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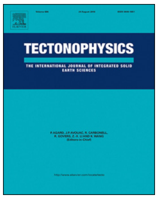

Physics of Earthquake Rupture Propagation

A comprehensive understanding of earthquake rupture propagation requires the study of not only the sudden release of elastic strain energy during co-seismic slip, but also of other processes that operate at a variety of spatiotemporal scales. For example, the accumulation of the elastic strain energy usually takes decades to hundreds of years, and rupture propagation and termination modify the bulk properties of the surrounding medium that can influence the behavior of future earthquakes. To share recent findings in the multiscale investigation of earthquake rupture propagation, we held a session entitled "Physics of Earthquake Rupture Propagation" during the 2016 American Geophysical Union (AGU) Fall Meeting in San Francisco. The session included 46 poster and 32 oral presentations, reporting observations of natural earthquakes, numerical and experimental simulations of earthquake ruptures, and studies of earthquake fault friction. These presentations and discussions during and after the session suggested a need to document more formally the research findings, particularly new observations and views different from conventional ones, complexities in fault zone properties and loading conditions, the diversity of fault slip modes and their interactions, the evaluation of observational and model uncertainties, and comparison between empirical and physics-based models. Therefore, we organize this Special Issue (SI) of Tectonophysics under the same title as our AGU session, hoping to inspire future investigations. Eighteen articles (marked with "this issue") are included in this SI and grouped into the following six categories.

1. Review of past megathrust earthquakes

Two review-type articles summarize what has been learned from past megathrust earthquakes and discuss outstanding issues to be addressed by future studies. Lay (In this issue) focuses on the 2011 Tohoku-oki earthquake and reviews published research on pre-mainshock locking, precursory slow slip and foreshock activity, source models for the mainshock, and post-seismic deformations including aftershocks, afterslip, and viscoelastic stress relaxation. The results indicate that information derived from land-based observations only can be misleading and therefore offshore near-trench observations are needed. This earthquake demonstrates that megathrust rupture may propagate to the trench and possibly penetrate into fault areas that had recently been ruptured. Ruiz and Madariaga (In this issue) review the history of megathrust earthquakes along the Chilean margin, which is known for its along-strike segmentation of seismogenic behavior. They conclude that the concepts of seismic gap, earthquake periodicity, characteristic earthquakes, and earthquake super-cycles need to be re-examined for the Chilean margin, due to the quantitatively inaccurate information used for constraining historic events. They suggest that the along-strike segmentation of the Chilean subduction zone be re-evaluated by taking into account variable along-dip rupture extents of earthquakes and by distinguishing between interplate and intraplate events.

2. Geometric control on earthquake faulting

Faults exhibit geometrical complexity (kink, bend, jog, stepover, topographic relief, etc.) that may either hinder or facilitate rupture propagation (King and Nábělek, 1985; Wesnousky, 2006; Wang and Bilek, 2011). Whether the effects on seismogenesis are persistent over multiple earthquake cycles is important for the assessment of earthquake hazard. Elliott et al. (In this issue) evaluate the likelihood of natural earthquakes being terminated by a double restraining bend, based on field studies along a section of the Altyn Tagh fault bounding the Tibetan Plateau to the north. Their results support previous numerical simulations that a change in strike angle greater than 18 degrees impedes rupture propagation. Yu et al. (In this issue) examine seismic potential along the Manila subduction zone using three-dimensional (3-D) quasi-dynamic earthquake cycle simulation. Their results show that along-strike segmentation typically leads to partial ruptures confined to segments but occasionally allows whole-margin ruptures, depending on details in stress accumulation.

In addition to influencing earthquake propagation, geometrical complexities can affect the slip partitioning and radiation characteristics of earthquakes (Toda et al., 2016; Madariaga et al., 2006; Dunham et al., 2011). Kobayashi et al. (In this issue) analyze InSAR and GNSS data to infer source parameters of the 2014 Northern Nagano earthquake in Japan. The authors prefer a two-plane fault model to fit the geodetic observations, and propose a localized deep inter-seismic slip patch to understand the prestress condition leading to the partitioned co-seismic slip on each of the fault planes. Wang et al. (In this issue) use seismological and GPS data to investigate source properties of the 2016 Kaikoura earthquake in New Zealand. Their results show different source locations in different frequency bands, suggesting that fault geometrical complexity (e.g. kink, branch, and segmentation) may explain the excitation of high-frequency seismic signals in locations that did not undergo large slip.

3. Interplay between fluids and earthquakes

Fluids have been suggested to influence fault strength through hydro-mechanical coupling or physicochemical processes (Scholz, 2002). Norbeck and Horne (In this issue) study the magnitude of injection-induced earthquakes by modeling the interaction between fluid flow within faulted porous media and quasi-elastodynamics along the

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fault. They categorize the modeled earthquakes into two classes: pressure-constrained rupture and runaway rupture, which can be explained by initial shear-to-normal stress ratio relative to dynamic friction.

Tung et al. (In this issue) investigate triggering of the M7.3 aftershock of the 2015 M7.8 Gorkha Nepal earthquake using numerical modeling. Taking into account poroelasticity, they suggest a generic role of pore fluids in triggering aftershocks. Yoshida and Hasegawa (In this issue) analyze seismological data to understand why an earthquake swarm was induced by the 2011 Tohoku-oki earthquake in a stress shadow region. They suggest that fluid release and upward migration were responsible for causing the swarm. Both Tung et al. (In this issue) and Yoshida and Hasegawa (In this issue) note that the behavior of fluid-driven earthquakes can be useful for constraining crustal properties such as permeability and hydraulic diffusivity.

4. Earthquake source properties from observations

Chounet et al. (In this issue) analyze the apparent source time functions in the SCARDEC database for earthquake magnitude larger than 5.6-6 to study rupture directivity, rupture speed regime, and relation between stress drop and rupture speed. They consider issues like bi-material effects, faulting regime, and off-fault damage to explain their results. Clerc et al. (In this issue) analyze ancient rock records preserved in exhumed fault zones to infer earthquake source properties in the lower crust of western Norway. The authors conclude that a single fossil earthquake with almost complete stress drop can explain observed pseudotachylyte. They further infer a fast post-earthquake cooling process, based on the spatial distribution and growth size of garnets in the pseudotachylyte.

5. Physics of fault rupture: Insights from laboratory experiments

Boneh and Reches (In this issue) propose a combination of tribology with geosciences (called geotribology) to study fault wear and friction. They compile many experimental data on rock wear and friction and show that those data can be unified in simple forms using tribological parameters such as stress and slip velocity. Fukuyama et al. (In this issue) monitor the 2-D evolution of slip during earthquake nucleation using borehole strain gauge arrays beneath a 0.5-meter-wide synthetic fault. They categorize the observed evolution patterns into three types based on the number of slip fronts and initiation locations. Yamashita et al. (In this issue) investigate how fault roughness could affect earthquake preparation process along a meter-scale-long and 0.1-meter-wide synthetic fault. By repeatedly conducting frictional sliding experiments along fault surface with variable degrees of roughness, they show that greater fault roughness generally leads to greater spatio-temporal complexity of slow slips preceding main shocks. Xu et al. (In this issue) conduct meter-scale rock friction experiments to examine if strain rate plays a critical role in determining the mode of fault slip. By varying the applied loading rate while fixing all other conditions, they observe an increasing trend of fault slip instability with increasing strain rate. They invoke strain-rate-dependent mechanisms to explain the variations of healing efficiency (during stick period) and weakening rate (during slip period) under different loading rates.

6. Earthquake cycle simulations

Allison and Dunham (In this issue) incorporate off-fault viscoelasticity in antiplane earthquake cycle simulations and analyze results of different geothermal gradients. Their results show that, although the inclusion of viscous flow in the lower crust and upper mantle does not significantly affect the overall behavior of earthquake sequence, it can affect the partitioning of surface deformation caused by fault slip and by viscoelastic relaxation. Luo and Ampuero (In this issue) conduct 2.5-D earthquake cycle simulations to study how heterogeneity in fault properties and effective normal stress could influence the stability mode of fault slip. They identify three stability regimes (stable slip, partial- and total-instability) and show that each regime can be predicted by theoretical linear stability analysis. van den Ende et al. (In this issue) compare simulated earthquake cycle behaviors based on either the classical rate-and-state friction (RSF) or a microphysical model. A major difference exists in the sense that equivalent RSF parameters derived from the microphysical model depend on in-situ loading conditions and hence can evolve during slip. As a result, the simulated earthquake cycles have smaller seismic events and a more stable fault slip behavior using the microphysical model than using the classical RSF.

To conclude, this SI includes studies of past megathrust earthquakes, the role of fault geometrical complexity in controlling earthquake nucleation and propagation, interaction between fluid flow, aseismic slip, and earthquake generation, earthquake source properties dependent on depth, faulting regime, and fault structural maturity, relation between diversity in fault slip modes and complexity in fault zone properties or loading conditions, relation between wear and friction at different stages of faulting, and comparisons of simulated earthquake cycles based on different theories. In addition, articles in this SI highlight the importance to employ offshore observations, to enhance laboratory studies, to perform joint inversion of multi-disciplinary data to constrain earthquake rupture history, to model deformation throughout earthquake cycles, to re-examine conventional concepts pertaining to earthquake recurrence, to study fault zone heterogeneity and complexity and their influence on fault slip behavior across scales, and to evaluate observational and model uncertainties. Therefore, we hope that this SI not only serves to summarize some of the recent progresses in earthquake study, but also provides ideas and examples for the direction of future earthquake research.

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