The Physics of Rock Failure and Earthquakes

Physical modeling of earthquake generation processes is essential to further our understanding of seismic hazard. However, the scale-dependent nature of earthquake rupture processes is further complicated by the heterogeneous nature of the crust. Despite significant advances in the understanding of earthquake generation processes, and the derivation of underlying physical laws, controversy remains regarding what the constitutive law for earthquake ruptures ought to be, and how it should be formulated. It is extremely difficult to obtain field data to define physical properties along a fault during a rupture event, at sufficiently high spatial and temporal resolution to resolve the controversy. Instead, laboratory experiments offer a means of obtaining high-resolution measurements that allow the physical nature of shear rupture processes to be deduced.

This important new book is written using consistent notation, providing a deeper understanding of earthquake processes from nucleation to their dynamic propagation. Its key focus is a deductive approach based on laboratory-derived physical laws and formulae, such as a unifying constitutive law, a constitutive scaling law, and a physical model of shear rupture nucleation. Topics covered include: the fundamentals of rock failure physics, earthquake generation processes, physical scale-dependence, and large-earthquake generation cycles and their seismic activity.

Providing cutting-edge information on earthquake physics, this book is designed for researchers and professional practitioners in earthquake seismology and rock failure physics, and also in adjacent fields such as geology and earthquake engineering. It is also a valuable reference for graduate students in earthquake physics, rock physics, and earthquake seismology.

Mitiyasu Ohnaka has been a Professor Emeritus at the Earthquake Research Institute, the University of Tokyo, since his retirement in 2001. Previously, he worked at the ERI in the fields of rock physics, experimental seismology, and the physics of earthquakes, from 1970 onwards, as well as holding various positions such as Honorary Professor at University College London, and invited lecturer or visiting scholar at many worldwide institutions, including the Kavli Institute for Theoretical Physics at UC Santa Barbara. Professor Ohnaka has also worked widely in Japan, supervising researchers and students, and delivering undergraduate and post-graduate lectures, at institutions from the University of Tokyo to Yamagata University and more. He is the co-author of *The Physics of Earthquake Generation*, *Earthquakes and Faults*, and *The Role of Water in Earthquake Generation* (these three in Japanese), and *Theory of Earthquake Premonitory and Fracture Processes* (Polish Scientific Publishers, 1995). Professor Ohnaka was Executive Committee member of the International Association of Seismology and Physics of the Earth's Interior (IASPEI) from 1991 to 1995, and also Chair of the Sub-Commission on Modeling the Earthquake Source from 1991 to 2001 in IASPEI. He is a member of the Seismological Society of Japan, and the American Geophysical Union.

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Preface

Over the past four decades, great progress has been made in scientifically understanding earthquake source processes; in particular, advances in the field of earthquake physics have contributed substantially to a profound understanding of earthquake generation processes in terms of the underlying physics. Yet, a fundamental problem has remained unresolved in this field. The constitutive law governing the behavior of earthquake ruptures provides the basis of earthquake physics, and the governing law plays a fundamental role in accounting quantitatively for the entire process of a scale-dependent earthquake rupture, from its nucleation to its dynamic propagation to its arrest, in a unified and consistent manner. Therefore, it is critically important to strictly formulate the constitutive law for earthquake ruptures, based on positive facts, from a comprehensive viewpoint.

Over the past two decades, however, there has been controversy regarding what the constitutive law for earthquake ruptures ought to be, and how it should be formulated. For the physics of earthquakes to be a quantitative science in the true sense, it is essential to resolve this controversy. Regrettably, the resolution of seismological data observed in the field is not high enough to end the controversy. In order to resolve this controversy, therefore, it is critically important to formulate the constitutive law based on positive facts elucidated by high-resolution laboratory experiments properly devised for the purpose intended, by correctly recognizing the real situation of seismogenic fault properties. Without a rational formulation of the law governing real earthquake ruptures, the physics of earthquakes cannot be a quantitative science in the true sense. Hence, there is an urgent need to rationally formulate the constitutive law for earthquake ruptures, based on positive facts, from a comprehensive viewpoint. Resolution of this controversy is a necessary step towards a more complete, unified theory of earthquake physics.

As described in Chapter 1, individual faults embedded in the Earth's crust are inherently inhomogeneous. Fault inhomogeneity has profound implications for the strict formulation of the constitutive law for earthquake ruptures. The process of an earthquake rupture at shallow crustal depths is not a simple process of frictional slip failure on a uniformly precut weak fault, but a more complex process, including the fracture of initially intact rock at some local strong areas on an inhomogeneous fault (see Chapter 1). Accordingly, the constitutive law for real earthquake ruptures must be formulated as a unifying law that governs not only frictional slip failure at precut-interface (or frictional contact) areas on faults but also shear fracture at some local strong areas on the faults. This requirement must be met when we strictly formulate the constitutive law for real earthquake ruptures (Chapters 3 and 4).

In addition, rupture phenomena, including earthquakes, are inherently scale-dependent; indeed, some of the physical quantities inherent in shear rupture exhibit scale-dependence (see Chapters 5 and 6). To quantitatively account, in a unified and consistent manner, for scale-dependent physical quantities inherent in the rupture over a broad scale range, it is critically important to formulate the governing law so as to incorporate the scaling property inherent in the rupture breakdown. This is another requirement that must be met for the constitutive formulation for scale-dependent earthquake ruptures (Chapters 3 and 4).

Accordingly, the properties of fault heterogeneity and of physical scaling are the keys to rational formulation of the constitutive law for earthquake ruptures. In light of these properties, it is possible to rationally formulate the governing law (or constitutive law) for earthquake ruptures, based on the basic research on the physics of rock fracture and friction.

The primary reason I had for writing this book was that there are no published books on earthquake physics written deductively in a consistent manner based on the basic research on the physics of rock fracture and friction, achieved by high-resolution laboratory experiments. The time is ripe to write such a book, because underlying physical laws, such as a unifying constitutive law and a constitutive scaling law, and a physical model of shear rupture nucleation have been derived from high-resolution laboratory experiments properly devised for the purpose intended.

Chapter 1 of this book is an introductory chapter mostly devoted to the description of seismogenic fault inhomogeneities. Fundamental items of rock fracture/friction mechanics are described in Chapter 2. The central theme of this book is described in the remaining chapters. A key characteristic of this book is that the constitutive law for shear rupture, including earthquake ruptures, is formulated as a unifying law which governs not only frictional slip failure on a precut rock interface but also the shear fracture of intact rock, and into which the scaling property inherent in shear-rupture breakdown is incorporated. This is the common thread that runs through the entire book. In terms of a single constitutive law, the process of a shear rupture generation – from its stable, quasi-static nucleation to its unstable, dynamic propagation – is accounted for quantitatively in a unified and consistent manner, and scale-dependent physical quantities inherent in the rupture over a broad range from laboratory-scale to field-scale are treated consistently and quantitatively in a unified manner.

High-resolution laboratory experiments on shear rupture on an inhomogeneous fault are best suited for fully elucidating the physical nature of a scale-dependent shear rupture generation process from its nucleation to the subsequent dynamic rupture. Based on these experiments, therefore, the shear rupture nucleation process is physically modeled (Section 5.1), and observed data on seismic nucleation are consistently accounted for in quantitative terms based on the physical model (Section 5.2). In addition, strong motion source parameters such as peak slip velocity and peak slip acceleration are theoretically derived from the laboratory-derived constitutive equation, and discussed in quantitative terms (Section 5.3). Chapter 6 focuses on the root cause of scale-dependent physical quantities, and it is shown that the scale-dependence of scale-dependent physical quantities, such as slip acceleration, nucleation zone size and the duration time of nucleation, is attributed to the scale-dependent breakdown displacement or the characteristic length representing the geometric irregularity of rupturing surfaces. In Chapter 7, the final chapter, it is shown that large-earthquake generation cycles and accompanying seismic activity can be accounted for consistently under the premise that the governing law for earthquake ruptures is a slip-dependent constitutive law, and that the seismogenic layer and individual faults therein are heterogeneous. In addition, the final section of this chapter focuses on the predictability of large earthquakes.

Since 1985, I have had many opportunities to present my research findings at international meetings, and to discuss outstanding issues regarding earthquake phenomena with leading researchers from around the world. In these international meetings, I also had opportunities to personally get to know leading senior colleagues in the field of earthquake seismology. From the early 2000s, some of those who expressed a positive interest in my leading-edge research findings and deductive approach to addressing outstanding issues regarding earthquake phenomena encouraged me to write a book about the physics of earthquakes on the basis of laboratory-derived physical laws or formulae and physical model of shear rupture nucleation. Since I myself had intended to write such a book, their encouragement gave me the inspiration and keen desire to do so. Hence, I am grateful to international meetings' organizers/conveners for inviting me to take part in their meetings, and to scientific participants for fruitful or critical discussions. In particular, I wish to thank the following: the late Leon Knopoff, the late Keiiti Aki, Massimo Cocco, Shamita Das, James H. Dieterich, Raul Madariaga, Mitsuhiro Matsu'ura, Takeshi Mikumo, Peter Mora, James R. Rice, Christopher H. Scholz, and Xiang-chu Yin.

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