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Imaging, Modeling and Assimilation in Seismology

郦永刚　主编

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Preface

This book is a monograph of the earth science specializing in observational, computational, and interpretational seismology, containing the full-3D waveform tomography method and one-return propagator method in modeling and imaging of subsurface structure, observations and 3-D finite-difference simulations of fault-zone trapped wave for high-resolution characterization of fault internal structure and physical properties, co-seismic rock damage and post-mainshock heal, spontaneous dynamic source and strong ground motion simulations, and earthquake hazard assessment, discrete element method for earthquake mechanics and fracture modeling, and stress load and unload measurements for earthquake prediction and hazard assessment. The editor approaches this as a broad interdisciplinary effort, with well balanced observational, modeling and applied aspects. Linked with these topics, the book highlights the importance for imaging the detailed subsurface structures and fault zones at seismic depths that are closely related to earthquake occurrence and rupture dynamics.

Researchers and graduate students in solid earth sciences will broaden their horizons about observational, computational and applied geophysics, seismology and earthquake sciences. This book covers multi-disciplinary topics to allow readers to grasp the new methods and techniques used in data acquisition, assimilation, analysis and numerical modeling for structural, physical and mechanical interpretation of earthquake phenomena, and to strengthen the understanding of earthquake processes and hazards, thus helping readers to evaluate potential earthquake risk in seismogenic regions globally. Readers of this book can make full use of the present knowledge and techniques to reduce earthquake disasters.

Contents

Imaging, Modeling and Assimilation in Seismology: An Overview

Yong-Gang Li

This book presents recent findings, methods and techniques in observational, computational and analytical seismology for earthquake sciences. Authors from global institutions present multi-disciplinary topics with case studies to illuminate high-resolution imaging of complex crustal structures and active faults by full-3D waveform tomography, one-return propagator and fault zone trapped waves, as well as earthquake physics and hazard assessment by dynamic rupture, discrete element modeling and stress load/unload analysis.

In order to relate present-day crustal stresses and fault motions to the geological structures formed by previous ruptures, we must understand the evolution of fault systems on many spatial and temporal scales in the complex earth crust. Extensive researches in the field, in laboratories, and with numerical simulations have illuminated that the fault zone undergoes high, fluctuating stress and pervasive cracking during an earthquake (e.g., Aki, 1984; Mooney and Ginzburg, 1986; Scholz, 1990; Rice, 1992; Kanamori, 1994). Rupture models that involve variations in fault-zone fluid pressure over the earthquake cycle have been proposed (e.g., Dieterich, 1979; Blanpied et al., 1992; Olsen et al., 1998). Structural fault variations and rheological fault variations (e.g., Sibson et al., 1975; Angevine et al., 1982; Chester, 1994; Hickman, 1995; Taira et al., 2008) as well as variations in strength and stress may affect the earthquake rupture (e.g., Vidale et al., 1994; Beroza et al., 1995; Marone et al., 1995; Massonnet et al., 1996; Schaff and Beroza, 2004; Rubinstein and Beroza, 2005). Actually, earthquake-related fault-zone damage and healing *in-situ* have been documented (e.g. Karageorgi et al., 1997; Li et al., 1998, 2006, 2007; Korneev et al., 2000, Vidale and Li, 2003; Yasuhara et al., 2004). Since the spatial extent of fault weakness, and the loss and recovery of strength across the earthquake cycle are critical ingredients in understanding of fault mechanics, knowledge of the fine-scale internal structures in the earth crust, such as active faults and plate boundaries, holds the key to understanding the physics of earthquakes and estimation of earthquake risk.

Seismic studies show that the active faults, like the San Andreas fault in California, undergo strong dynamic stresses and pervasive cracking during major ruptures, on which a distinct low-velocity zone (LVZ) has been imaged with high-resolution (e.g., Thurber et al., 2004; Korneev et al., 2003; Li and Malin, 2008, 2010; Wu et al., 2010). We interpreted this LVZ as a remnant of damage zone (process zone in dynamic rupture) that accumulated damage from historical earthquakes. The zone co-seismically weakens during the earthquake and subsequently heals (partially) during the interseismic period. The damage structure of fault zones is of great interest because the factors that control the initiation, propagation, and termination of rupture are not well understood. Since the fault plane is thought to be a weakness plane in the earth crust, it facilitates slip to occur under the prevailing stress orientation. As suggested by laboratory experiments, shear faulting is highly resisted in brittle material and proceeds as re-activated faults along surfaces which have already encountered considerable damage (e.g., Dieterich, 1997; Marone, 1998). Field evidences show that the rupture plane of slip on a mature fault occurs at a more restricted position, the edge of damage zone at the plane of contact with the intact wall rock (Chester et al., 1993; Chester and Chester, 1998). Assuming this to be an actual picture of rupture preparation on the major fault such as the San Andreas Fault in California, US (Li et al., 2011, see Chapter 3 in this book) and the Longmen-Shan Fault in Sichuan, China (Li et al., 2011, see Chapter 4 in this book), monitoring microseismic events that occur close to or on the principal rupture plane would be crucial for earthquake prediction. The slip of these events in series with the main fault is most likely to load the principal slip plane to a point of a major through-going rupture. In contrast, the slip on minor faults parallel to the main fault, but laterally offset some distance (hundreds of meters to several kilometers), is likely to unload than to load the main fault. In these circumstance, where the principal fault plane accompanied with damage zone at depth is a challenging problem to seismologists and geologists.

Clues to the role of fault zone strength in the earthquake may come from many directions, but are not yet clearly in focus. While we know slip is localized on faults because of their lower strength than the surrounding bedrock, there are certain critical parameters are practically unknown. For example, one of the long-standing problems in geodesy and crustal dynamics is an apparent difference between the dynamic elastic modules of the crustal rocks determined from seismic velocities and the static elastic modules appropriate for the secular tectonic deformation. Another question is whether the geodetically observed co-seismic strain across the fault zones is primarily due to static or dynamic stress changes. In the latter case, the permanent co-seismic strain might result from dynamic reductions in rigidity such that the dynamic strains are remnant after shaking stops (e.g., Fialko et al., 2001; Fialko, 2004; Duan, 2010). If the fault strength is proportional to the effective shear modulus of rocks within the fault zone, observations of the "soft" fault zones may be a direct evidence for weakness (in both relative and absolute sense) of large seismogenic faults. Testing of these hypotheses requires an accurate description of the complexity of mechanical properties of fault zones along strike and with depth as well as the crustal heterogeneity.

Detailing the fault structure and local variations in seismic velocities has also implications for near-fault hazards and expected ground shaking. Greater amplitude shaking is expected near faults due to both proximity to the fault and due to localized amplification in damaged material. Structurally, major crustal faults are often marked by zones of lowered velocity with a width of a few hundred meters to a few kilometers (e.g., Michelini and McEvilly, 1991; Li et al, 2000, 2002, 2004; Li et al., 2007; Wu et al., 2010). The low-velocity zone can be caused by intense fracturing during earthquakes, brecciation, liquid-saturation, and possibly high pore-fluid pressure near the fault. Recent results have suggested damage zones can extend up to a kilometer from the main slip trace (e.g., Fialko et al., 2002; Cochran et al., 2009) with implications for rupture mechanics and seismic hazard estimates. Examining the geometry and damage structure of a fault will help us understand the origin of spatial and temporal variations in rock damage and the evolution of heterogeneities in stress and strain on a well-developed fault zone, like the San Andreas fault. The fine structure of fault zones is of great interest because it controls to the initiation, propagation, and termination of rupture. Observations suggest that fault zone complexity may segment fault zones (Aki, 1984; Ellsworth, 1992) or control the timing of moment release in earthquakes (e.g., Harris and Day, 1997). Other studies predict that a larger portion of rupture energy is expended in cracking and damaging rocks in less developed fault zones (Mooney and Ginzburg, 1986), or increased roughness of the fault zone (Sagy et al., 2007).

Moreover, quantitative studies of earthquakes based on the fault model in the past decades took kinematic and dynamic approaches. The kinematic approach is basically solving an inverse problem in which we determine the fault slip function in space and time from observed seismic records by means of the elasto-dynamic representation theorem; kinematic model parameters are also interpreted in terms of fracture mechanics. On the other hand, the dynamic approach attempts to predict the fault slip function based on a given distribution of rupture strength over the fault plane and the loading stress condition by means of the principle of rupture mechanics. The two approaches are now combined to produce the distribution of stress drop and that of fracture strength over the fault plane. For all these models, knowledge of spatial and temporal variations in fault geometry and physical properties will help predict the behavior of future earthquakes, and such knowledge will help evaluate the models as well. It would be crucial to know what they are physically, especially when we need to predict ground motion for a future earthquake on a given active fault.

In this book, we introduce the new methodology and technology used in data assimilation for defining subsurface complexity, seismically imaging the multi-scale crustal heterogeneity and fault zone geometry, characterizing fault damage magnitude and heal progression, and its physical properties with high-resolution. We also introduce a sophisticated finite-element method for ground-motion simulation with dynamic rupture and source characterization, the discrete element method with fracture mechanics for earthquake simulation, and the stress load-unload response ratio evaluation for earthquake prediction. This book includes seven chapters.

The Chapters:

Chapter 1: "Full-Wave Seismic Data Assimilation: A Unified Methodology for Seismic Waveform Inversion" by Po Chen

Po Chen (2011) presents theoretical background and recent advances of full-physics seismic data assimilation in Chapter 1. First, he reviews some recent applications of the full-physics methodology in seismic tomography and source parameter inversion (Chen et al., 2007a, b), and then discusses some challenging issues related to the computational implementation and the effective exploitation of seismic waveform data as case study in this chapter. Using the data assimilation methodology, he has formulated the seismological inverse problem for estimating seismic source and earth structure parameters in the form of weak-constraint generalized inverse, in which the seismic wave equation and the associated initial and boundary conditions are allowed to contain errors. The resulting Euler-Lagrange equations are closely related to the adjoint method and the scattering-integral method, which have been successfully applied in full-3D, full-physics seismic tomography and earthquake source parameter inversions (Chen et al., 2010a, b). Capabilities of this unified methodology are demonstrated using examples and several challenging issues facing today's seismologists are discussed at the end of this chapter.

The study of the solid Earth system by seismological methods involving with the proper use of simulation-based predictions to make valid scientific inferences requires a continually iterated cycle of model formulation verification, simulation-based predictions, validation against observations, and data assimilation to improve the model and reinitiate the cycle at a higher level where the model is deficient. Recent advances in parallel computing technology and numerical methods have made large-scale, three-dimensional numerical simulations of seismic wave-fields much more affordable, and they have opened up the possibility of full-physics seismic data assimilation, in which seismological observations of ground motions are combined with the underlying dynamic principles described by seismic wave equations to produce realistic estimations of the properties of the seismic sources that generate seismic waves and the geological structures through which seismic waves propagate. In this chapter, Chen formulates the seismic data assimilation problem in the generalized inverse framework (Evensen, 2009). The full physics of the underlying dynamic principles is accounted for using the three-dimensional seismic wave equation. The starting point of the derivation is the Bayes' theorem, which defines the posterior probability density functions of the poorly known seismic source and structure parameters conditioned on a set of seismological observations. The adjoint method, which was adopted to solve seismic imaging problems in Tarantola (1984) and later extended to solve both seismic source and structure inverse problems in Tromp et al. (2005), can be considered as a simplification of the generalized inverse, in which the dynamic model is assumed to have zero model error. A slight alteration in the derivation of the generalized inverse naturally leads to the scattering integral method used for full-3D waveform tomography in Chen et al. (2007a, b) and for earthquake moment tensor inversion in Zhao et al. (2006).

Chapter 2: "One-Return Propagators and the Applications in Modeling and Imaging" by Ru-Shan Wu, Xiao-Bi Xie and Shengwen Jin

Ru-Shan Wu, Xiao-Bi Xie and Shengwen Jin (2011) present the elastic one-return propagator and its application in modeling and imaging of crustal complex in Chapter 2. The earth has been revealed to have hierarchical, multi-scaled heterogeneities everywhere, and keeping change all the time. The place is more heterogeneous, the more interesting processes (subduction, collision, accretion) can be found around that place. Seismology played and is still playing an important role in the movement. The introduction of broadband and multi-component seismometers, installation of various seismic networks and arrays (from global, regional and local networks, to small aperture arrays), digital recording and networking, etc. have tremendously increased the data amount and quality available to the seismological community. Combined with even faster progress of super-computing and parallel processing, the opportunity of discoveries and contributions in front of seismologists are ever greater than before. Wu (2003) has initiated advance wave propagation and scattering theory and high-resolution geophysical imaging methods (diffraction and scattering tomography). Wu et al. (2001) are taking full advantage of the new development in data acquisition and computing capacity, to join the adventure of penetrating the Earth and discovering new features. They have studied the small-scale heterogeneities in the crust and upper mantle and their statistical characteristics (modeled as random media) directly (from well-logging data) and indirectly (from seismic wave scattering). Influences of diffraction/scattering and random scattering by small-scale heterogeneities to tomography of large-scale structures are also in their research topics.

Based on the multiple forward-scattering and single backscattering (MFSB) approximation (Wu et al., 1995, Wu and Xie, 2006), the authors derived a method which can calculate forward propagations and primary reflections for acoustic and elastic waves in complex velocity models shown in this chapter. This method can be implemented using an iterative marching algorithm shuttling between the space and wave-number domain. Single backscattering is calculated for each marching step (a thin-slab) to handle primary reflections. Therefore, it is also called the one-return method. For models where reverberation and resonance scattering can be neglected, this method provides an accurate and highly efficient algorithm. Two versions of the one-return method, the thin slab method and screen method are given in this chapter. From the screen approximation, which involves a small-angle approximation for the wave-medium interaction, the forward scattered or converted waves are mainly controlled by velocity perturbations; while the backscattered or reflected waves are mainly controlled by impedance perturbations. This method is suitable for simulating wave propagation in multiple-scale velocity models and at high-frequencies. Numerical examples are presented to demonstrate its wide applications in seismic modeling, imaging and inversion of complicated subsurface crustal structure.

Chapter 3: "Fault-Zone Trapped Waves: High-Resolution Characterization of the Damage Zone on the Parkfield San Andreas Fault at Depth" by Yong-Gang Li, Peter E. Malin and Elizabeth S. Cochran

Yong-Gang Li, Peter Malin and Elizabeth Cochran (2011) present their recent results from fault-zone trapped waves to characterize the damage zone on the Parkfield San Andreas Fault (SAF) at seismogenic depths with high resolution in Chapter 3. The internal structure of major faults holds the key to understanding how earthquakes come about and how plate boundaries are lubricated. This chapter provides fundamental information on the nature and source of the fault damage and healing in situ, and therefore enables us to better understand the relationship between the fault zone structure and dynamic rupture as well as the physical basis of the earthquake cycle related to the build-up and release of stresses in large earthquakes.

The fault-zone trapped waves (FZTWs) were first discovered at the Oroville and San Andreas fault zones in California (Li et al., 1990; Li and Leary, 1990). Because FZTWs arise from constructive interference of multiple reflections at the boundaries between the low-velocity fault zone and high-velocity surrounding rocks, their dispersive features, including amplitudes and frequency contents, are strongly dependent on the fault-zone geometry and physical properties. These waves have been shown to be ability to reveal detailed information of the fine structure at the heart of fault zones and its variations laterally and with depth. Therefore, we can use FZTWs to resolve fine internal damage structure in the range of tens to several hundreds of meters. The previous results from the FZTWs recorded at ruptures of the 1992 *M*7.4 Landers and 1999 *M*7.1 Hector Mine earthquakes in California indicated that the active faults undergo strong dynamic stresses and pervasive cracking resulted from these earthquakes, on which we have delineated a distinct low-velocity zone (LVZ) using FZTWs (Li et al., 1994; 2002). They interpret this LVZ as a remnant of damage zone (break-down zone in dynamic rupture) that accumulates damages from historical earthquakes. The zone co-seismically weakens during the earthquake and subsequently heals (partially) during the interseismic period (Li et al., 1998; Vidale and Li, 2003). The damage zone on these ruptures is approximately 200-m wide with the velocity reduction of 20%-50% from wall-rock velocities and likely extends across the seismogenic depths. The distinct LVZ naturally forms a waveguide to trap seismic waves as a source is located within or close to it.

In this chapter, Li et al. (2011) present the new result from a combination of FZTWs generated by earthquakes and explosions and recorded at a cross-fault surface array and borehole seismographs at the San Andreas Fault Observatory at Depth (SAFOD) site to document the details of fault zone geometry, subsurface fine structure and material properties. Observations and 3-D finite-difference simulations of these FZTWs at dominant frequencies of 2-10 Hz show the downward tapering SAF characterized by a 30-40-m wide fault core with the maximum velocity reduction up to ~50% embedded in a 100-200-m wide zone with velocities reduced by 25%-40% in average from wall-rock velocities. The width and velocity reduction of the damage zone at 3 km depth delineated by FZTWs are verified by the direct measurements in SAFOD drilling and logging studies at this depth (Hickman et al., 2007). The results indicate the localization of severe rock damage on the SAF likely reflecting pervasive cracking caused by historical earthquakes on it. The magnitude of damage varies with depth and along the fault strike due to rupture distributions and stress variations over multiple length and time scale, and is also asymmetric across the main slip plane but extends farther on the southwest side of the main fault trace. Based on the depths of earthquakes generating prominent FZTWs, we estimate that the low-velocity damage zone along the strike-slipping SAF at Parkfield extends at least to depths of ~7-8 km.

Chapter 4: "Fault-Zone Trapped Waves at a Dip Fault: Documentation of Rock Damage on the Thrusting Longmen-Shan Fault Ruptured in the 2008 *M*8 Wenchuan Earthquake" by Yong-Gang Li, Jin-Rong Su, and Tian-Chang Chen

In Chapter 4, Yong-Gang Li, Jin-Rong Su, and Tian-Chang Chen (2011) present observations and 3-D finite-difference simulations of fault-zone trapped waves (FZTWs) recorded at the south Longmen-Shan fault (LSF) with varying dip angles, which ruptured in the 2008 *M*8 Wenchuan earthquake in Sichuan, China. Li et al. examined rock damage and heal on the LSF using the data recorded at Sichuan Seismic Network and portable stations in the source region where the LSF is characterized by reverse thrusting. The dominating FZTWs generated by on-fault aftershocks illustrate the coherent interference phenomenon of wave propagation in a highly fractured low-velocity fault zone bounded by high-velocity crustal intact rocks. 3-D finite-difference simulations of these FZTWs show a distinct low-velocity wave-guide (LVWG) a few hundred-meters wide on the south LSF, in which the maximum velocity reduction is ~50% or more at shallow depth, likely extends across seismogenic depths at varying dip angles with depth. Because of the sensitivity of trapped wave excitation to the source location from the LVGW, it allows to depict the principal slip plane along with the LSF in the Wenchuan *M*8 mainshock at depth inferred by precise locations of aftershocks generating prominent FZTWS. The width, velocity and shape of the LSF at shallow depth delineated by FZTWS are generally consistent with the results from geological mapping and fault-zone drilling at the southern LSF (Xu et al., 2008a, b, 2009).

Li et al. (2011) interpret this LVGW as a damage zone in dynamic rupture that accumulated damage from historical earthquakes, particularly from the 2008 *M*8 Wenchuan earthquake. The fault zone co-seismically weakening during the major earthquake and subsequently healing (partially) on the LSF have been studied using similar earthquakes occurring before and after the Wenchuan earthquake. They examined the changes in amplitude and dispersion of FZTWS recorded at the same seismic station for earthquakes at the same places between 2006 and 2009. Results suggest that seismic velocities within the south LSF zone could be co-seismically reduced by $\sim$10%-15% due to the rock damage caused by the *M*8 mainshock on May 12, 2008. The moving-window cross-correlations of waveforms for body waves and FZTWs from repeated aftershocks show that seismic velocities near the LSF increased by $\sim$5% or even more in the first year after the Wenchuan earthquake, with an approximately logarithmic healing rate with time and the largest healing in the earliest stage, indicating the post-main shock healing with rigidity recovery of fault-zone rocks damaged in the *M*8 quake. The magnitude of rock damage and heal observed at the Longman-Shan fault is larger than those observed at the San Andreas fault ruptured in the 2004 *M*6 Parkfield earthquake and also on ruptures of the 1992 *M*7.4 Landers and 1999 *M*7.1 Hector Mine earthquakes. This difference is probably related to the different earthquake magnitude, faulting mechanism and stress drop.

The significance of this investigation is to illuminate the subsurface rock damage along a dip fault at seismogenic depths associated with the 2008 *M*8 Wenchuan earthquake. The data from the 2008 Wenchuan earthquake add the information into previous results of the spatio-temporal variations of fault zone properties associated with large earthquakes (Li et al., 1994, 1998, 2002, 2003, 2004, 2006; Vidale and Li, 2003). The spatial extent of fault-zone damage and the loss and recovery of strength across the earthquake cycle are critical ingredients in understanding of fault mechanics and physics. A comparison of the results from a reverse-thrusting dip faults, like the Longmen-Shan fault, with those at the strike-slipping faults, like the San Andreas fault at Parkfield in California, is helpful in examination if the magnitude of fault rock damage is a function of earthquake size and to evaluate potential earthquake risk in seismogenic regions globally. These results also provide the useful information of subsurface rock damage caused by the 2008 Wenchuan earthquake in site selection for re-construction in the earthquake hazardous areas.

The application of fault-zone trapped waves at the Parkfield San Andreas Fault and south Longmen-Shan fault described in Chapter 3 and Chapter 4 can be taken as case studies of the fault-zone trapped wave method and technique used in seismic imaging, modeling and characterization of crustal fault rock damage magnitude and lateral extension at seismogenic depth.

Chapter 5: "Ground-Motion Simulations with Dynamic Source Characterization and

Parallel Computing" by Benchun Duan

Benchun Duan (2011) presents dynamic source characterization and parallel computing technique for ground-motion simulations in Chapter 5. An emerging trend in simulation of ground-motion caused by earthquakes is to use spontaneous rupture models to characterize dynamic earthquake sources and to use rapid developing high performance computing resources with evolving, sophisticated computer algorithms to predict time histories of ground motion in seismically active regions. Here, a sophisticated finite element method (FEM) algorithm EQdyna is introduced and two examples of ground-motion related applications are presented. Duan first reviews the basics of spontaneous rupture models (e.g., Andrews, 1976; Dieterich, 1979; Day, 1982; Ruina, 1983) and recent development of the FEM algorithm in parallelization using a hybrid MPI/OpenMP approach, and then provides its application to the convergence test of a benchmark problem in this chapter.

Synthetic seismograms for possible future moderate and large earthquakes are one of the key products that seismologists can provide to engineers. These seismograms are used by engineers in the design of earthquake-resistant structures. Thus, ground-motion simulations are a vital bridge between earthquake seismology and earthquake engineering. In particular, for close-in distances near active faults, the ground motion recordings from real earthquakes are sparse. Synthetic seismograms can fill this gap. In addition, with increasing usage of nonlinear analyses in the seismic design of structure, time histories of ground motion becomes more important for completely determining structure response and damage estimation from future significant earthquakes. Synthetic seismograms also allow engineers to examine the variability in the structure response to different earthquake scenarios with different rupture directivity and slip distributions, which would not be available in recorded data. With rapid development of modern high performance computing systems, particularly cluster systems with CMPs (Chip MultiProcessors), parallel computing has been becoming increasingly important and popular in numerical simulations of rupture dynamics and ground motion. Parallel computing allows seismologists to explore small-scale rupture complexities observed in large earthquakes and to augment high frequency limits of deterministically simulated ground motions.

Chapter 6: "Load-Unload Response Ratio and Its New Progress" by Xiang-Chu Yin, Yue Liu, Lang-Ping Zhang, and Shuai Yuan

In Chapter 6, Xiang-Chu Yin, Yue Liu, Lang-Ping Zhang, and Shuai Yuan introduce the stress load-unload response ratio (LURR) for earthquake prediction and its new progress in detail. The motivation, basic ideas, fundamental problems of the LURR and assessment of earthquake prediction status using LURR are discussed in this chapter. From the viewpoint of mechanics, the physical essence of earthquake is an abrupt shear rupture in seismic source region accompanying with sudden release of strain energy and a damage process of the focal media leading to the abrupt shear rupture (Meakin, 1991). In other words, the earthquake genesis process is damage evolution. From the microscopic viewpoint, there are a large number of disordered defects (cracks, fissures, joints, faults, caves etc.) with different sizes, shapes and orientations in rock. The damage process involves the nucleation and extension of micro-damages, coalescence between micro-damages and the formation of a main crack that leads to the eventual fracture (e.g., Wei et al., 2000;

Xie et al., 2002). It is an irreversible, far-from-equilibrium, nonlinear, multi-scale and multi-physics phenomenon, which has been intensively studied for decades but a series of fundamental questions are still open (e.g., Yin et al., 1995, 2004). From the macroscopic viewpoint, the constitutive relation between stress and strain is a comprehensive description of the mechanical behaviors of any materials. If the load acting on the material increases monotonously, the material will experience the regimes of elastic, damage and failure or destabilization. The most essential characteristic of the elastic regime is its reversibility, i.e., the positive process and the contrary process are reversible. In other words, the loading modulus and the unloading one are equal to each other. Contrary to the elastic regime, the damage one is irreversible, hence the loading response is different from the unloading one, or the loading modulus is different from the unloading one. This difference indicates the deterioration of material due to damage. Yin formulated the load-unload response ratio in rock block for measuring the damage degree and proximity to failure, which acts as a precursor for earthquake prediction or forecasting.

Yin et al. (2011) present the evaluation law in LURR to be applied before large earthquakes and the dimensional method to evaluate the applicable range of the LURR for earthquake prediction. The results from laboratory experiment, numerical simulation, analytical and the real seismic data show that the value of LURR fluctuate around unit 1 in the early stage of interseismic period, then the value rise swiftly and to its peak point (abbreviated PP) before the earthquake occurs. The catastrophic events do not happen at the time of peak point, but after it, namely the catastrophic events lag behind the PP. The evolution law of LURR is important for an actual earthquake prediction, by which we may predict the occurrence time of the earthquake quantitatively (by scale of months) if the time of the PP can be verified. Above all, monitoring the variations of LURR allows us to track the seismogenic process in the earthquake cycle eventually achieve prediction of the forthcoming earthquake. Yin et al. (2011) provides the maps of the LURR anomaly regions in the mainland of China calculated in the end of 2003, 2004, 2005 and 2006 and also the epicenters distribution of earthquakes with magnitude $M_L \geqslant 5$ occurred in the next year (2004, 2005, 2006 and 2007). The variation of LURR observed around the $M8$ Wenchuan earthquake occurring on May 12, 2008 is also taken as a case study in this chapter.

Chapter 7: "Discrete Element Method and Its Applications in Earthquake and Rock Fracture Modeling" by Yucang Wang, Sheng Xue, and Jun Xie

In Chapter 7, Yucang Wang, Sheng Xue, and Jun Xie (2011) present the discrete element method (DEM), a powerful numerical tool in many scientific and engineering applications. Here, the DEM is used to model fault mechanics and brittle rock fracture associated with earthquakes. One advantage of DEM is that highly complex systems can be modeled using basic methodologies without any assumptions on the constitutive behaviors of the materials and any predisposition about where and how cracks may occur and propagate. Owing to its discrete nature, DEM is extremely suitable to model large deformation and dynamics phenomena (Wang and Mora, 2008). While different types of DEMs have appeared in the past decades, the Esys_Particle code has been developed most recently (Wang and Mora, 2009). Wang et al. (2011) outline the recent developments of the Esys_Particle code, including incorporation of single particle rotation, new contact