

## The Mechanics of Earthquakes and Faulting

### 2nd Edition

Our understanding of earthquakes and faulting processes has developed significantly since publication of the first edition of this book in 1990. This revised edition has therefore been thoroughly up-dated whilst maintaining and developing the two major themes of the first edition.

The first of these themes is the intimate connection between fault and earthquake mechanics, including fault scaling laws, the nature of fault populations, and how these result from the processes of fault growth and interaction. This has led to a fuller appreciation of how faulting and earthquakes are actually different timescale manifestations of the same dynamical system. The second major theme is the central role of the rate-state friction laws in earthquake mechanics. It is now understood that these friction laws not only govern the earthquake instability itself, but also result in a gamut of other earthquake phenomena including seismic coupling and decoupling, pre- and post-seismic deformation, earthquake triggering, and the relative insensitivity of earthquake to transients such as earth tides. Thus friction laws provide a unifying framework within which a wide range of faulting phenomena can be interpreted.

With the inclusion of two chapters which explain brittle fracture and rock friction from first principles, this book is written at a level which will appeal to scientists from a variety of disciplines for whom a complete understanding of faulting and earthquakes is the ultimate goal. Graduate students and research scientists in the fields of seismology, physics, geology, geodesy, and rock mechanics will greatly benefit from this book.

**Christopher Scholz** experienced his first earthquake in California at the age of nine and has been asking questions about faulting and earthquakes ever since. He is now Professor of Earth Science and Applied Mathematics at the Lamont-Doherty Earth Observatory, Columbia University, where he uses laboratory experiments, theory, and field-based techniques to study brittle deformation processes that occur in the outermost layer of the Earth. In addition to over 160 papers in the primary literature, Professor Scholz is also the author of *Fieldwork: a geologist's memoir of the Kalahari* (1997) and coeditor of *Fractals in Geophysics* (1989).

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A photograph by G.K. Gilbert of the surface rupture produced by the 1906 San Francisco earthquake. (Photo courtesy of the US Geological Survey.)

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# The Mechanics of Earthquakes and Faulting

2nd edition

Christopher H. Scholz

Lamont-Doherty Geological Observatory and  
Department of Earth and Environmental Sciences,  
Columbia University



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*...and then there would not be friction any more, and the sound would cease, and the dancers would stop...*

Leonardo da Vinci

From a notebook dated September, 1508

MacCurdy, E. 1958. *The Notebooks of Leonardo da Vinci*, p. 282, New York: George Braziller.

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## Preface to the first edition

It has now been more than thirty years since the publication of E. M. Anderson's *The Dynamics of Faulting* and C. F. Richter's *Elementary Seismology*. Several generations of earth scientists were raised on these texts. Although these books are still well worth reading today for their excellent descriptions of faults and earthquakes, the mechanical principles they espoused are now well understood by the undergraduate student at the second or third year. In the meantime a great deal has been learned about these subjects, and the two topics, faulting and earthquakes, described in those books have merged into one broader field, as earthquakes have been more clearly understood to be one manifestation of faulting. During this period of rapid progress there has not been a single book written that adequately fills the gap left by these two classics. As a result it has become increasingly difficult for the student or active researcher in this area to obtain an overall grasp of the subject that is both up-to-date and comprehensive and that is based firmly on fundamental mechanical principles. This book has been written to fill this need.

Not least among the difficulties facing the researcher in this field is the interdisciplinary nature of the subject. For historical reasons earthquakes are considered to be the province of the seismologist and the study of faults is that of the geologist. However, because earthquakes are a result of an instability in faulting that is so pervasive that on many faults most slip occurs during them, the interests of these two disciplines must necessarily become intertwined. Moreover, when considering the mechanics of these processes the rock mechanist also becomes involved, because the natural phenomena are a consequence of the material properties of the rock and its surfaces.

It is a consequence of the way in which science is organized that the scientist is trained by discipline, not by topic, and so interdisciplinary

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subjects such as this one tend to be attacked in a piecemeal fashion from the vantage of the different specialties that find application in studying it. This is disadvantageous because progress is hindered by lack of communication between the different disciplines, misunderstandings can abound, and different, sometimes conflicting, schools of thought can flourish in the relative isolation of separate fields. Workers in one field may be ignorant of relevant facts established in another, or, more likely, be unaware of the skein of evidence that weights the convictions of workers in another field. This leads not only to a neglect of some aspects in considering a question, but also to the quoting of results attributed to another field with greater confidence than workers in that field would themselves maintain. It is not enough to be aware, second-hand, of the contributions of another field – one must know the basis, within the internal structure of the evidence and tools of that field, upon which that result is maintained. Only then is one in a position to take the results of all the disciplines and place them, with their proper weight, in the correct position of the overall jigsaw puzzle. Because the literature on this topic has become both large and diverse, a guide is useful in this process, together with some unifying mechanical principles that allow the contours of the forest to be seen from between the trees.

Although I have dabbled, to one degree or another, in the various different disciplinary approaches to this problem and therefore have a rudimentary working knowledge of them, my own specialty is rock mechanics, and so this approach is the one most emphasized in this book. Faults are treated as shear cracks, the propagation of which may be understood through the application of fracture mechanics. The stability of this fault movement, which determines whether the faulting is seismic or aseismic, is determined by the frictional constitutive law of the fault surface, and so that is the second major theme applied throughout this treatment. The application of these principles to geology is not straightforward. One cannot actually do a laboratory experiment that duplicates natural conditions. Laboratory studies can only be used to establish physical processes and validate theories. To apply the results of this work to natural phenomena requires a conceptual jump, because of problems of scale and because both the nature of the materials and the physical conditions are not well known. In order to do this one must have constant recourse to geological and geophysical observations and, working backwards, through these physical

principles determine the underlying cause of the behavior of faults. For this reason, much of this book is taken up in describing observations of natural cases.

Because rock mechanics is not taught universally in earth science curricula, the first two chapters present an account of brittle fracture and friction of rock, beginning from first principles. These chapters provide the basis for the later discussion of geological phenomena. The subsequent chapters assume a beginning graduate level understanding of the earth science disciplines involved. In these chapters the results of geology, seismology, and geodesy are presented, but the techniques employed by the various specialties are not described at any length. The emphasis is on providing an overall understanding of a scientific topic rather than teaching a specific craft. A goal was to describe each topic accurately, but at such a level that it could be understood by workers in other fields.

A book may be structured in many different ways. In this case, I found it difficult to choose between organizing the book around the physical mechanisms or around the natural phenomena in which they are manifested. The latter scheme would be more familiar to the earth scientist, the former to the mechanist. Ultimately, I adopted a system arranged around mechanics, but which still retains many of the more familiar traditional associations. Because some mechanisms are important in a number of different phenomena, which might otherwise be considered quite distant, and some earthquakes provide examples of several phenomena, there are often more than two connections to other topics. Therefore, it was not always possible to present the subject matter in a serial sequence. I consequently adopted a system of cross-referencing that allows the reader to traverse the book in alternative paths. I hope this system will be more helpful than confusing.

When I first entered graduate school twenty-five years ago, most of the material described in this book was not yet known. The first generation of understanding, outlined in Anderson's and Richter's books, has been augmented by a second generation of mechanics, much more thorough and quantitative than the preceding. This has been a most productive era, which this book celebrates. I owe my own development to associations with many people. My first mentor, W. F. Brace, set me on this path, and the way has been lit by many others since. I have also been a beneficiary of an enlightened system of scientific funding during this period, which has

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allowed me to pursue many interesting topics, often at no little expense. For this I particularly would like to thank the National Science Foundation, the US Geological Survey, and NASA.

Many have helped in the preparation of this book. In particular I acknowledge the assistance of my editor, Peter-John Leone, Kazuko Nagao, who produced many of the illustrations, and those who have reviewed various parts of the manuscript: T.-F. Wong, W. Means, J. Logan, S. Das, P. Molnar, J. Boatwright, L. Sykes, D. Simpson, and C. Sammis. Particular thanks are due to T. C. Hanks, who offered many helpful comments on the text, and who, over the course of a twenty-year association, has not failed to point out my foibles. I dedicate the book to my wife, Yoshiko, who provided me with the stability in my personal life necessary for carrying out this task.

## Preface to the second edition

When the first edition of this book was completed in 1989 the study of earthquakes and faulting was still developing rapidly and has continued to do so in the intervening years. It thus seemed necessary, in order to keep this work useful, that an extensively revised and updated new edition be prepared.

Progress during these dozen years has not, of course, been uniform. There have been rapid developments in some areas whereas others have been relatively static. As a result, some sections and chapters have been extensively revised while others remain almost the same, undergoing only minor updating. A goal in this revision was to retain the same overall length, and this has been largely successful. This necessitated the removal of material which in hindsight no longer seemed as vital as it once did or which had been superseded by more recent results.

The two major themes of the first edition have been further developed in the interim. The first of these is the intimate connection between fault and earthquake mechanics. Fault mechanics in 1989 was still in a primitive state, but rapid progress during the 1990s has brought the discovery of the main fault scaling laws, the nature of fault populations, and how these result from the processes of fault growth and interaction. This new knowledge of fault mechanics provides a fuller appreciation of faulting and earthquakes as two aspects of the same dynamical system: the former its long-timescale and the latter its short-timescale manifestation. One major development along these lines is the realization that neither faulting nor earthquakes behave in an isolated manner but interact with other faults or earthquakes through their stress fields, sometimes stimulating the activity of neighboring faults, sometimes inhibiting it, the totality of such interactions resulting in the populations, of both faults and earthquakes, that are formed.

xvi    **Preface to second edition**

The second major theme is the central role of the rate–state friction laws in earthquake mechanics. These friction laws are now known to not only produce the earthquake instability itself but to result in a gamut of other earthquake phenomena: seismic coupling and decoupling, pre- and post-seismic phenomena, earthquake triggering, and the relative insensitivity of earthquakes to transients such as earth tides. Thus the friction laws provide a unifying strand for understanding the commonality of many phenomena previously thought to be disparate. Meanwhile the physics behind these friction laws has become better understood, rendering them less opaque than previously.

The development and deployment of telemetered networks of broadband digital seismometers and of space based geodesy with GPS and InSAR has provided far more detailed descriptions of earthquakes and the earthquake cycle than ever before. These observations have allowed for their inversion for the internal kinematics of large earthquakes in well monitored regions like California as well as detailed descriptions of interseismic loading and postseismic relaxation, all of which has improved our understanding of the underlying dynamics.

Many people have helped in my preparation of this revised edition. I am particularly indebted to Masao Nakatani, who offered many comments on shortcomings of the first edition and who helped me to better understand the physical basis of the rate–state-variable friction laws.

Palisades, New York, April, 2001

C. H. S.



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From *Advances in Geophysics*: Plates 3, 4, and 5, King and Cocco (2000) 44: 1.

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From *Science*: Figures 2.26 and 2.27, Raleigh *et al.* (1976) 191: 1230–7; Figures 2.13 and 2.22, Shimamoto (1986) 231: 711–14; Figures 7.22 and 7.30, Scholz *et al.* (1973) 181: 803–9; Figures 7.21, Scholz (1978) 201: 441–2; Figure 4.17, Staff, USGS (1990) 247: 286.

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From *Journal of Geophysical Research*: Figure 2.2, Brown and Scholz (1985) 90: 5531; Figure 2.3b, Brown and Scholz (1985) 90: 12575; Figure 7.17, Das and Scholz (1981) 86: 6039; Figure 5.3, Fitch and Scholz (1971) 76: 7260; Figure 5.23, Schwartz and Coppersmith (1984) 89: 5681; Figure 6.5, Scholz (1980) 85: 6174; Figures 7.31 and 7.32 Wesnousky *et al.* (1983) 88: 9331; Figure 2.5, Boitnott *et al.* (1992) 97: 8965; Figure 2.7, Wang and Scholz (1995) 100: 4243; Figure 2.11, Blanpied *et al.* (1995) 100: 13045; Figure 3.11, Vermilye and Scholz (1998) 103: 12223; Figure 2.21, Blanpied *et al.* (1998) 103: 9691; Figure 3.20 and 6.9, Cowie *et al.* (1993) 98: 17911; Figure 4.14, Hauksson *et al.* (1993)

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98: 19835; Figure 5.5, Savage *et al.* (1999) 104: 4995; Figure 5.6, Savage (1995) 100: 6339; Figure 5.7, Savage and Thatcher (1992) 97: 11117; Figure 5.9, Gilbert *et al.* (1994) 99: 975; Figure 5.10, Peltzer *et al.* (1998) 103: 30131; Figure 5.11, Muir-Wood and King (1993) 98: 22035; Figure 5.36, Shaw (1995) 100: 18239; Figures 6.15 and 6.16, Scholz and Campos (1995) 100: 22103; Figure 7.28, Dodge *et al.* (1996) 101: 22371; Plate 8, Triep and Sykes (1997) 102: 9923.

From *Eos*, Plate 6, Shen *et al.* (1997) 78: 477.

From *Earthquake Prediction, an International Review*. M. Ewing Ser. 4 (1981). Figure 4.28, Einarsson *et al.*, p. 141; Figure 5.28, Sykes *et al.*, p. 1784; Figures 7.2 and 7.3, Ohtake *et al.*, p. 53.

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From *Tectonics*: Figure 6.4, Byrne *et al.* (1988) 7: 833.

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From *Physical Review B – Condensed Matter*: Figure 2.20, Baumberger *et al.* (1999) 60: 3928.

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From *Annual Reviews of Earth and Planetary Sciences*: Figures 1.18, 3.2, 6.13, 6.20, Scholz (1989) 17: 309–34; Figure 5.2, Mavko (1981) 9: 81–111; Figure 6.20, Simpson (1986) 14: 21–42, Figure 2.17, Marone (1998) 26, 643; Figure 6.13, Frohlich (1989) 17: 227.

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From *Pageoph*: Figure 2.9, Byerlee (1978) 116: 625; Figure 4.10, Hanks (1977) 115: 441; Figure 7.1, Scholz (1988) 126: 701; Figure 7.10, Sato (1988) 126: 465; Figure 7.11, Roeloffs (1988) 126: 177; Figure 7.12, Wakita (1988) 126: 267; Figures 7.23 and 7.24, Rudnicki (1988) 126: 531; Figures 7.25, 7.26, and 7.27, Stuart (1988) 126: 619; Figure 7.1, Sykes *et al.* (1999) 155: 207.

From *Faulting, Friction and Earthquake Mechanics*: Plate 1, Dieterich and Kilgore (1994), 283.

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From *Tectonophysics*: Figures 6.7, Uyeda (1982) 81: 133.

From *Journal of Structural Geology*: Figure 3.16, Contreras *et al.* (2000) 22: 159.

## GEOLOGICAL SOCIETY OF AMERICA

From *GSA Bulletin*: Figure 3.27, Tchalenka and Berberian (1975) 86: 703; Figure 5.21, Sieh and Jahns (1984) 95: 883.

From *Geology*: Figures 2.14 and 3.14, Scholz (1987) 15: 493; Figure 3.38, Sibson (1987) 15: 701; Figure 3.9, Dawers *et al.* (1993) 21: 1107; Figure 3.10, Schlische *et al.* (1996) 24: 683; Figure 3.18, Ackermann and Schlische (1997) 25: 1127.

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From *Nature*: Figure 3.15, Wesnousky (1988) 335: 340; Figures 1.16 and 1.17, Lockner *et al.* (1991) 350: 39; Figure 5.4, Bourne *et al.* (1998) 391: 655.

## SEISMOLOGICAL SOCIETY OF AMERICA

From *Bulletin of the Seismological Society of America*: Figure 4.4, Andrews (1985) 75: 1; Figure 5.33, Nishenko and Buland (1987) 77: 1382; Figure 4.18, Beroza (1991) 81: 1603; Figure 4.19, Wald *et al.* (1996) 86: S49; Figure 6.19, Chen and Talwani (2001) 91: in press; Figure 7.27, Abercrombie *et al.* (1995) 85: 1873.

## UTAH GEOLOGICAL AND MINERAL SURVEY

From *Utah Geological and Mineral Survey Special Studies* 62 (1983): Figure 5.23, Schwartz *et al.*, p. 45.

# List of symbols

A listing is given of the most important symbols in alphabetical order, first in the Latin, then the Greek alphabets. The point of first appearance is given in brackets, which refers to an equation unless otherwise indicated. In some cases the same symbol is used for different meanings, and vice versa, as indicated, but the meaning is clear within the context used. Arbitrary constants and very common usages are not listed.

- $a$  atomic spacing [(1.1)]; crack radius [(4.24)]
- $a(\text{H}_2\text{O})$  chemical activity of water [(1.52)]
- $\alpha$  direct friction velocity parameter [(2.26)]
- $\alpha - b$  combined friction velocity parameter [(2.27)]
- $A$  area [Section 2.1.2]
- $A_r$  real area of contact [(2.1)]
- $b$  steady-state friction velocity parameter(s) [(2.26)]
- $B$  exponent in the earthquake size distribution [(4.31)]
- $B$  Skempton's coefficient [(6.10)]
- $c$  crack length [(1.5)]
- $C_0$  uniaxial compressive strength [(1.34)]
- $d$  contact diameter [(2.18)]
- $d_e$  effective working distance of contact [(2.19)]
- $d_s$  offset of jog (or step) [Section 3.5.1]
- $d_0$  critical slip distance (in slip weakening model) [(4.14)]
- $D$  total fault slip [(2.21)]; asthenospheric diffusivity [(5.1)]
- $D_c$  critical slip distance (in rate-state friction) [(2.26)]
- $E$  Young's modulus [(1.2)]

|                  |                                                                |
|------------------|----------------------------------------------------------------|
| $E$              | effective modulus [(1.8)]                                      |
| $E^*$            | activation energy [(1.52)]                                     |
| $E_s$            | seismic energy [(3.5)]                                         |
| $f_{ij}(\theta)$ | stress function [(1.20)]                                       |
| $f_i(\theta)$    | displacement function [(1.20)]                                 |
| $f_0$            | corner frequency [Section 4.3.1]                               |
| $F$              | shear force [(2.2)]                                            |
| $F_{SA}$         | sea anchor force [(6.6)]                                       |
| $F_{SU}$         | slab suction force [(6.6)]                                     |
| $F_{SP}$         | slab pull force [(6.7)]                                        |
| $g$              | acceleration of gravity [(3.2)]                                |
| $G$              | energy release rate [(1.21)]                                   |
| $G$              | shear modulus [(6.10)]                                         |
| $\mathcal{G}_c$  | critical energy release rate (fracture energy) [(1.24)]        |
| $h$              | hardness parameter [(2.1)]                                     |
| $k, K$           | stiffness [(5.3)], [(2.24)]                                    |
| $K_n$            | stress intensity factor (mode) [(1.20)]                        |
| $\mathcal{H}_c$  | critical stress intensity factor (fracture toughness) [(1.24)] |
| $\mathcal{H}_0$  | stress-corrosion limit [Figure 1.21]                           |
| $l$              | slip zone length [(2.33)]                                      |
| $l_c$            | critical slip zone length [(2.34)]                             |
| $L$              | length of rupture [Section 4.3.2]                              |
| $L_c$            | critical crack length [(4.13)]                                 |
| $m$              | mass [(2.33)]                                                  |
| $M$              | magnitude [Section 4.3.1]                                      |
| $M_s$            | surface wave magnitude [(4.26)]                                |
| $M_w$            | moment magnitude [Section 4.3.1]                               |
| $M_0, M_{0ij}$   | seismic moment [(4.25)]                                        |
| $M_0^s$          | seismic moment release rate [(6.4)]                            |
| $M_0^g$          | geologic moment release rate [(6.4)]                           |
| $n$              | stress-corrosion index [(1.46)]                                |

xxii    **List of symbols**

|                     |                                                                                                     |
|---------------------|-----------------------------------------------------------------------------------------------------|
| $N$                 | normal force [(2.1)]                                                                                |
| $N$                 | number of contact junctions [(2.19)]                                                                |
| $p$                 | pressure [(2.37)]; pore pressure [(1.43)]; penetration hardness [(2.1)]                             |
| $\Delta p_p$        | change in pore pressure [(6.11)]                                                                    |
| $q$                 | heat flow [(3.6)]                                                                                   |
| $Q$                 | heat [(3.5)]                                                                                        |
| $R$                 | gas constant [(1.49)]                                                                               |
| $s$                 | shear strength [(2.2)]                                                                              |
| $S$                 | dynamic strength parameter [(4.20)]                                                                 |
| $t$                 | time [(4.21)]                                                                                       |
| $t_h$               | healing time [(4.21)]                                                                               |
| $t_r$               | rise time [(2.36)]                                                                                  |
| $\langle t \rangle$ | mean failure time [(1.53)]                                                                          |
| $T$                 | temperature [(1.49)]; thickness of gouge layer [(2.22)]; earthquake recurrence time [Section 5.2.2] |
| $T_{\text{exp}}$    | expected recurrence time [(7.6)]                                                                    |
| $T_{\text{ave}}$    | average recurrence time [Section 7.4.3]                                                             |
| $T_0$               | uniaxial tensile strength [(1.29)]                                                                  |
| $\mathcal{T}_1$     | lower stability transition [Section 3.4.1]                                                          |
| $\mathcal{T}_2$     | semibrittle-plastic transition [Section 3.4.1]                                                      |
| $\mathcal{T}_3$     | schizosphere-plastosphere boundary [Section 3.4.1]                                                  |
| $\mathcal{T}_4$     | upper stability transition [Section 3.4.1]                                                          |
| $u, u_i$            | displacement [(1.20)]                                                                               |
| $u_p$               | afterslip [(6.6)]                                                                                   |
| $\Delta u_i$        | slip in earthquake (offset) [(4.25)]                                                                |
| $\Delta u$          | mean slip in earthquake [(4.5)]                                                                     |
| $U$                 | total energy [(1.6)]                                                                                |
| $U_e$               | internal strain energy [(1.6)]                                                                      |
| $U_s$               | surface energy [(1.6)]                                                                              |
| $U_k$               | kinetic energy [(4.1)]                                                                              |
| $U_f$               | frictional work [(4.1)]                                                                             |

|                           |                                                                                                    |
|---------------------------|----------------------------------------------------------------------------------------------------|
| $v$                       | crack-tip velocity [(1.46)]                                                                        |
| $\dot{u}$                 | particle velocity [(2.35)]                                                                         |
| $\dot{u}_{\text{max}}$    | maximum particle velocity [(4.22)]                                                                 |
| $\dot{u}_0$               | asymptotic particle velocity [(4.23)]                                                              |
| $v_{\text{pl}}$           | remote plate velocity [Section 5.2.2]                                                              |
| $v_{\text{c}}$            | plate convergence rate [Section 6.4.2]                                                             |
| $v_{\text{s}}$            | plate subduction rate [Section 6.4.2]                                                              |
| $V_{\text{p}}$            | P wave velocity [Section 6.4.2]                                                                    |
| $V_{\text{s}}$            | S wave velocity [Section 7.2.2]                                                                    |
| $v_{\text{r}}$            | rupture velocity [(4.19)]                                                                          |
| $V$                       | volume of wear fragments [(2.20)]; slip velocity [(2.26)] volume [(4.3)]                           |
| $V_{\text{c}}$            | coseismic slip velocity [(6.8)]                                                                    |
| $W$                       | work [(1.6)]; width of fault (or rupture) [Section 3.2.2]                                          |
| $W_{\text{fr}}$           | frictional work [Section 3.2.2]                                                                    |
| $W_{\text{f}}$            | work of faulting [(3.8)]                                                                           |
| $\beta$                   | shear wave velocity [(4.16)]                                                                       |
| $\gamma$                  | specific surface energy [(1.4)]                                                                    |
| $\Gamma$                  | Irwin's energy dissipation factor [(1.27)]                                                         |
| $\delta$                  | joint closure [(2.7)]                                                                              |
| $\delta_{ij}$             | Kronecker delta [(1.43)]                                                                           |
| $\epsilon_{ij}$           | strain [Section 6.2.2]                                                                             |
| $\Delta\epsilon_{\omega}$ | volume strain change [(6.11)]                                                                      |
| $\eta$                    | seismic efficiency [(4.8)]; asthenospheric viscosity [Section 5.2.2]                               |
| $\theta_{\text{s}}$       | angle of jog (or step) [Figure 3.26]                                                               |
| $\kappa$                  | wear coefficient [(2.22)]                                                                          |
| $\lambda_{\text{c}}$      | critical aperture wavelength [(2.39)]                                                              |
| $\mu$                     | friction coefficient [(1.30)]; coefficient of internal friction [(1.31)];<br>shear modulus [(4.9)] |
| $\mu_0$                   | base friction coefficient [(2.27)]                                                                 |
| $\mu_{\text{ss}}$         | steady-state friction coefficient [(2.27)]                                                         |
| $\mu_{\text{s}}$          | static coefficient of friction [(2.28)]                                                            |

|                       |                                                                       |
|-----------------------|-----------------------------------------------------------------------|
| $\mu_d$               | dynamic coefficient of friction [(2.28)]                              |
| $\Delta\mu$           | change in friction [(2.37)]                                           |
| $\nu$                 | Poisson's ratio [(1.23)]                                              |
| $\rho$                | density [(3.2)]; radius of curvature [(1.5)]                          |
| $\sigma, \sigma_{ij}$ | stress [(1.1)]                                                        |
| $\sigma_t$            | theoretical strength [(1.1)]                                          |
| $\sigma_f$            | Griffith strength [(1.12)]                                            |
| $\sigma_n$            | normal stress [(1.30)]                                                |
| $\bar{\sigma}_{ij}$   | effective stress [(1.43)]                                             |
| $\sigma_c$            | mean contact stress [(2.15)]                                          |
| $\sigma_1$            | initial stress [(4.6)]                                                |
| $\sigma_2$            | final stress [(4.6)]                                                  |
| $\sigma_f$            | frictional stress [(4.6)]                                             |
| $\sigma_y$            | yield stress [(4.20)]                                                 |
| $\sigma_D$            | intrinsic standard deviation [(7.5)]                                  |
| $\Delta\sigma$        | static stress drop [(4.7)]                                            |
| $\Delta\sigma_d$      | dynamic stress drop [Section 4.2.1]                                   |
| $\tau$                | shear stress [(1.30)]; asthenospheric relaxation time [Section 5.2.2] |
| $\tau_0$              | cohesion [(1.31)]                                                     |
| $\Delta\tau$          | coseismic stress jump [(5.1)]                                         |
| $\Phi$                | friction characteristic [(5.3)]                                       |
| $\chi$                | seismic coupling coefficient [(6.5)]                                  |
| $\theta$              | friction state variable [(2.26)]                                      |
| $\bar{\omega}_{ij}$   | rotation [Section 6.2.2]                                              |