Frontiers in Studies of Earthquakes and Faults: Introduction

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The knowledge on properties and dynamics of earthquakes and faults remains highly incomplete despite considerable research spanning over 100 years. The main difficulties stem from the limited resolution of the available observations, strongly nonlinear behavior and other complexities in the governing physics, along with existence of multi-scale multi-phase (solid, granular, fluid) crustal heterogeneities. Recent theoretical and technique developments, novel laboratory experiments, dense seismic arrays, and other high quality data sets provide new opportunities for advancing the understanding of earthquakes and fault zones. These and related topics were discussed in a workshop titled “Frontiers in Studies of Earthquakes and Faults”, conducted during Nov 27–Dec 1, 2017 at the Southern University of Science and Technology, Shenzhen, China. The papers in this topical issue are based on presentations given at the workshop and additional contributions, and they describe the state-of-the-art in several key frontiers. Topics covered in this volume include analysis of earthquake source properties, models of dynamic ruptures and slow slip events, imaging fault zones and the crust, detection of small earthquakes, high-resolution results from laboratory fracturing experiments, quantifying temporal changes of seismic properties, inversions of focal mechanisms to stress and more.

Madariaga et al. (2019) discuss spectra of the Mw 8.4, 2014, Iquique earthquake observed in Chile at various distances from the source. They show that many displacement spectra have ω^{-1} low frequency decay associated with near-intermediate fields and the finite static displacement, and that the standard ω^{-2} decay is observed only at large distances compared to the rupture zone size. Not recognizing the near and intermediate field terms when present can lead to various erroneous interpretations of the data. Kurzon et al. (2019) present simulation results of dynamic ruptures and seismic radiation in a model governed by a continuum damage–breakage brittle rheology. Dynamic changes of elastic moduli during the rupture process produce expansion–compaction around the rupture front and isotropic source term. Significant shear heating is generated only at some distance behind the rupture front with sufficient accumulation of slip. The S/P energy partitioning and far field radiation patterns of the waves are significantly different from those in standard models without brittle damage, especially for S waves.

Ide and Yabe (2019) use a 2D probabilistic cellular automaton model to simulate slow slip events. Each cell can have at any time a state of either slip or stuck, which is updated as a Markov process that depends on the state of the cell and its neighbors. The simulation results mimic various observational properties of slow earthquakes. Separating the effects of loading and dissipation can explain variations in episodic slow slip activity. Bergen and Beroza (2019) compare four methods for producing fingerprints for a detection approach based on waveform similarity without templates from time–frequency data. They synthesize a dataset of earthquake seismograms from real earthquake and noise data recorded in northern California and use this dataset to systematically analyze the performance of each algorithm. They quantify the

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performance of different methods in the context of blind similarity-based detection and show that the FAST fingerprinting method generally performs best in terms of discriminative ability.

Hauksson and Meier (2019) use earthquake depth distributions in 16 distinct lithotectonic regions in southern California and constraints on strain rate and temperature to infer the crustal yield strength envelope (assuming Byerlee's friction and non-linear dislocation creep law) in each region. Five different crustal lithologies and the inferred thermo-mechanical properties agree well with expectations from past tectonics in the area. The differential yield stress is generally smaller and peaks at a shallower depth in hotter and more quartz rich regions, and is larger and peaks at greater depths for colder and predominantly diorite crust. Renard et al. (2019) present results from triaxial compression deformation experiments of low porosity sandstone under confining pressure of 10–20 MPa and room temperature, accompanied by X-ray tomography imaging at various stages of the experiments. The images allow separating the rock volume into host rock matrix, pore space and fractures, and digital volume correlations provide time series of three-dimensional incremental strain tensor fields throughout the experiments. The samples deform after the yielding level first by dilatant opening and propagation of microfractures, and then by shear sliding via grain rotation and strain localization producing system-size faults.

Share et al. (2019b) derive high-resolution V_P and V_S models for the southern California plate boundary from a triple-difference tomography incorporating both event-pair and station-pair differential times. The results include low velocities along major fault segments, V_P/V_S anomalies, and clear across-fault velocity contrasts. The geometries of contrasts in seismic properties across fault sections imply a near vertical San Andreas fault northwest of San Geronio Pass, and northeast dipping San Andreas fault southeast of that area. Abolfathian et al. (2019) invert earthquake focal mechanisms around the San Jacinto fault zone in southern California for the background stress field, and compare the results with coseismic strain parameters derived from earthquake potencies and b -values of the seismicity. The results indicate clockwise rotation of maximum horizontal

compression direction with increasing depth, along with changes in the principal stress and strain plunges. Significant stress changes are not observed across the time of the 2010 Mw 7.2 El Mayor–Cucapah earthquake ~ 150 km to the southeast of the study area.

Share et al. (2019a) use earthquake waveforms recorded by a dense linear array to image the internal structure of the San Jacinto fault zone at Blackburn Saddle. Analysis of fault zone head waves reveal a deep bimaterial interface with significant velocity contrast that extends at least 50 km to the southeast. Analyses of body wave delay times and trapped waves indicate a damage zone northeast of the fault that is several hundred m wide and includes an inner trapping structure with width of ~ 150 m and depth extent of ~ 2 km. The results are consistent with preferred propagation direction of earthquake ruptures in the area to the northwest. Gu et al. (2019) image the region around the Tanlu fault zone in eastern China using ambient noise data recorded by a local seismic array. Fundamental-mode Rayleigh waves with periods in the range 0.2–5 s are constructed from the vertical component of the noise data and are inverted to 3D shear wave velocity model using a direct surface-wave tomographic method. The fault zone is shown to be associated with shallow high-velocity anomaly corresponding to metamorphic rocks. Low-velocity anomalies to the west of the fault are associated with thick sedimentary rocks in the Hefei Basin.

Huang and Yao (2019) use an improved compressive-sensing back-projection method to study seismic radiation by the 2008 Mw 7.9 Wenchuan earthquake, China, in multiple frequency bands. The radiation from the earthquake rupture is shown to be frequency-dependent and related to geometrical fault properties. Low frequency waves are radiated from smooth fault segments with large coseismic slip. High frequencies are radiated primarily from fault complexities that produce strong changes of rupture velocity. Jiang et al. (2019) relocate earthquakes around the time of the 2016 Yunlong Ms5.0 earthquake in China and use these as templates to detect additional events. The derived catalog has about three times more events than those listed in the Yunnan Seismic Networks catalog. The results suggest three

stages of seismic activity during the Yunlong earthquake sequence. The event locations and refined focal mechanisms for a dozen $M \geq 3$ events provide information on the fault strike and dip angles.

Obermann et al. (2019) use 3-D sensitivity kernels of multiply scattered body and surface waves in a heterogeneous solid to provide constraints on the depth of changes of seismic velocities inferred from analysis of coda waves. The accuracy of the estimated location depends on the sources-receivers geometry and proper characterization of scattering at the subsurface. The method is applied to estimate the depth of velocity changes obtained from correlations of ambient noise in the region around the 2008 Wenchuan earthquake. Yang et al. (2019) use synthetic calculations in simple 1-D layered models with low velocities and attenuation coefficients in the top 2 km to examine effects of shallow and deep changes of seismic properties on Rayleigh waves. Large structural changes limited to the top 1–3 km are found to produce significant phase-velocity drops in the period range 5–20s. The results indicate that analyses using different frequency ranges and calculations of delay times over multiple period bands are essential for resolving the depth range of temporal changes of properties.

Wollin et al. (2019) invert earthquake focal mechanisms for the background stress field in the Sea of Marmara region in Turkey. The results show an overall combined strike-slip and normal faulting consistent with the transtensional setting along with internal variations. The eastern Sea of Marmara has primarily a strike-slip regime in the north and normal faulting in the south. The central Marmara region is dominated by normal faulting, while the western Sea of Marmara has primarily strike-slip regime. The results suggest that future large events can be associated with either strike-slip or normal faulting. Kaduri et al. (2019) assess aseismic deformation along sections of the North Anatolian fault in Turkey based on microstructural and chemical analyses of rock samples collected along locked and creeping sections of the fault. The relation between finite strain and volume change is used to quantify the evolution of the penetrative pressure solution cleavage mechanism of creep. The cumulative aseismic displacement is estimated with the aid of geodetic and geologic

data to be in the range 9–49% of the total displacement in the creeping sections and negligible in locked sections.

Li (2019) performs stress inversions of focal mechanisms in the focal region of the Tohoku-Oki mainshock for six time intervals between 2006 and 2017, and uses a 2D model to estimate from the inversion results corresponding changes in the deviatoric stress field. The results suggest that the stress accumulation may have had an acceleration phase several years before the Tohoku-Oki earthquake. This was followed by a significant release of the deviatoric stress field during the Tohoku-Oki event and rapid post mainshock reloading. Yoshida et al. (2019) analyze earthquake focal mechanisms and stress inversion results to examine triggering mechanisms of seismicity in inland Tohoku by the 2011 M9 Tohoku-Oki mainshock. Earthquake clusters triggered by the Tohoku-Oki earthquake tend to occur in regions having similar orientations of the background stress field to that associated with the static stress change by the Tohoku-Oki mainshock. Swarm sequences in central Tohoku in regions associated with stress reduction by the Tohoku-Oki earthquake may have been triggered by fluid movements along major geological boundaries.

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