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Preface to the Topical Volume *Earthquake Source Physics on Various Scales*

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A robust understanding of the physical processes that occur during earthquake rupture is of key importance for improving our ability to reliably predict earthquake ground motions from future damaging events. The past few decades have seen intensive research in this field and scientists became aware of the remarkable complexity of earthquake rupture, which has been shown to be highly variable at all scales and to span a wide dynamic range, from slow to super-shear earthquakes.

Despite significant advances that have been made and the availability of more and more high-quality data sets, many aspects of the earthquake source process remain unclear and highly controversial. A prime example for this situation is the scaling of source parameters between small and large earthquakes, where conflicting results are still obtained by different research groups, even when considering the same data sets. Scientists around the world are working towards improving the understanding of these open questions, using data sets from earthquakes of all sizes, ranging from induced and natural micro-earthquakes to giant megathrust events. More recently, state-of-the-art laboratory rock friction experiments have also received growing attention, being able nowadays to more closely recreate the in situ conditions on a fault during rupture, such as slip velocity, normal stresses and displacements.

This Topical Volume of *Pure and Applied Geophysics* represents an attempt to bring together studies of the seismic source process on all scales in order to put better constraints on their interlinkage, give a state-of-the-art overview of current knowledge, and contribute to the conciliation of conflicting views. The idea for and objectives of this volume stem from a workshop with the same title, *Earthquake source physics on various scales*, organized by the European Center for Geodynamics and Seismology (ECGS) in Luxembourg in October 2012, where most of the included papers were presented. The 17 articles cover theoretical and observational aspects of the seismic source process, from "laboratory earthquakes" as small as magnitude (M) -6 to source complexity and radiated energy of the world's greatest earthquakes, such as the 2011 M 9 Tohoku event. They address the relationship of earthquake recurrence time with fault frictional parameters, how the results of laboratory friction experiments relate to observational source studies, whether small and large earthquakes scale self-similarly or show differences in their dynamic source characteristics, and how geometrical source complexity can be quantified.

The volume begins with contributions that deal with numerical rupture models and theoretical aspects of earthquake source physics. Bizzarri and Crupi investigate the relationship between earthquake recurrence time and fault frictional characteristics on the basis of a synthetic catalogue of nearly 500 sequences using a one-dimensional (1D) single-degree-of-freedom spring-slider model with three versions of rate-dependent and state-dependent friction laws. By exploring the parameter space, they show, among others, that the recurrence time is

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directly proportional to recovery stress and inversely proportional to the loading rate, but that the exact relation strongly depends on many aspects, such as the specific form of the used constitutive model. They therefore conclude that even in the most idealized case of a characteristic earthquake model, the exact calculation of recurrence intervals becomes at least highly complicated, if not virtually impossible. Huang *et al.* present two-dimensional (2D) dynamic rupture models of the 2011 Tohoku earthquake, assuming that the fault is characterized by slip-weakening friction and composed of asperities with varying frictional properties. Their dynamic models show rupture behavior (such as final slip, slip rate, and rupture velocity) consistent with observed slip distributions, finding that the subduction wedge significantly promoted the up-dip rupture propagation. Avlonitis and Papadopoulos study an analytical enrichment of a 2D spring-block model of the Olami-Feder-Christensen type. They show that low b values observed in foreshock sequences can be modeled by a process of material softening within the seismogenic volume, i.e., by a process of strain rate increasing with time under constant stress conditions, but that during aftershocks, material processes are not expected to strongly affect the macroscopic b value behavior. Gusev revisits the classical ω^{-2} earthquake source model in order to study its theoretical foundation. To this end, he introduces stochastic elements both into the final structure of the fault and into the mode of rupture propagation, which leads to the definition of a "doubly stochastic" model. The resulting source spectra behave as ω^{-2} at high frequencies, with source spectral level inversely related to the slip pulse width for a given seismic moment and rms stress drop.

Following these numerical and theoretical studies, laboratory scale and micro-seismic mining-induced earthquakes are investigated. McLaskey *et al.* discuss whether mm-scale earthquake-like seismic events generated in laboratory experiments are consistent with our understanding of the physics of large earthquakes in nature. The combined usage of a large experimental apparatus, high-fidelity sensors and rigorous treatment of wave propagation effects allow the authors to show that the M −6 events generated in their apparatus are consistent with double-couple focal mechanisms caused by left-lateral shear-slip on a mm-scale fault patch and show source properties that are consistent with those determined from large natural earthquakes, such as stress drops of the order of 1–10 MPa. Verberne *et al.* perform direct shear tests on calcite-rich fault gouges sheared at sub-seismic sliding velocities. They carry out an in-depth microstructural analysis and show that both wet and dry gauges, while depicting somewhat different levels of steady-state frictional strength, undergo a transition from stable velocity-strengthening to velocity-weakening slip above 80–100 °C. The authors suggest that frictional behavior in their experiments is controlled by a competition between crystal plastic and granular flow processes that are active in the observed shear bands, and discuss the geological implications of their findings. Niemeijer and Collettini carry out rotary shear experiments on rock samples obtained from the low-angle normal Zuccale fault exposed on the Isle of Elba in Central Italy. They vary the testing conditions on the samples, ranging from room temperature to in situ conditions of temperature, normal stress and fluid saturation, and a large range of sliding velocities in order to analyze the effect of the hydrothermal conditions on frictional stability and strength. All their samples exhibit velocity-strengthening behavior under room temperature, while for the strongest samples low in phyllosilicate content, velocity-weakening and stick–slip behavior is observed at high temperatures and sliding velocities. Naoi *et al.* investigate the frequency-magnitude distribution of micro-seismic earthquakes induced around a mining-front in a deep South African gold mine. The question whether or not the frequency-magnitude distribution follows a power law down to such extremely small events is of great importance, since it relates to fault frictional properties. The authors remove data from blast events and show that the frequency-magnitude distribution of their acoustic-emission and accelerometer data obeys a Gutenberg-Richter relationship with a b value of about 1.2 between M −3.7 and 1.

The article of Malagnini, Mayeda *et al.* provides a bridge from the laboratory and microseismic scale to seismological source scaling observations on local and regional scales. The authors study coda-derived moment-rate spectral ratios of 20 crustal earthquake sequences that occurred in various regions of the world. Their analysis indicates that apparent stress and stress drop increase with earthquake size, contrasting the typical findings of self-similar source scaling on large earthquake data sets from a range of previous studies, but that for earthquakes with moment magnitude (M_W) above about 5.5, apparent stress and stress drop seem to stop increasing, and their variability at large magnitude seems to be significantly smaller than at lower magnitudes. The authors link these observations with the results of recent laboratory friction experiments performed at seismic slip velocities, interpreting their scaling results in terms of increasing fault lubrication with increasing slip and consequent slip-weaking up to full lubrication at $M_W > 5.5$. In a second paper, MALAGNINI, MUNAFO' *et al.* extend on these concepts, analyzing in detail the 2009 L'Aquila and the 1994 Northridge seismic sequences. The authors study the scaling properties of two subsets of events belonging to these sequences and also study the scaling characteristics of seismologically estimated fracture energy, proposing a functional form for the evolution of a fault's shear stress with increasing slip that asymptotically tends to a steady-state value. ROVELLI and CALDERONI present a stress drop study of several earthquakes belonging to the 1997–1998 Colfiorito earthquake sequence, which took place in the Umbria–Marche region in Central Italy. The authors use a spectral ratio approach combined with a second step of ground motion modeling to estimate stress drop values, and discuss their results in the context of previous studies that present contradictory findings on stress drop scaling in order to better understand what the reasons for these discrepancies might be, invoking the importance of the crustal transfer function in stress drop computations. The work of SOMEI *et al.* deals with stress drop estimates from coda spectral ratios of nearly 300 earthquakes that occurred in 17 inland crustal earthquake sequences in Japan, spanning a wide magnitude range. Similar to the study of MALAGNINI, MAYEDA *et al.* mentioned above, the authors describe a break in self-similar scaling properties, in their case for events with magnitudes below and respectively above M_W 4.5. They also consider the determined stress drop values in conjunction with focal depth and mechanism, as well as the event locations with respect to the high strain-rate Niigata-Kobe tectonic zone, and conclude that crack size values determined from their corner frequency analysis correspond to the total rupture area of heterogeneous slip models for the large events in their data set. OTH and KAISER apply a generalized inversion technique to study the stress drops of more than 200 events belonging to the 2010–2011 Canterbury sequence on the South Island of New Zealand. With this approach, they isolate the source spectra from path and site contributions and calculate stress drop values based on the classical ω^{-2} model. The results show that the stress drops of these intraplate type events in a low strain-rate region are generally very high, elevated by about a factor of five compared to results from the more seismically active Japan using the same methodology. The authors find nearly self-similar scaling characteristics and discuss the lateral stress drop variations during the sequence, where the highest stress drop values tend to cluster at the fault edges of the two major events, the M_W 7.2 Darfield and M_W 6.2 Christchurch events.

The volume also includes studies that use focal mechanism investigations for gaining insights into earthquake source complexity. A case where such a description is highly valuable is, for instance, related to hydraulic stimulation of enhanced geothermal reservoirs, where the mode of fracturing (e.g., tensile vs. shear) during induced seismic events is of interest. However, for small earthquakes, the usage of full moment tensor inversion often leads to ambiguous results due to insufficient data quality. ŠÍLENÝ *et al.* systematically investigate this issue, using the case of the Soultz-sous-Forêts reservoir in France as an example. They perform a synthetic study to explore how effects such as mislocations, mismodeling, and noise contamination of the data influence the results, showing that the quality of the monitoring system and potential noise contamination are the most important factors for obtaining robust inversion results. With this synthetic study as a foundation, they investigate several observed small earthquakes in the Soultz-sous-Forêts system, finding that their source mechanisms are dominantly pure shear slips on pre-existing faults. ORTEGA *et al.* present a method for analyzing source complexity of earthquakes of different sizes using a simple formulation that relates the elastic constants obtained from independent studies with the angle between the slip and fault normal vector. With this methodology, the authors analyze earthquakes in the Gulf of California that exhibit a significant isotropic component, coming to the conclusion that small and moderate earthquakes are equally complex, and that in areas where the most relevant earthquakes occur on transform faults, full moment tensor inversion better resolves the fault orientation trend as compared to standard deviatoric inversion.

On the top end of the scale range investigated in this volume, Rivera and Kanamori use W phase inversions with teleseismic data to investigate source geometrical complexity of large earthquakes. The authors analyze large earthquakes with $M_W \geq 7.9$ that occurred since 1990 and focus on the variation of the determined scalar moment, the amount of non-double couple component and the overall focal mechanism with frequency. Their results show that these characteristics can be used to quickly diagnose geometrical complexity. Finally, the volume concludes with a study by Baltay *et al.* on the radiated energy characteristics of the six largest earthquakes worldwide that occurred during the past 10 years, where the authors expand on a teleseismic empirical Green's functions technique used in previous work on the 2011 Tohoku earthquake. They present apparent stress values consistent with self-similar source parameter scaling as obtained in a range of studies for smaller events, and find that the 2012 Off-Sumatra strike-slip event shows a higher apparent stress than the megathrust events in their data set, consistent with previous studies that argue for higher apparent stresses in strike-slip events. The technique proposed in their article might be an attractive tool to calculate radiated energies of great earthquakes in near-real time, an approach that could potentially contribute to rapid response measures.

The results presented in the above contributions provide an excellent illustration of the complexities of the earthquake rupture process and the strong potential of combining the states of knowledge from the study of these processes on different scales, but also of the variety of methodological approaches that can be used in this endeavor. In particular, in the source scaling debate, the wide breath of methodologies and their often significantly different underlying assumptions and constraints still hamper a full and clear comparison of results. Only recently, systematic and robust comparisons of the influence of different approaches have become possible through the availability of the vast databases necessary for this purpose, and further studies are therefore required to clarify how much this factor contributes to contradicting findings. As demonstrated by this volume, significant advances have been made to include all possible scales into the study of the seismic source process. However, the most challenging part of the path, i.e., the full integration of the results obtained on these various scales into a unified picture, still lies ahead of us.

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