PAGEOPH, Vol. 143, No. 1/2/3 (1994)

0033-4553/94/030001-05$1.50 + 0.20/0


# Introduction

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The study of faulting crosses the traditional boundaries between theoretical, field, and laboratory studies. For these reasons, the study of faults and earthquakes is fundamentally multidisciplinary, drawing from laboratory friction and fracture experiments, field studies of natural faults, seismological studies of earthquake rupture, and numerical modeling of fault behavior and crack dynamics. This collection of papers grew out of a desire to pull together these varied approaches to fault and earthquake mechanics and to highlight the multidisciplinary nature of this research. A symposium at the May, 1993 meeting of the American Geophysical Union provided the initial stimulus for the papers contained here, although many papers were contributed later. A testimony to the level of activity in this broad field of inquiry comes from the large number of outstanding papers received. As a consequence, the special issue is being published in two parts. Part I contained 17 papers and Part II, this volume, contains 18.

We have organized the papers into three broad themes based on disciplinary viewpoints, while recognizing that many of the studies fall into two, or even all three, of these themes. These themes echo those in Part I of this special issue.

The volume begins with six papers on the theme of *Fault Mechanics, Rupture Processes, and Fracture: Theory and Observation.* This group of papers focuses on the calculated or measured deformation properties of simple systems to gain insights into macroscopic brittle failure and earthquake cyclicity. In the first paper, Sleep and Blanpied present a model for slip on a porous, creeping fault zone, in which changes in porosity associated with the earthquake cycle cause large variations in fluid pressure. High fluid pressure at the time of earthquake failure allows slip at low shear stress, offering an explanation for the observations of small seismic stress drop in large earthquakes, and for the lack of heat-flow anomaly over the San

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Andreas fault, California. In a companion paper Sleep examines in detail the micromechanical processes by which ductile, pressure solution creep may occur in fault zones at modest depths in the crust. The simultaneous action of grain fracture (cataclasis) and grain growth (Ostwald ripening) establishes a steady-state grain size distribution. Creep viscosities for quartz and feldspar calculated from the model suggest that ductile creep should efficiently remove porosity on the time scale of an earthquake cycle.

Two studies employ dynamic modeling to investigate faulting processes, and find clues to the origin of unexpected field observations. Mora and Place describe a lattice solid model which numerically simulates frictional sliding between rough surfaces, stick-slip, and seismic wave propagation. By monitoring particle trajectories on both sides of the fault, they make the surprising observation that the fault surfaces jump apart during the propagation of a dynamic slip pulse. Although the process by which this normal motion occurs in the model is unclear, a similar observation was made in a laboratory fault model by Anooshehpoor and Brune (published in Part I of this volume). They, like Mora and Place, suggest that reduced normal stress during dynamic slip could provide an alternative explanation for "weak" faults. Yamashita and Umeda present a numerical study of dynamic crack growth and interactions. They show that the rate of dynamic crack growth is strongly influenced by the presence of nearby cracks. This limits the number of cracks which can grow simultaneously within a limited volume, causing sudden rupture termination or crack coalescence. The authors postulate that these interactions occurring within a small volume of fault rock may emit abundant high-frequency elastic waves, appearing as a seismic "bright spot".

Continuing on the issue of crack interactions, Germanovich, Sagalnik, Dyskin, and Lee summarize the fundamentals of crack interactions in two dimensions, then go on to show that this approach is insufficient to fully describe the complexities of crack growth and interactions in three dimensions. They illustrate this point with unique crack-growth experiments in transparent materials, and argue that inferences about the macroscopic failure process drawn from 2-D crack studies may not apply in 3-D. The theme concludes with a paper by Dunning, Douglas, Miller, and McDonald, who present new data on the influence of chemical environment (both ionic strength and pH) on the rate of slow crack growth in quartz and calcite. Based on these experiments and others in the literature, they propose a link between chemical environment, the rate of gouge creation through comminution, and the shearing strength of fault gouges.

Four papers make up our second theme, *Faulting and Fault Zones: Field Observations*. These studies examine in detail the deformation microstructure of materials in and around fault zones. Insodoing, they illustrate the wide range of observational and analytical techniques now available. The first two papers involve faulting at brittle conditions. Antonellini, Aydin, Pollard, and D'Onfro introduce two recent methods for characterizing the porosity structure in rocks: petrographic image analysis, and X-ray computerized tomography. They contrast these methods with each other and with more conventional methods, then illustrate the use of both techniques in a detailed study of the porosity and permeability structure of small faults in sandstone. They infer that porosity reduction associated with fault development could generate hydraulic seals in an otherwise quite permeable rock. An and Sammis examine natural fault gouges formed instead from granitic rocks. They show that the particle sizes in the gouge materials can be described using a combination of log-normal and fractal (power-law) distributions, and infer from modeling of the cataclastic process that a "grinding limit" inhibits grain breakage below a certain size.

The second two papers examine faulting at deeper levels, where fault motion is accommodated by both brittle and ductile deformation mechanisms. Knipe and Lloyd use a range of observational techniques to examine quartzite in and around a small fault which was formed at several kilometers depth. They develop a generalized model of the "birth, life, and death" of a fault, with each stage characterized by a unique association of strain rates and deformation mechanisms, and leaving a distinct microstructure. Hadizadeh describes variations in microstructure and mineral chemistry across a major carbonate thrust fault. He documents a complex interaction between cataclastic flow and pressure solution creep, accompanied by selective redistribution of carbonates and by fluid pressure cycling. Elemental distributions in the fault zone are used to argue that deformation at low strain rates induces a dolomite-to-calcite transformation in the fault zone.

The final section, on the theme of *Rock Friction and Shear Zone Mechanics: Laboratory Studies*, begins with five papers examining the micromechanics of the frictional sliding process. Dieterich and Kilgore present perhaps the first-ever direct observations of sliding surfaces during frictional sliding. Using transparent sample materials and a variety of observational techniques, they measure the real area of contact between rough surfaces, the geometry of the asperity contacts, and how the area of contact changes with time, normal stress and sliding rate. The results of this important study provide a physical basis for the rate- and state-dependent friction constitutive framework. This framework has been widely used in laboratory friction studies and in models of the earthquake instability, as illustrated by the next three papers. Wang and Scholz provide detailed measurements of the effects of slip rate and normal stress on frictional strength and closure across a friction interface in granite. They show that changes in normal stress affect friction both through changes in contact area, as in the previous paper, and also through changes in the degree to which the rough fault surfaces interlock. Reinen, Weeks, and Tullis turn their attention to the frictional properties of serpentinite, a rock type found along both continental and oceanic fault zones. They show that frictional strength varies widely between the lizardite and antigorite serpentine polymorphs, and suggest that a component of non-brittle flow should promote stable fault creep at tectonic slip rates. Marone and Cox explore the physical basis of the characteristic friction distance, $D_c$. They measure frictional strength and $D_c$ for slip to large distances on faults in gabbro. The results indicate that for very rough surfaces $D_c$ no longer scales with roughness in a simple way. Further, they show a dependence of $D_c$ on the thickness of accumulated fault gouge, which has implications for the extrapolation of laboratory results to natural faulting. Gu and Wong also examine in detail the evolution of fault gouge, in this case the development of localized shear surfaces (Riedel shears) within a pre-existing gouge layer. Progressive evolution from slip on inclined $R_1$ shears to slip on boundary-parallel $Y$ shears is found to correlate with decreasing slip stability. A model is presented to explain the observations, in which internal friction remains fixed by the apparent friction rises with accumulating shear strain.

David, Wong, Zhu and Zhang examine the relation between pressure, porosity and permeability, through laboratory compaction experiments on sandstones. They present numerical simulations of compaction and fluid flow, and argue that compaction occurring through a combination of mechanical and chemical processes provides an efficient way to develop excess pore pressure in upper crustal basins and fault zones. The paper by King summarizes findings from a laboratory fault model constructed of coupled masses and springs. Measurements of stress drop, event size and other observables are compared to analogous measurements from natural faults and from numerical spring-block models. In the final paper, Hueckel, Peano, and Pellegrini present a constitutive framework for deformation of rocks based on thermo-plasticity, macroscopic theory which has been used in studies of metals but rarely for rocks. The paper outlines the fundamental features of the constitutive law, then illustrates its use by modeling suites of deformation tests on marble and granite over a broad range of temperatures.

*Acknowledgements*

This volume benefited from the work of many people. The Guest Editors thank Marie Sénat for ably coordinating our editorial efforts, the authors for contributing high-quality papers, Renata Dmowska for her editorial advice and encouragement, and David Scott for co-convening with CM the original AGU session. In addition, we would like to acknowledge the institutional support of MIT and the USGS, and CM gratefully acknowledges financial support from the Kerr-McGee foundation.

We also thank the many colleagues who donated their time and insight in providing careful reviews of the submitted manuscripts: R. Abercrombie, J. Andrews, T. Barr, N. Beeler, Y. Ben-Zion, J. Boatwright, G. Boitnott, S. Brown, R. Bruhn, J. Byerlee, J. Carlson, D. Castillo, G. Chen, F. Chester, S. F. Cox, S. J. D. Cox, S. Das, Y. Du, T. Engelder, B. Evans, J. Evans, R. Fournier, J. Fredrich, L. Gilbert, J.-P. Gratier, J. Hadizadeh, T. Hanks, R. Harris, G. Hirth, J. Huang, D. Karig, B. Kilgore, L. Knopoff, A. Kronenberg, S. Larsen, B. Lawn, M. Linker, G.

Lloyd, D. Lockner, J. Logan, I. Main, A. Malinverno, G. Mandl, A. McGarr, P. Meredith, D. Moore, D. Moos, F. Morrison, Y. Okada, E. Okal, S. Olig, W. Power, J. Rice, D. Rothman, J. Rudnicki, J. Rundle, E. Rutter, C. Sammis, D. Sanderson, C. Scholz, D. Scott, B. Shaw, K. Shimazaki, N. Sleep, H. Spetzler, M. Spiegelman, J. Spray, D. Stanley, S. Steacy, W. Thatcher, T. Tullis, D. Turcotte, J. Wait, J. Walsh, W. Wang, J. Weeks, S. Wesnousky, T.-F. Wong, P. Young, and M. L. Zoback.