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Properties and Processes of Crustal Fault Zones: Volume I

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1. Introduction

Crustal fault zones are complex regions of localized deformation with evolving geometries and altered rheological properties from those of the host material. Seismic ruptures modify the geometry, internal structure, and material properties of fault zones. Conversely, properties of earthquake ruptures, seismic radiation, inter- and post-seismic deformation, and local seismicity patterns are controlled by the fault zone structure. It is also well established that faulting modifies the porosity and permeability of the crust and that faults serve as both conduits and barriers to fluid flow. The geometrical complexity, material heterogeneities and wide range of effective space–time scales make the quantification of fault zone properties and processes highly challenging. Many fundamental questions concerning the structure and evolution of fault zones in relation to earthquake properties and generated ground motion remain unanswered despite considerable research spanning over 100 years.

Recent theoretical developments, acquisitions of large seismic and other data sets, detailed geological studies, and novel laboratory experiments provide new opportunities for advancing the understanding of fault zone and earthquake properties. The state-of-the-art in the field was discussed at the 40th Workshop of the International School of Geophysics titled "Properties and Processes of Crustal Fault Zones", conducted during May 18–24, 2013, in the Ettore Majorana Foundation and Centre for Scientific Culture of Erice, Sicily. The papers in the present and follow-up volumes provide broad perspectives on crustal fault zones based on presentations given at the workshop and additional contributions. Topics covered in this volume include fluids and faulting, characterization of fault zone materials, seismic ground motion, geodetic deformation, seismicity and hazard, imaging fault zone structures, experiments on fault evolution, and damage-based rheologies for shear deformation.

Sibson provides an overview on fluid overpressures in different fault zone environments. The results indicate that fluid overpressures are more likely to exist in compressional/transpressional crustal regimes, and subduction interface shear zones, compared to extensional/transtensional settings. Whether earthquakes tend to nucleate or just rupture through overpressure regions and the heterogeneity of overpressuring remain to be clarified in future studies. Place *et al.* describe an experimental approach to estimate the normal and tangential compliances of a rough interface by comparing source P and S waves with reflected phases. The ratio of the compliances depends on the type of saturating fluids and effective pressure. Measuring the temporal variations of the ratio may be used to monitor the evolution in the state of the interface. Curren and Bird use plane-stress clay experiments to study the evolution of strike-slip faults in the presence of preexisting, obliquely oriented faults and joints. The results indicate that preexisting fault networks can cause deflection from pure strike-slip faulting, suppress the development of a through-going fault and lead to distributed shear deformation. Several corresponding examples from natural faulting areas are discussed.

Rockwell *et al.* use non-central principal component analysis to study chemical alteration in rock

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samples from different internal units of the San Jacinto fault zone in southern California. Differences between the fault core and surrounding damage units, combined with XRD results, are interpreted in terms of illite/smectite mineralogical changes during brittle rock damage aided by hot acidic fluids. LINDSEY *et al.* analyze interseismic geodetic deformation across the San Jacinto fault near Anza. GPS and InSAR data indicate a 2–3 km wide shear zone deforming more than twice as fast as the background strain rate. Model simulations show that reduced shear modulus in the fault zone consistent with tomographic images can explain about 50 % of the elevated strain rate, with a best-fitting locking depth several kilometers less than the depth of seismicity. A deep fault zone with larger shear modulus reduction and deeper locking depth can explain fully the elevated strain rate. Additional possibilities include significant fault creep in the section of deep microseismicity, or reduced yield strength and distributed plastic failure in the interseismic period within the upper fault zone. ZÖLLER and BEN-ZION discuss spatio-temporal seismicity patterns along the San Jacinto fault zone, using a long simulated record generated by a model that reproduces the main statistical properties of the available instrumental and paleoseismic data. Augmenting the limited observed data with the longer simulated record increases significantly the hazard associated with a future large San Jacinto earthquake. The simulations indicate further that the recent observed increasing number of moderate events is a robust precursory statistical feature, and that the hypocenters of the moderate events move progressively toward the location of the future large earthquake.

SCHULTE-PELKUM and MAHAN present receiver function results on imaging faults and shear zones that separate isotropic S or anisotropic P structures. Synthetic calculations clarify features of dipping interfaces that may be used to determine their strike and depth; other interface parameters are subjected to trade-offs. Realistic shear fabric anisotropy is shown to produce signals with amplitudes comparable to that generated by the Moho. The method is applied to image the Wind River thrust fault in the western U.S. as a steeply dipping interface in the middle crust that flattens in the lower crust, and to predict seismic signatures from microstructural data of exhumed ductile shear zones in Scotland and the western Canadian Shield. ALLAM *et al.* analyze early P waveforms generated by earthquakes along the Hayward fault, CA, to detect and utilize fault zone head waves that refract along a major bimaterial fault interface. Time differences between the head and direct P arrivals at stations on the slower crustal block vs. propagation distance along the fault are used to calculate average velocity contrasts across different fault sections. The results imply a continuous bimaterial interface in the seismogenic zone spanning the entire $\sim$80 km examined fault length, and structural complexities near the junction between the Hayward and Calaveras faults and the city of Oakland. ZHANG *et al.* incorporate surface wave dispersion data into double-difference tomography of body wave arrival times, and apply the method to obtain three-dimensional P and S velocity models around the site of the San Andreas Fault Observatory at Depth. An appropriate weighting of the body and surface waves data defines an optimal joint solution. Adding the surface-wave constraints to the body waves inversion provides a smoother S wave velocity model.

BOORE describes the global database of the Pacific Earthquake Engineering Center used to develop regional Ground Motion Prediction Equations, along with relevant parameters and techniques, and discusses properties of seismic ground motion near faults based on these data. The available seismic records near faults have complex distributions of motion amplitude and polarization. Scaling relations of the observed ground motion in the entire data set are consistent on average with simple models of source, path and site effects. KURZON *et al.* develop Ground Motion Prediction Equations based exclusively on seismograms recorded in close proximity to the San Jacinto fault zone. The results indicate systematic rupture directivities for given fault sections even for small events, which have significant effects on the ground motion. Fault zone amplification within a region several kilometers wide around the fault is also shown to have an important impact on the observed motion. PANZERA *et al.* analyze directional amplification in ambient seismic noise recorded across and around fault zones in the western flank of Mt. Etna. Near-fault results exhibit systematic motion amplification in a direction close to the fault normal, which is lacking in data several kilometers away and is interpreted in terms of compliance anisotropy of the damage zone. Across-fault variations of the spectral peak frequency may reflect fault damage asymmetry.

Lyakhovsky and Ben-Zion present continuum damage-breakage model results on phase transitions between solid and granular states of material during brittle deformation. The developed framework accounts for faulting with fracturing, granulation, and friction. Shear localization and dynamic instability involve solid-granular transition in the failure zone, while material healing between failure episodes produces the reverse granular-solid transition. Boneh *et al.* study wear and friction in laboratory shear experiments with a high-velocity rotary apparatus and five rock types. An early wear stage of fault roughening is followed by simultaneous reduction of friction and wear-rate, followed by steady-state deformation with low friction and wear-rate when the fault is covered by a gouge layer. The final stage is most relevant to deformation of natural faults with preexisting gouge zones. Lyakhovsky *et al.* uses the damage-breakage framework to develop a model for the wear-rate in the rotary shear experiments as a propagating damage front. Simulation results fit the measured friction and wear-rate in experiments with several types of rocks and loadings. The model predicts that the thickness of the generated gouge depends strongly on the frictional strength. Veveakis and Regenauer-Lieb provide a theoretical explanation for double-localization of shear deformation, observed under both brittle and ductile conditions, in terms of solid–fluid transitions that lead to a second internal localization. Microstructural evolutionary processes govern the time-scale of the transition between slow background shear and rapid episodic localization instabilities. Additional papers on properties and processes of crustal fault zones will be published in a follow up Volume II.

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