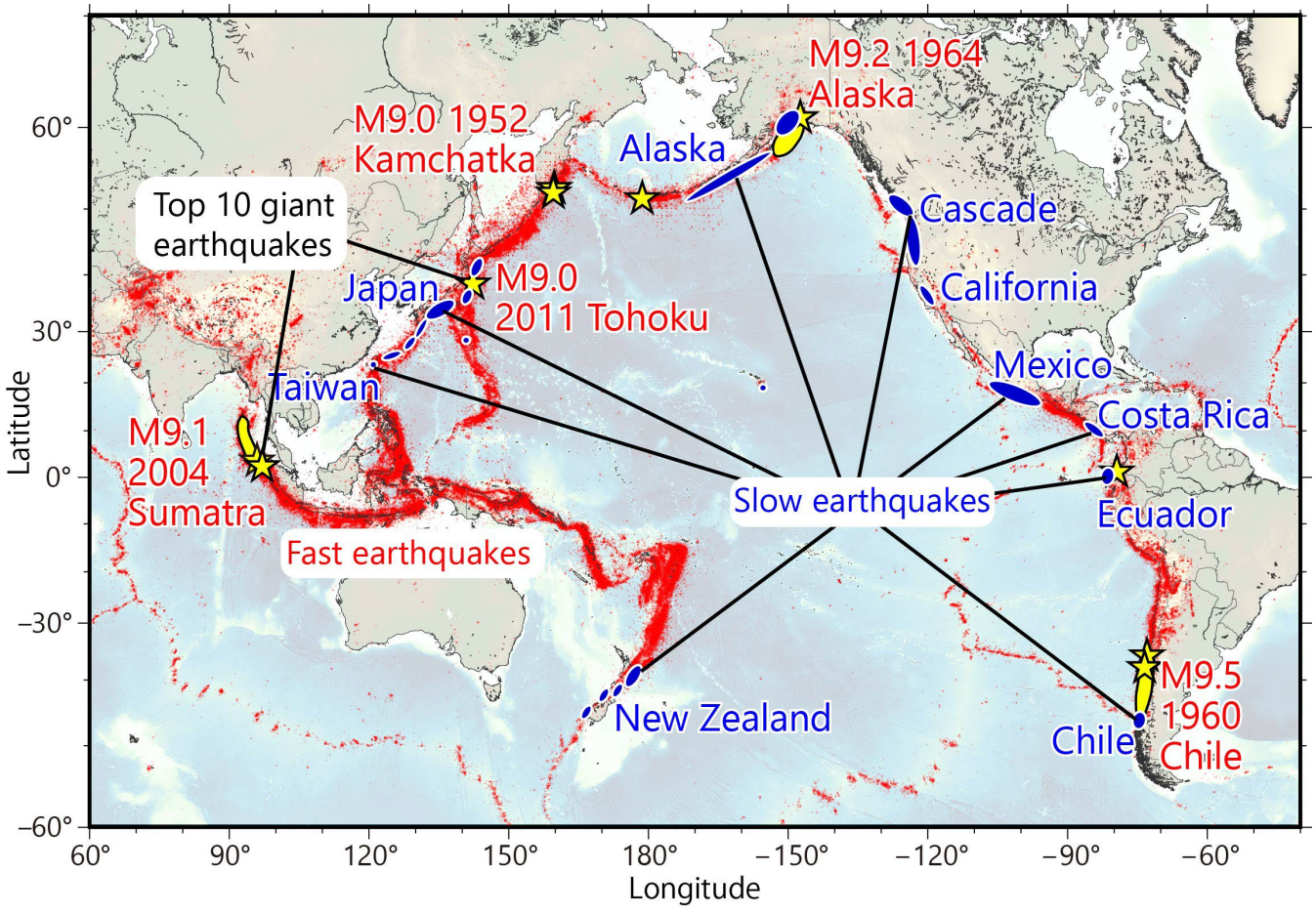


Figure 1: Distribution of slow and fast earthquake worldwide.

Small red dots indicate the hypocenters of fast earthquakes. Blue ellipses represent regions with significant slow earthquake activity. Yellow stars and polygon highlight the top 10 large earthquakes recorded since 1900.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

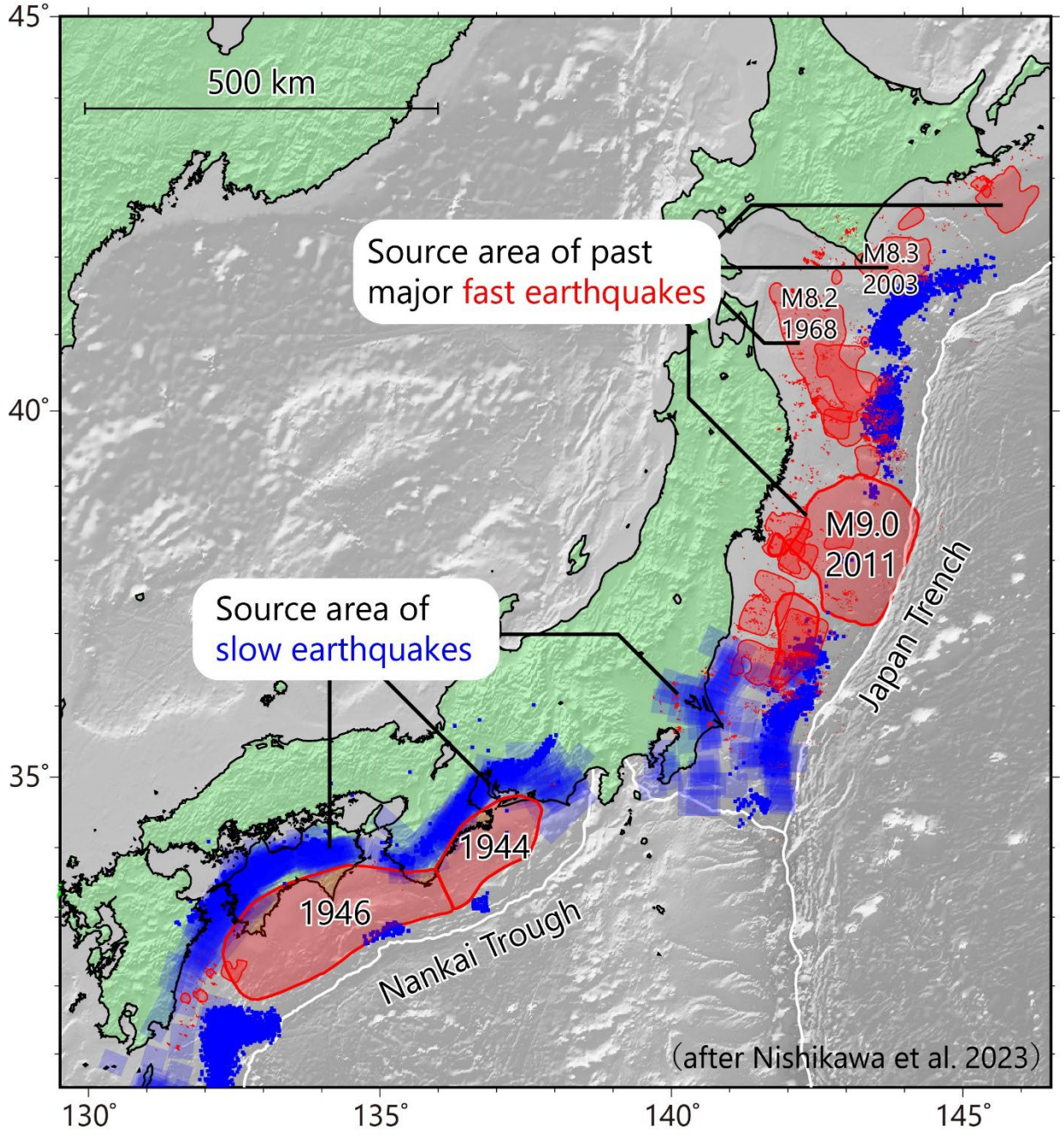
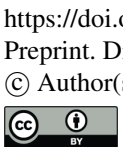


Figure 2: Slow and fast earthquakes around Japan.

Distribution of slow and fast earthquakes in the Nankai Trough and the Japan Trench. Red polygons indicate the source areas of past major earthquakes, and blue polygons show the source areas of slow earthquakes. Modified after Nishikawa et al. (2023).

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.



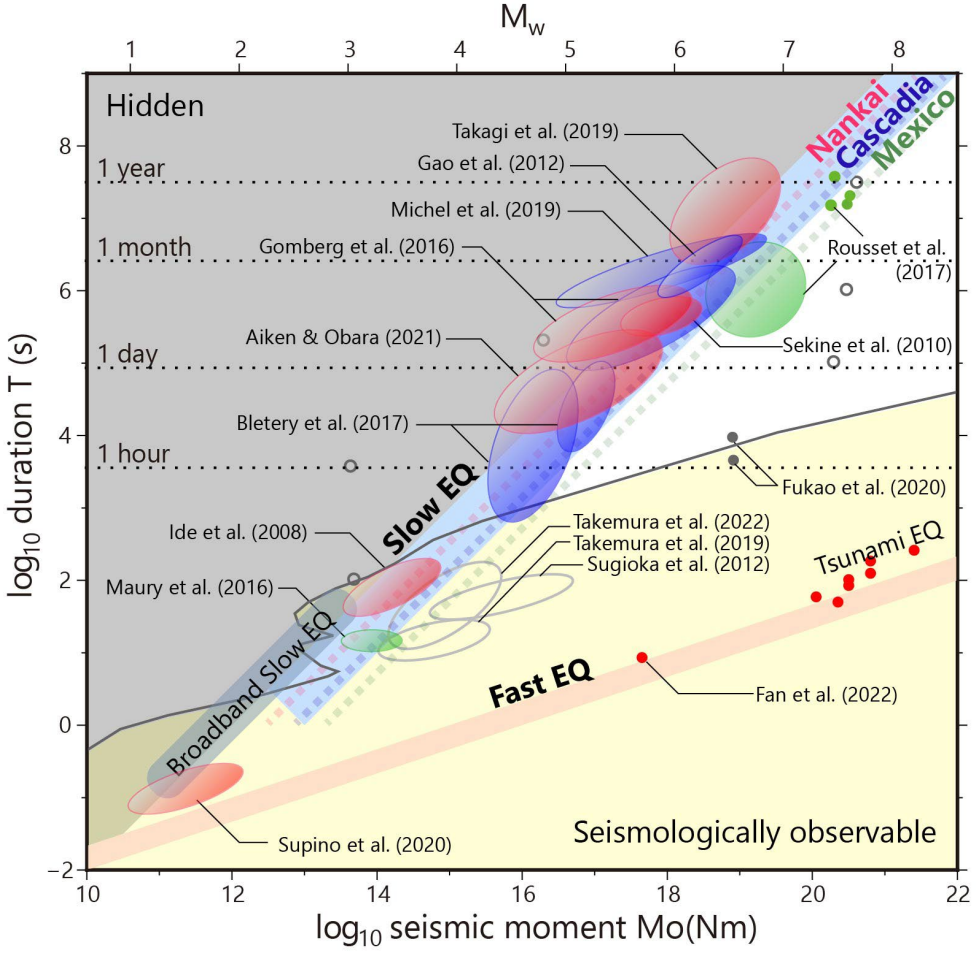


Figure 3: Seismic moment and duration for slow and fast earthquakes.

Each ellipse shows a region containing about 95% of events for each study. Red, blue, and green symbols show estimation for Nankai, Cascadia, and Mexico, respectively. Four large SSEs in Mexico are shown by green dots. Gray ellipses show the estimation for VLFEs. Tsunami earthquakes and an M_W 5.7 event are plotted using red dots. Gray dots show two events determined in the Izu-Bonin Trench, and open gray dots show events in the 2007 diagram (Ide et al., 2007a), except for those in Nankai, Cascadia, and Mexico. Thick blue and red lines show the scaling between seismic moment and duration for slow and fast earthquakes, respectively. The grey curve limits seismologically observable domain with the USGS noise model. The signal of broadband slow earthquakes are continuous between 0.1 and 100 s. "Hidden" means unobservable due to detection limitation. Reprinted with permission from Ide and Beroza (2023), Proceedings of the National Academy of Sciences. Copyright 2023 National Academy of Sciences.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

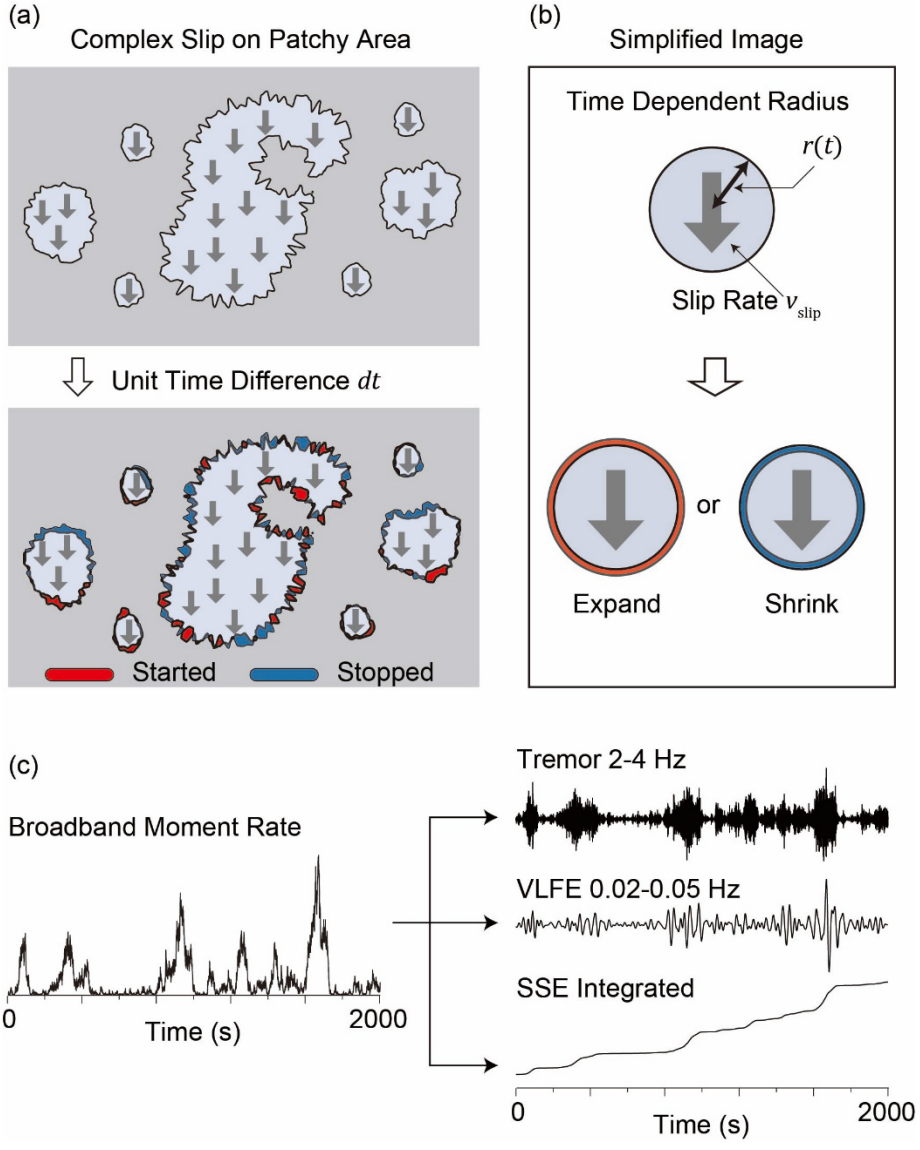


Figure 4: Schematic illustration of the Brownian slow earthquake model (Ide, 2008; Ide and Maury, 2018).

(a) The slip area changes at each time step, as slip starts and stops at various points in the model. (b) If we approximate the slip region as a circle, the change in slip area is represented by the change in the circle's radius, which follows a stochastic differential equation. (c) An example of moment rate function, with $dt = 0.1\ s, \alpha = 0.01\ s^{-1}, \sigma = 300\ m/s^{1/2}$.. After bandpass filtering or integration, this function is recognized as a different manifestation of slow earthquakes.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

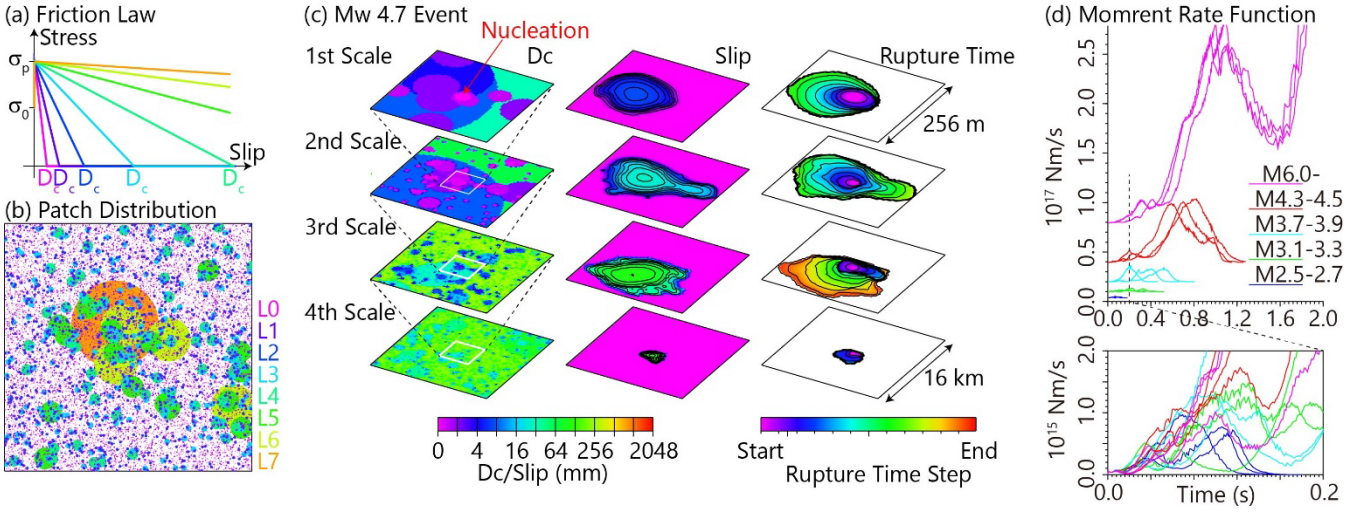


Figure 5: Cascade-up circular patch model of Ide and Aochi (2005).

(a) Slip-weakening friction law is assumed for each patch, with common initial (σ_0) and peak (σ_p) stress and slip-weakening distance (D_c), which is proportional to the patch radius. (b) Example of patch distribution with 8 levels. (c) An example of M_W 4.7 event. Calculation was done for 4 scales. Distribution of D_c, slip at the final moment, and rupture time in each scale are shown. (d) Moment rate functions of some selected events from M_W 2.5 to M_W 6 +. Zoom-up of the initial part is also shown.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Table 1. Comparison of slow and fast earthquakes.

	Slow Earthquakes	(Fast) Earthquakes
Mechanism	Shear Slip	Shear Slip
Size (M_w)	0 (LFE), 3 to 4 (VLFE), 5 to 7 (SSE)	−10 to −4 (AE), −5 to 1 (Rock Burst), −1 to 9.5 (Natural Earthquakes)
Duration (T)	0.2 s (LFE) to Years (SSE) $T \propto M_0$ (Upper Limit of $\dot{M}_0$)	Up to Minutes $T \propto M_0^{1/3}$
Expansion Speed	Variable, 0.01 m/s(SSE) to 100 m/s (Tremor Cluster)	Nearly Constant, ~3 km/s
Stress Change	1 to 100 kPa	1 to 10 MPa
Scaled Energy (E_s/M_0)	10^{-11} to 10^{-8}	10^{-6} to 10^{-4}
Governing Law	Diffusion Equation	Wave Equation

Code and data availability

No new data and codes are used for this manuscript.

Supplement link

No supplement is provided.

Author contributions

This is a single-authored manuscript.

Competing interests

The author has no competing interests.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Disclaimer

Copernicus Publications adds a standard disclaimer: "Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors. Views expressed in the text are those of the authors and do not necessarily reflect the views of the publisher."
Please feel free to add disclaimer text at your choice, if applicable.

Acknowledgements

The contents of this paper are based on the Beno Gutenberg medal lecture at the 2026 EGU assembly held in Vienna. The English is brushed-up by Google Gemini.

Financial support

This work was funded by the Japan Society for the Promotion of Science Grants-in-Aid for Scientific Research (21H04505, 21H05200, 25K22037, and 26H02081) and the Ministry of education, culture, Sports, Science and technology of Japan, under its earthquake and volcano hazards Observation and Research Program.

Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

References

Aiken, C. and Obara, K.: Data-Driven Clustering Reveals More Than 900 Small Magnitude Slow Earthquakes and Their Characteristics, Geophysical Research Letters, 48, e2020GL091764, https://doi.org/10.1029/2020GL091764, 2021.

Aki K.: Generation and Propagation of G Waves from the Niigata Earthquake of June 16, 1964. : Part 2. Estimation of earthquake moment, released energy, and stress-strain drop from the G wave spectrum, Bull. Earthquake Res. Inst. Univ. Tokyo, 44, 73-88, 1966.

Aki, K. and Richards, P.: Quantitative seismology, 2nd edition., University Science Books, 2002.

Ando, R., Takeda, N., and Yamashita, T.: Propagation dynamics of seismic and aseismic slip governed by fault heterogeneity and Newtonian rheology, Journal of Geophysical Research: Solid Earth, 117, https://doi.org/10.1029/2012JB009532, 2012.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Aso, N., Ando, R., and Ide, S.: Ordinary and Slow Earthquakes Reproduced in a Simple Continuum System With Stochastic Temporal Stress Fluctuations, Geophysical Research Letters, 46, 14347–14357, https://doi.org/10.1029/2019GL085010, 2019.

Azúa, K., Ide, S., Yano, S., Ruiz, S., Sugioka, H., Shiobara, H., Ito, A., Miller, M., and Iwamori, H.: Shallow Tectonic Tremors Reveal the Beginning of the Slab Window at the Chilean Triple Junction, Geophysical Research Letters, 52, e2025GL115019, https://doi.org/10.1029/2025GL115019, 2025.

Azúa, K., Ruiz, S., and Ide, S.: Tectonic Tremor Reveals Slow Deformation Along the Antarctic–South American Subduction Zone, Geophysical Research Letters, 53, e2026GL124449, https://doi.org/10.1029/2026GL124449, 2026.

Backus, G. and Mulcahy, M.: Moment Tensors and other Phenomenological Descriptions of Seismic Sources—I. Continuous Displacements, Geophysical Journal International, 46, 341–361, https://doi.org/10.1111/j.1365-246X.1976.tb04162.x, 1976.

Bartlow, N. M., Miyazaki, S., Bradley, A. M., and Segall, P.: Space-time correlation of slip and tremor during the 2009 Cascadia slow slip event, Geophysical Research Letters, 38, https://doi.org/10.1029/2011GL048714, 2011.

Beroza, G. C. and Ide, S.: Slow Earthquakes and Nonvolcanic Tremor, Annual Review of Earth and Planetary Sciences, 39, 271–296, https://doi.org/10.1146/annurev-earth-040809-152531, 2011.

Beroza, G. C. and Spudich, P.: Linearized inversion for fault rupture behavior: Application to the 1984 Morgan Hill, California, earthquake, Journal of Geophysical Research: Solid Earth, 93, 6275–6296, https://doi.org/10.1029/JB093iB06p06275, 1988.

Bletery, Q., Thomas, A. M., Hawthorne, J. C., Skarbek, R. M., Rempel, A. W., and Krogstad, R. D.: Characteristics of secondary slip fronts associated with slow earthquakes in Cascadia, Earth and Planetary Science Letters, 463, 212–220, https://doi.org/10.1016/j.epsl.2017.01.046, 2017.

Bostock, M. G., Royer, A. A., Hearn, E. H., and Peacock, S. M.: Low frequency earthquakes below southern Vancouver Island, Geochemistry, Geophysics, Geosystems, 13, https://doi.org/10.1029/2012GC004391, 2012.

Bouchon, M.: The state of stress on some faults of the San Andreas System as inferred from near-field strong motion data, Journal of Geophysical Research: Solid Earth, 102, 11731–11744, https://doi.org/10.1029/97JB00623, 1997.

Brown, J. R., Beroza, G. C., Ide, S., Ohta, K., Shelly, D. R., Schwartz, S. Y., Rabbel, W., Thorwart, M., and Kao, H.: Deep low-frequency earthquakes in tremor localize to the plate interface in multiple subduction zones, Geophysical Research Letters, 36, https://doi.org/10.1029/2009GL040027, 2009.

Burridge, R. and Knopoff, L.: Body force equivalents for seismic dislocations, Bulletin of the Seismological Society of America, 54, 1875–1888, https://doi.org/10.1785/BSSA05406A1875, 1964.

Burridge, R. and Knopoff, L.: Model and theoretical seismicity, Bulletin of the Seismological Society of America, 57, 341–371, https://doi.org/10.1785/BSSA0570030341, 1967.

Chamberlain, C. J., Shelly, D. R., Townend, J., and Stern, T. A.: Low-frequency earthquakes reveal punctuated slow slip on the deep extent of the Alpine Fault, New Zealand, Geochemistry, Geophysics, Geosystems, 15, 2984–2999, https://doi.org/10.1002/2014GC005436, 2014.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Chang, T.-W. and Ide, S.: Hypocenter Hotspots Illuminated Using a New Cross-Correlation-Based Hypocenter and Centroid Relocation Method, Journal of Geophysical Research: Solid Earth, 126, e2021JB021991, https://doi.org/10.1029/2021JB021991, 2021.

Di Toro, G., Han, R., Hirose, T., De Paola, N., Nielsen, S., Mizoguchi, K., Ferri, F., Cocco, M., and Shimamoto, T.: Fault lubrication during earthquakes, Nature, 471, 494–498, https://doi.org/10.1038/nature09838, 2011.

Dieterich, J.: A constitutive law for rate of earthquake production and its application to earthquake clustering, Journal of Geophysical Research: Solid Earth, 99, 2601–2618, https://doi.org/10.1029/93JB02581, 1994.

Dieterich, J. H.: Modeling of rock friction: 1. Experimental results and constitutive equations, Journal of Geophysical Research: Solid Earth, 84, 2161–2168, https://doi.org/10.1029/JB084iB05p02161, 1979.

Dieterich, J. H.: Earthquake nucleation on faults with rate-and state-dependent strength, Tectonophysics, 211, 115–134, https://doi.org/10.1016/0040-1951(92)90055-B, 1992.

Douglas, A., Beavan, J., Wallace, L., and Townend, J.: Slow slip on the northern Hikurangi subduction interface, New Zealand, Geophysical Research Letters, 32, https://doi.org/10.1029/2005GL023607, 2005.

Dragert, H., Wang, K., and James, T. S.: A Silent Slip Event on the Deeper Cascadia Subduction Interface, Science, 292, 1525–1528, https://doi.org/10.1126/science.1060152, 2001.

Dragert, H., Wang, K., and Rogers, G.: Geodetic and seismic signatures of episodic tremor and slip in the northern Cascadia subduction zone, Earth, Planets and Space, 56, 1143–1150, https://doi.org/10.1186/BF03353333, 2004.

Ellsworth, W. L. and Beroza, G. C.: Seismic Evidence for an Earthquake Nucleation Phase, Science, 268, 851–855, https://doi.org/10.1126/science.268.5212.851, 1995.

Fukuyama, E. and Irikura, K.: Rupture process of the 1983 Japan Sea (Akita-Oki) earthquake using a waveform inversion method, Bulletin of the Seismological Society of America, 76, 1623–1640, https://doi.org/10.1785/BSSA0760061623, 1986.

Gao, D. and Ide, S.: Hierarchical repeating earthquakes with strong downward directivity, Science Advances, 12, eaeb3563, https://doi.org/10.1126/sciadv.aeb3563, 2026.

Gao, H., Schmidt, D. A., and Weldon, R. J.: Scaling Relationships of Source Parameters for Slow Slip Events, Bulletin of the Seismological Society of America, 102, 352–360, https://doi.org/10.1785/0120110096, 2012.

Ghosh, A., Vidale, J. E., Sweet, J. R., Creager, K. C., Wech, A. G., Houston, H., and Brodsky, E. E.: Rapid, continuous streaking of tremor in Cascadia, Geochemistry, Geophysics, Geosystems, 11, https://doi.org/10.1029/2010GC003305, 2010.

Goebel, T. H. W., Schorlemmer, D., Becker, T. W., Dresen, G., and Sammis, C. G.: Acoustic emissions document stress changes over many seismic cycles in stick-slip experiments, Geophysical Research Letters, 40, 2049–2054, https://doi.org/10.1002/grl.50507, 2013.

Goebel, T. H. W., Kwiatek, G., Becker, T. W., Brodsky, E. E., and Dresen, G.: What allows seismic events to grow big?: Insights from b-value and fault roughness analysis in laboratory stick-slip experiments, Geology, 45, 815–818, https://doi.org/10.1130/G39147.1, 2017.

Gomberg, J., Wech, A., Creager, K., Obara, K., and Agnew, D.: Reconsidering earthquake scaling, Geophysical Research Letters, 43, 6243–6251, https://doi.org/10.1002/2016GL069967, 2016.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Graham, S. E., DeMets, C., Cabral-Cano, E., Kostoglodov, V., Walpersdorf, A., Cotte, N., Brudzinski, M., McCaffrey, R., and Salazar-Tlaczani, L.: GPS constraints on the 2011–2012 Oaxaca slow slip event that preceded the 2012 March 20 Ometepec earthquake, southern Mexico, Geophysical Journal International, 197, 1593–1607, https://doi.org/10.1093/gji/ggu019, 2014.

Guatteri, M. and Spudich, P.: What Can Strong-Motion Data Tell Us about Slip-Weakening Fault-Friction Laws?, Bulletin of the Seismological Society of America, 90, 98–116, https://doi.org/10.1785/0119990053, 2000.

Guatteri, M., Mai, P. M., and Beroza, G. C.: A Pseudo-Dynamic Approximation to Dynamic Rupture Models for Strong Ground Motion Prediction, Bulletin of the Seismological Society of America, 94, 2051–2063, https://doi.org/10.1785/0120040037, 2004.

Gulia, L. and Wiemer, S.: Real-time discrimination of earthquake foreshocks and aftershocks, Nature, 574, 193–199, https://doi.org/10.1038/s41586-019-1606-4, 2019.

Gutenberg, B. and Richter, C. F.: Earthquake magnitude, intensity, energy, and acceleration, Bulletin of the Seismological Society of America, 32, 163–191, https://doi.org/10.1785/BSSA0320030163, 1942.

Gutenberg, B. and Richter, C. F.: Frequency of earthquakes in California, Bulletin of the Seismological Society of America, 34, 185–188, https://doi.org/10.1785/BSSA0340040185, 1944.

Gutenberg, B. and Richter, C. F.: MAGNITUDE AND ENERGY OF EARTHQUAKES, Annals of Geophysics, 9, 1–15, https://doi.org/10.4401/ag-5590, 1956.

Hartzell, S. H. and Heaton, T. H.: Inversion of strong ground motion and teleseismic waveform data for the fault rupture history of the 1979 Imperial Valley, California, earthquake, Bulletin of the Seismological Society of America, 73, 1553–1583, https://doi.org/10.1785/BSSA07306A1553, 1983.

Heki, K. and Kataoka, T.: On the biannually repeating slow-slip events at the Ryukyu Trench, southwestern Japan, Journal of Geophysical Research: Solid Earth, 113, https://doi.org/10.1029/2008JB005739, 2008.

Hirose, H., Hirahara, K., Kimata, F., Fujii, N., and Miyazaki, S.: A slow thrust slip event following the two 1996 Hyuganada Earthquakes beneath the Bungo Channel, southwest Japan, Geophysical Research Letters, 26, 3237–3240, https://doi.org/10.1029/1999GL010999, 1999.

Ide, S.: A Brownian walk model for slow earthquakes, Geophysical Research Letters, 35, https://doi.org/10.1029/2008GL034821, 2008.

Ide, S.: Striations, duration, migration and tidal response in deep tremor, Nature, 466, 356–359, https://doi.org/10.1038/nature09251, 2010.

Ide, S.: Variety and spatial heterogeneity of tectonic tremor worldwide, Journal of Geophysical Research: Solid Earth, 117, https://doi.org/10.1029/2011JB008840, 2012.

Ide, S.: Frequent observations of identical onsets of large and small earthquakes, Nature, 573, 112–116, https://doi.org/10.1038/s41586-019-1508-5, 2019.

Ide, S. and Aochi, H.: Earthquakes as multiscale dynamic ruptures with heterogeneous fracture surface energy, Journal of Geophysical Research: Solid Earth, 110, https://doi.org/10.1029/2004JB003591, 2005.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Ide, S. and Aochi, H.: Historical seismicity and dynamic rupture process of the 2011 Tohoku-Oki earthquake, Tectonophysics, 600, 1–13, https://doi.org/10.1016/j.tecto.2012.10.018, 2013.

Ide, S. and Beroza, G. C.: Does apparent stress vary with earthquake size?, Geophysical Research Letters, 28, 3349–3352, https://doi.org/10.1029/2001GL013106, 2001.

Ide, S. and Beroza, G. C.: Slow earthquake scaling reconsidered as a boundary between distinct modes of rupture propagation, Proceedings of the National Academy of Sciences, 120, e2222102120, https://doi.org/10.1073/pnas.2222102120, 2023.

Ide, S. and Chen, K. H.: Spatiotemporal Characteristics of Tectonic Tremors in the Collisional Orogen of Taiwan, Geophysical Research Letters, 51, e2023GL106759, https://doi.org/10.1029/2023GL106759, 2024.

Ide, S. and Maury, J.: Seismic Moment, Seismic Energy, and Source Duration of Slow Earthquakes: Application of Brownian slow earthquake model to three major subduction zones, Geophysical Research Letters, 45, 3059–3067, https://doi.org/10.1002/2018GL077461, 2018.

Ide, S. and Takeo, M.: Determination of constitutive relations of fault slip based on seismic wave analysis, Journal of Geophysical Research: Solid Earth, 102, 27379–27391, https://doi.org/10.1029/97JB02675, 1997.

Ide, S. and Yabe, S.: Two-Dimensional Probabilistic Cell Automaton Model for Broadband Slow Earthquakes, Pure Appl. Geophys., 176, 1021–1036, https://doi.org/10.1007/s00024-018-1976-9, 2019.

Ide, S. and Yoshida, K.: Predictable and unpredictable aspects of earthquakes from P-wave onsets of acceleration seismograms, Earth Planets Space, 78, 28, https://doi.org/10.1186/s40623-025-02357-9, 2026.

Ide, S., Beroza, G. C., Shelly, D. R., and Uchide, T.: A scaling law for slow earthquakes, Nature, 447, 76–79, https://doi.org/10.1038/nature05780, 2007a.

Ide, S., Shelly, D. R., and Beroza, G. C.: Mechanism of deep low frequency earthquakes: Further evidence that deep non-volcanic tremor is generated by shear slip on the plate interface, Geophysical Research Letters, 34, https://doi.org/10.1029/2006GL028890, 2007b.

Ide, S., Baltay, A., and Beroza, G. C.: Shallow Dynamic Overshoot and Energetic Deep Rupture in the 2011 Mw 9.0 Tohoku-Oki Earthquake, Science, 332, 1426–1429, https://doi.org/10.1126/science.1207020, 2011.

Ide, S., Yabe, S., and Tanaka, Y.: Earthquake potential revealed by tidal influence on earthquake size–frequency statistics, Nature Geosci, 9, 834–837, https://doi.org/10.1038/ngeo2796, 2016.

Ide, S., Furuichi, M., and Sato, D. S. K.: Ultralow-angle faults produce giant earthquakes, Science Advances, 12, eaee3921, https://doi.org/10.1126/sciadv.aee3921, 2026.

Iio, Y.: Slow initial phase of the P-wave velocity pulse generated by microearthquakes, Geophysical Research Letters, 19, 477–480, https://doi.org/10.1029/92GL00179, 1992.

Ito, Y. and Obara, K.: Very low frequency earthquakes within accretionary prisms are very low stress-drop earthquakes, Geophysical Research Letters, 33, https://doi.org/10.1029/2006GL025883, 2006.

Ito, Y., Obara, K., Shiomi, K., Sekine, S., and Hirose, H.: Slow Earthquakes Coincident with Episodic Tremors and Slow Slip Events, Science, 315, 503–506, https://doi.org/10.1126/science.1134454, 2007.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Jara, J., Jolivet, R., Socquet, A., Comte, D., and Norabuena, E.: Detection of slow slip events along the southern Peru - northern Chile subduction zone, Seismica, 3, https://doi.org/10.26443/seismica.v3i1.980, 2024.

Kanamori, H.: The energy release in great earthquakes, Journal of Geophysical Research (1896-1977), 82, 2981–2987, https://doi.org/10.1029/JB082i020p02981, 1977.

Kanamori, H. and Anderson, D. L.: Theoretical basis of some empirical relations in seismology, Bulletin of the Seismological Society of America, 65, 1073–1095, https://doi.org/10.1785/BSSA0650051073, 1975.

Kaneko, L., Ide, S., and Nakano, M.: Slow Earthquakes in the Microseism Frequency Band (0.1–1.0 Hz) off Kii Peninsula, Japan, Geophysical Research Letters, 45, 2618–2624, https://doi.org/10.1002/2017GL076773, 2018.

Kato, A. and Nakagawa, S.: Detection of deep low-frequency earthquakes in the Nankai subduction zone over 11 years using a matched filter technique, Earth, Planets and Space, 72, 128, https://doi.org/10.1186/s40623-020-01257-4, 2020.

Kato, A., Obara, K., Igarashi, T., Tsuruoka, H., Nakagawa, S., and Hirata, N.: Propagation of Slow Slip Leading Up to the 2011 Mw 9.0 Tohoku-Oki Earthquake, Science, 335, 705–708, https://doi.org/10.1126/science.1215141, 2012.

Kostoglodov, V., Husker, A., Shapiro, N. M., Payero, J. S., Campillo, M., Cotte, N., and Clayton, R.: The 2006 slow slip event and nonvolcanic tremor in the Mexican subduction zone, Geophysical Research Letters, 37, https://doi.org/10.1029/2010GL045424, 2010.

Kostrov, B. V.: Selfsimilar problems of propagation of shear cracks, Journal of Applied Mathematics and Mechanics, 28, 1077–1087, https://doi.org/10.1016/0021-8928(64)90010-3, 1964.

Lowry, A. R., Larson, K. M., Kostoglodov, V., and Bilham, R.: Transient fault slip in Guerrero, southern Mexico, Geophysical Research Letters, 28, 3753–3756, https://doi.org/10.1029/2001GL013238, 2001.

Lu, W. and Ide, S.: Spatiotemporal Characteristics of Tectonic Tremors in California, Geophysical Research Letters, 53, e2025GL120742, https://doi.org/10.1029/2025GL120742, 2026.

Lu, W., Ide, S., and Yue, H.: Feature of cascading rupture frequently observed in Northern California, Commun Earth Environ, 6, 1–9, https://doi.org/10.1038/s43247-025-02138-y, 2025.

Marone, C.: Laboratory-Derived Friction Laws and Their Application to Seismic Faulting, Annual Review of Earth and Planetary Sciences, 26, 643–696, https://doi.org/10.1146/annurev.earth.26.1.643, 1998.

Marone, C. J., Scholtz, C. H., and Bilham, R.: On the mechanics of earthquake afterslip, Journal of Geophysical Research: Solid Earth, 96, 8441–8452, https://doi.org/10.1029/91JB00275, 1991.

Maruyama T.: On the Force Equivalents of Dynamical Elastic Dislocations with Reference to the Earthquake Mechanism, Bull. Earthquake Res. Inst. Univ. Tokyo, 41, 467-486, 1963.

Masuda, K., Ide, S., Ohta, K., and Matsuzawa, T.: Bridging the gap between low-frequency and very-low-frequency earthquakes, Earth, Planets and Space, 72, 47, https://doi.org/10.1186/s40623-020-01172-8, 2020.

Matsumoto, S., Iio, Y., Sakai, S., and Kato, A.: Strength dependency of frequency–magnitude distribution in earthquakes and implications for stress state criticality, Nat Commun, 15, 4957, https://doi.org/10.1038/s41467-024-49422-7, 2024.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Meier, M.-A., Heaton, T., and Clinton, J.: Evidence for universal earthquake rupture initiation behavior, Geophysical Research Letters, 43, 7991–7996, https://doi.org/10.1002/2016GL070081, 2016.

Miyatake, T.: Reconstruction of dynamic rupture process of an earthquake with constraints of kinematic parameters, Geophysical Research Letters, 19, 349–352, https://doi.org/10.1029/92GL00082, 1992.

Mizuno, N. and Ide, S.: Development of a modified envelope correlation method based on maximum-likelihood method and application to detecting and locating deep tectonic tremors in western Japan, Earth, Planets and Space, 71, 40, https://doi.org/10.1186/s40623-019-1022-x, 2019.

Mori, J. and Kanamori, H.: Initial rupture of earthquakes in the 1995 Ridgecrest, California Sequence, Geophysical Research Letters, 23, 2437–2440, https://doi.org/10.1029/96GL02491, 1996.

Mousavi, S. M., Ellsworth, W. L., Zhu, W., Chuang, L. Y., and Beroza, G. C.: Earthquake transformer—an attentive deep-learning model for simultaneous earthquake detection and phase picking, Nat Commun, 11, 3952, https://doi.org/10.1038/s41467-020-17591-w, 2020.

Nadeau, R. M. and Dolenc, D.: Nonvolcanic Tremors Deep Beneath the San Andreas Fault, Science, 307, 389–389, https://doi.org/10.1126/science.1107142, 2005.

Nakata, R., Hori, T., Aochi, H., and Ide, S.: Comprehensive Earthquake Cycle Modeling With Multiscale Patches: Unified Simulation Reproducing Observed Laws and Characteristics, Journal of Geophysical Research: Solid Earth, 131, e2025JB032802, https://doi.org/10.1029/2025JB032802, 2026.

Nanjo, K. Z., Hirata, N., Obara, K., and Kasahara, K.: Decade-scale decrease inb value prior to the M9-class 2011 Tohoku and 2004 Sumatra quakes, Geophysical Research Letters, 39, https://doi.org/10.1029/2012GL052997, 2012.

Nishikawa, T., Matsuzawa, T., Ohta, K., Uchida, N., Nishimura, T., and Ide, S.: The slow earthquake spectrum in the Japan Trench illuminated by the S-net seafloor observatories, Science, 365, 808–813, https://doi.org/10.1126/science.aax5618, 2019.

Nishikawa, T., Ide, S., and Nishimura, T.: A review on slow earthquakes in the Japan Trench, Prog Earth Planet Sci, 10, 1, https://doi.org/10.1186/s40645-022-00528-w, 2023.

Noda, S. and Ellsworth, W. L.: Scaling relation between earthquake magnitude and the departure time from P wave similar growth, Geophysical Research Letters, 43, 9053–9060, https://doi.org/10.1002/2016GL070069, 2016.

Obara, K.: Nonvolcanic Deep Tremor Associated with Subduction in Southwest Japan, Science, 296, 1679–1681, https://doi.org/10.1126/science.1070378, 2002.

Obara, K. and Kato, A.: Connecting slow earthquakes to huge earthquakes, Science, 353, 253–257, https://doi.org/10.1126/science.aaf1512, 2016.

Ohta, Y., Freymueller, J. T., Hreinsdóttir, S., and Suito, H.: A large slow slip event and the depth of the seismogenic zone in the south central Alaska subduction zone, Earth and Planetary Science Letters, 247, 108–116, https://doi.org/10.1016/j.epsl.2006.05.013, 2006.

Olsen, K. B., Madariaga, R., and Archuleta, R. J.: Three-Dimensional Dynamic Simulation of the 1992 Landers Earthquake, Science, 278, 834–838, https://doi.org/10.1126/science.278.5339.834, 1997.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Olson, A. H. and Apsel, R. J.: Finite faults and inverse theory with applications to the 1979 Imperial Valley earthquake, Bulletin of the Seismological Society of America, 72, 1969–2001, https://doi.org/10.1785/BSSA07206A1969, 1982.

Olson, E. L. and Allen, R. M.: The deterministic nature of earthquake rupture, Nature, 438, 212–215, https://doi.org/10.1038/nature04214, 2005.

Outerbridge, K. C., Dixon, T. H., Schwartz, S. Y., Walter, J. I., Protti, M., Gonzalez, V., Biggs, J., Thorwart, M., and Rabbel, W.: A tremor and slip event on the Cocos-Caribbean subduction zone as measured by a global positioning system (GPS) and seismic network on the Nicoya Peninsula, Costa Rica, Journal of Geophysical Research: Solid Earth, 115, https://doi.org/10.1029/2009JB006845, 2010.

Palgunadi, K. H., Gabriel, A.-A., Garagash, D. I., Ulrich, T., and Mai, P. M.: Rupture Dynamics of Cascading Earthquakes in a Multiscale Fracture Network, Journal of Geophysical Research: Solid Earth, 129, e2023JB027578, https://doi.org/10.1029/2023JB027578, 2024.

Peng, Z. and Chao, K.: Non-volcanic tremor beneath the Central Range in Taiwan triggered by the 2001 Mw 7.8 Kunlun earthquake, Geophysical Journal International, 175, 825–829, https://doi.org/10.1111/j.1365-246X.2008.03886.x, 2008.

Peterson, C. L., McNutt, S. R., and Christensen, D. H.: Nonvolcanic Tremor in the Aleutian Arc, Bulletin of the Seismological Society of America, 101, 3081–3087, https://doi.org/10.1785/0120100241, 2011.

Quin, H.: Dynamic stress drop and rupture dynamics of the October 15, 1979 Imperial Valley, California, earthquake, Tectonophysics, 175, 93–117, https://doi.org/10.1016/0040-1951(90)90132-R, 1990.

Renou, J., Vallée, M., and Aochi, H.: Deciphering the Origins of Transient Seismic Moment Accelerations by Realistic Dynamic Rupture Simulations, Bulletin of the Seismological Society of America, https://doi.org/10.1785/0120210221, 2022.

Richter, C. F.: An instrumental earthquake magnitude scale, Bulletin of the Seismological Society of America, 25, 1–32, https://doi.org/10.1785/BSSA0250010001, 1935.

Rogers, G. and Dragert, H.: Episodic Tremor and Slip on the Cascadia Subduction Zone: The Chatter of Silent Slip, Science, 300, 1942–1943, https://doi.org/10.1126/science.1084783, 2003.

Romanet, P. and Ide, S.: Ambient tectonic tremors in Manawatu, Cape Turnagain, Marlborough, and Puysegur, New Zealand, Earth, Planets and Space, 71, 59, https://doi.org/10.1186/s40623-019-1039-1, 2019.

Royer, A. A. and Bostock, M. G.: A comparative study of low frequency earthquake templates in northern Cascadia, Earth and Planetary Science Letters, 402, 247–256, https://doi.org/10.1016/j.epsl.2013.08.040, 2014.

Rubin, A. M. and Armbruster, J. G.: Imaging slow slip fronts in Cascadia with high precision cross-station tremor locations, Geochemistry, Geophysics, Geosystems, 14, 5371–5392, https://doi.org/10.1002/2013GC005031, 2013.

Ruina, A.: Slip instability and state variable friction laws, Journal of Geophysical Research: Solid Earth, 88, 10359–10370, https://doi.org/10.1029/JB088iB12p10359, 1983.

Ruiz, S., Metois, M., Fuenzalida, A., Ruiz, J., Leyton, F., Grandin, R., Vigny, C., Madariaga, R., and Campos, J.: Intense foreshocks and a slow slip event preceded the 2014 Iquique Mw 8.1 earthquake, Science, 345, 1165–1169, https://doi.org/10.1126/science.1256074, 2014.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.

Rydelek, P. and Horiuchi, S.: Is earthquake rupture deterministic?, Nature, 442, E5–E6, https://doi.org/10.1038/nature04963, 2006.

Sagae, K., Kano, M., Yabe, S., and Uchide, T.: Machine Learning-Based Detection and Localization of Tectonic Tremors in the Japan Trench, Journal of Geophysical Research: Solid Earth, 130, e2025JB031348, https://doi.org/10.1029/2025JB031348, 2025.

Sato, T. and Hirasawa, T.: Body Wave Spectra from Propagating Shear Cracks, Journal of Physics of the Earth, 21, 415–431, https://doi.org/10.4294/jpe1952.21.415, 1973.

Scholz, C. H.: Earthquakes and friction laws, Nature, 391, 37–42, https://doi.org/10.1038/34097, 1998.

Scholz, C. H.: On the stress dependence of the earthquake b value, Geophysical Research Letters, 42, 1399–1402, https://doi.org/10.1002/2014GL062863, 2015.

Schorlemmer, D., Wiemer, S., and Wyss, M.: Variations in earthquake-size distribution across different stress regimes, Nature, 437, 539–542, https://doi.org/10.1038/nature04094, 2005.

Shelly, D. R.: A 15 year catalog of more than 1 million low-frequency earthquakes: Tracking tremor and slip along the deep San Andreas Fault, Journal of Geophysical Research: Solid Earth, 122, 3739–3753, https://doi.org/10.1002/2017JB014047, 2017.

Shelly, D. R., Beroza, G. C., and Ide, S.: Non-volcanic tremor and low-frequency earthquake swarms, Nature, 446, 305–307, https://doi.org/10.1038/nature05666, 2007.

Suzuki, W., Aoi, S., Sekiguchi, H., and Kunugi, T.: Rupture process of the 2011 Tohoku-Oki mega-thrust earthquake (M9.0) inverted from strong-motion data, Geophysical Research Letters, 38, https://doi.org/10.1029/2011GL049136, 2011.

Takeo, M., Ide, S., and Yoshida, Y.: The 1993 Kushiro-Oki, Japan, Earthquake: A high stress-drop event in a subducting slab, Geophysical Research Letters, 20, 2607–2610, https://doi.org/10.1029/93GL02864, 1993.

Tape, C., Holtkamp, S., Silwal, V., Hawthorne, J., Kaneko, Y., Ampuero, J. P., Ji, C., Ruppert, N., Smith, K., and West, M. E.: Earthquake nucleation and fault slip complexity in the lower crust of central Alaska, Nature Geosci, 11, 536–541, https://doi.org/10.1038/s41561-018-0144-2, 2018.

Tse, S. T. and Rice, J. R.: Crustal earthquake instability in relation to the depth variation of frictional slip properties, Journal of Geophysical Research: Solid Earth, 91, 9452–9472, https://doi.org/10.1029/JB091iB09p09452, 1986.

Uchida, N., Matsuzawa, T., Ellsworth, W. L., Imanishi, K., Shimamura, K., and Hasegawa, A.: Source parameters of microearthquakes on an interplate asperity off Kamaishi, NE Japan over two earthquake cycles, Geophysical Journal International, 189, 999–1014, https://doi.org/10.1111/j.1365-246X.2012.05377.x, 2012.

Uchide, T. and Ide, S.: Scaling of earthquake rupture growth in the Parkfield area: Self-similar growth and suppression by the finite seismogenic layer, Journal of Geophysical Research: Solid Earth, 115, https://doi.org/10.1029/2009JB007122, 2010.

Vallée, M., Nocquet, J.-M., Battaglia, J., Font, Y., Segovia, M., Régnier, M., Mothes, P., Jarrin, P., Cisneros, D., Vaca, S., Yepes, H., Martin, X., Béthoux, N., and Chlieh, M.: Intense interface seismicity triggered by a shallow slow slip event in the Central Ecuador subduction zone, Journal of Geophysical Research: Solid Earth, 118, 2965–2981, https://doi.org/10.1002/jgrb.50216, 2013.

https://doi.org/10.5194/egusphere-2026-5805
Preprint. Discussion started: 9 November 2026
© Author(s) 2026. CC BY 4.0 License.



Wald, D. J. and Heaton, T. H.: Spatial and temporal distribution of slip for the 1992 Landers, California, earthquake, Bulletin of the Seismological Society of America, 84, 668–691, https://doi.org/10.1785/BSSA0840030668, 1994.

Wech, A. G.: Cataloging Tectonic Tremor Energy Radiation in the Cascadia Subduction Zone, Journal of Geophysical Research: Solid Earth, 126, e2021JB022523, https://doi.org/10.1029/2021JB022523, 2021.

Wech, A. G., Boese, C. M., Stern, T. A., and Townend, J.: Tectonic tremor and deep slow slip on the Alpine Fault, Geophysical Research Letters, 39, https://doi.org/10.1029/2012GL051751, 2012.

Yamada, T. and Ide, S.: Limitation of the Predominant-Period Estimator for Earthquake Early Warning and the Initial Rupture of Earthquakes, Bulletin of the Seismological Society of America, 98, 2739–2745, https://doi.org/10.1785/0120080144, 2008.

Yokota, Y., Koketsu, K., Fujii, Y., Satake, K., Sakai, S., Shinohara, M., and Kanazawa, T.: Joint inversion of strong motion, teleseismic, geodetic, and tsunami datasets for the rupture process of the 2011 Tohoku earthquake, Geophysical Research Letters, 38, https://doi.org/10.1029/2011GL050098, 2011.

Yoshioka, S., Matsuoka, Y., and Ide, S.: Spatiotemporal slip distributions of three long-term slow slip events beneath the Bungo Channel, southwest Japan, inferred from inversion analyses of GPS data, Geophysical Journal International, 201, 1437–1455, https://doi.org/10.1093/gji/ggv022, 2015.

Zhu, W. and Beroza, G. C.: PhaseNet: a deep-neural-network-based seismic arrival-time picking method, Geophysical Journal International, 216, 261–273, https://doi.org/10.1093/gji/ggy423, 2019.