Diss. ETH No. 16430

ON THE ORIGIN OF EARTHQUAKE COMPLEXITY IN CONTINUUM FAULT MODELS WITH RATE AND STATE FRICTION

A dissertation submitted to the

SWISS FEDERAL INSTITUTE OF TECHNOLOGY

for the degree of

DOCTOR OF NATURAL SCIENCES

presented by

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Zurich, December 2005

Zusammenfassung

Es ist von grossem Interesse, den fundamentalen physikalischen Prozess zu isolieren, der die beobachteten Eigenschaften von Seismizitätsmustern erklärt. Wir präsentieren vier numerische Studien, die die Effektivität von Fluiden und der strukturellen Heterogenität von Verwerfungszonen im Hinblick auf die Genese von Erdbebenkomplexität untersuchen. Die dreidimensionalen, kontinuierlichen Modelle werden von der empirischen 'rate and state' Beschreibung der Entwicklung des Reibungskoeffizienten bestimmt, und—vom jeweiligen Problem abhängig—von elasto-hydraulischen Wechselwirkungen oder heterogenen Reibungsverhältnissen auf der zweidimensionalen Verwerfungszone. Zu Beginn wird gezeigt, dass für bestimmte Bereiche von hydraulisch relevanten Parametern der Prozess des 'dilatant hardening', d. h. Verhärtungen aufgrund der Erweiterung des Porenraumes, ausreicht, um beschleunigende Instabilitäten zu stabilisieren, was zu heterogenen raum-zeitlichen Verschiebungen führt. Das zweite Modell demonstriert die Fähigkeit von uneinheitlichen Porendrücken in einem hydraulisch abgeschlossenen System, komplexe Verschiebungsmuster zu produzieren, wobei unstabile Verschiebungsmoden mit Regionen niedriger Porendrücke korrespondieren. In der dritten Studie untersuchen wir die Rolle der komplexen Struktur von Verwerfungszonen, die durch heterogene Verteilungen der kritischen Verschiebungslänge in der 'rate and state' Theorie parameterisiert wird. Dieser Ansatz stellt eine umfassende und konsistente Methode dar, um Seismizität zu generieren, deren Eigenschaften der von beobachteter Seismizität ähnlich ist. Aufgrund der Effektivität dieser Parameterisierung setzen wir ihre Anwendung fort und untersuchen in der vierten Studie Verwerfungszonen in verschiedenen Entwicklungsstadien und die damit verbundenen seismischen Antwortcharakteristiken. Wir wenden heterogene zweidimensionale Verteilungen der kritischen Verschiebungslänge an, um systematisch den Effekt des Wertebereichs, der Korrelationslänge und eines Rauigkeitsparameters auf die Seismizität zu untersuchen. Zusammenfassend stellen wir einen Anstieg der Effektivität in der Erzeugung synthetischer Seismizität mit statistisch realistischen Eigenschaften von der ersten zur vierten Studie fest. Diese Beobachtung impliziert, dass die Ausdehnung des Wertebereichs der fundamentalste der hier untersuchten Parameter ist um die Komplexität von Erdbeben und verwandter Phänomene zu erklären. Im letzten Teil der Arbeit analysieren wir die erzeugten synthetischen Kataloge im Hinblick auf ihr Skalierungsverhalten. Wir beobachten, dass generelle Skalierungsten-

denzen von Herdeigenschaften der simulierten Verschiebungsverteilungen sehr gut mit Beobachtungen von realen Beben übereinstimmen. Wir zeigen ausserdem, dass der Herdmodell Katalog eine sinnvolle Datenbank von physikalisch konsistenten Szenario Erdbeben für die Simulation von Bodenbewegungen darstellt. Wir benutzen diese Datenbank um Wellenformen und Intensitätskarten von Bodenbewegungen für eine Auswahl von Beispiel Beben zu berechnen.

Abstract

It is of great interest to isolate the fundamental physical mechanism controlling observed statistical properties of seismicity patterns. We present four numerical studies investigating the efficiency of fluid related mechanisms and the role of fault zone heterogeneity in producing observed earthquake complexities. The 3-D models of the continuous class are governed by rate- and state-dependent friction and, depending on the problem, by elasto-hydraulic interactions or heterogeneous frictional properties on the 2-D fault plane. First, for certain ranges of hydraulically relevant parameters dilatant processes are shown to stabilize accelerating slip instabilities on a fluid infiltrated fault, leading to nonuniform spatio-temporal slip evolution. The second model demonstrates the ability of heterogeneous pore pressure conditions in an undrained environment to produce complex slip pattern, where unstable sliding corresponds to regions with low degrees of overpressurization. In the third study we focus on the role of complex fault zone structure, parameterized by heterogeneous distributions of the rate and state slip weakening distance. The approach is shown to be a powerful and consistent method to generate seismicity patterns with properties similar to those of natural seismicity. Due to the efficiency of this parameterization we use it in the fourth study to investigate fault zones at different evolutionary stages and associated seismic response types. Using heterogeneous, correlated maps of the slip weakening distance we explore systematically the effect of the range of size scales, correlation lengths and a statistical parameter related to roughness, on seismic response characteristics. In summary, we observe an increase in efficiency from the first to the last study to generate synthetic seismicity with realistic statistical properties, suggesting that the range of size scales is the most fundamental parameter in explaining complex earthquake related phenomena. In the last part we analyze the generated synthetic seismicity catalogs with respect to their overall source scaling behavior. We find that the general scaling trends of source properties of the simulated slip maps are in very good agreement with observations reported in the literature. We also show that the catalog of source models provides a useful resource on physically self-consistent scenario earthquakes for ground-motion simulations. We make use of this resource calculating waveforms and shake intensity maps for a suite of example events.

Nach meinem Begriff tut der, der ein Buch schreiben will, gut daran, gründlich über die Sache nachzudenken, über die er schreiben soll.

S. Kierkegaard

Contents

Introduction

Earthquakes occur on fault networks representing nonlinear dynamical systems driven by tectonic processes into a state characterized as metastable equilibrium [*Main*, 1996, and references therein]. Associated spatial length scales vary from centimeters for small cracks to thousands of kilometers along plate boundaries, while temporal scales range from seconds during earthquake rupture to many thousands of years for the formation of fault zones [e. g., *Scholz*, 1990; *Ben-Zion and Sammis*, 2003]. In the face of earthquake and fault interaction over wide ranges of spatio-temporal scales it is of great interest to isolate the fundamental physical processes leading to the numerous observations that can be attributed to complexity in earthquake-related phenomena. Despite the complexity of the Earth's crust and related processes, however, several empirical scaling relations are universal. Hence, any model or general theory on statistical physics of faulting needs to explain empirical observations related to earthquake occurrence, such as the power-law frequency-magnitude distribution (Gutenberg-Richter (GR) law), and the temporal decay of aftershocks (Omori's law) [*Main*, 1996]. At present, no single self-contained theory exists that explains the variety of observations related to natural seismicity in a consistent and closed framework.

To extract physical knowledge from a complex system like the Earth's crust, one must focus on the right level of description. A potential hybrid model that wants to account for the variety of processes that are known to influence seismogenesis, such as plate tectonics, viscoelastic rebound, fluid movement, chemical alteration, elastic and elastodynamic interactions, dynamic frictional processes during rapid slip, and seismic waves excitation would be utterly complicated. It would provide no insight into the governing mechanisms due to the nonlinear superposition of processes of different efficiency. There are three methodologies of investigation of systems like this: experimental, theoretical, and—becoming increasingly important—computational. Computers let theorists extend their studies of physical systems by solving difficult nonlinear problems like the one under consideration. Although the status of computational science has not reached the maturity of the first two classical ones [*Post and Votta*, 2005], computer simulations are often used to check the scientist's understanding of a particular physical process or situation.

Every good model starts from a question, and the modeler should always choose the correct level of detail to answer the question [e. g., *Goldenfeld and Kadanoff*, 1999], since usually the large scale structure is independent of detailed description of the motion of the smallest particles. The question that motivated the present thesis can be formulated as: "Which physical mechanism is the most fundamental in generating spatio-temporal complexity observed in natural seismicity patterns?" Our numerical experiments investigate the origin of nonuniform slip evolution and statistical properties of associated seismicity on a planar fault representation governed by an empirical friction law. The parameterization of a planar physical fault model is advantageous because of the numerically efficient mathematical formulation. It is substantially supported by the observation that fault structures tend to evolve with cumulative slip toward geometrical simplicity and the continuum-Euclidean framework at all scales. The empirical rate- and state-dependent (RS) friction formulation has been developed to describe experimental observations of variations of the frictional resistance dependent on slip rate and the maturity of contact populations [*Dieterich*, 1979, 1981], which has been parameterized by one or several state variables [e. g., *Ruina*, 1983; *Rice and Ruina*, 1983]. The concept has shown to be a powerful tool in modeling various stages of the seismic cycle, combining the logarithmic increase of static friction with hold time and the slip weakening behavior during dynamic instabilities in a unified and consistent manner. Rate- and state-dependent friction laws were applied in 1-D, 2-D and 3-D fault models to simulate seismic cycles including preseismic slip and nucleation, the growth of dynamic instabilities, healing of fault surfaces, earthquake afterslip, aftershocks, and long deformation histories [*Tse and Rice*, 1986; *Rice*, 1993; *Dieterich*, 1994; *Ben-Zion and Rice*, 1995; *Marone*, 1998]. It has also been used to describe variations of seismicity rates and related changes of earthquake patterns [*Dieterich et al.*, 2000; *Parsons et al.*, 2000; *Toda et al.*, 2002; *Stein*, 2003].

Related to the appropriate level of description is the question of spatial and temporal resolution of the model space. Considerations of simple 1-D spring slider models governed by RS friction allow the definition of a properly discretized physical problem to be solved in the 'continuum limit'. This concept states that results are independent of the spatial and temporal resolution of the numerical procedure used to solve the governing (mostly nonlinear partial or ordinary differential) equations. The desired independence of the obtained solution on the numerical grid is of special interest in the present problem, since models of the discrete class—where the spatial resolution becomes a free parameter—produce complexity just because they are discrete. 'Just because' expresses the fundamental observation that the interaction of single numerical entities governed by even very simple nearest-neighbor rules leads to unpredictable dynamical patterns. These cellular automata—numerical implementations of real-world problems whose vast number of discrete agents prohibits the application of fundamental physical laws in modeling spatio-temporal evolution—have widely been used to develop the concept of 'Self-Organized Criticality' (SOC). It evolved from implications of a sandpile toy-model by *Bak et al.* [1988], where the statistics of avalanche sizes can be described by a power law, which is—among others—interpreted as an indicator for SOC [for implicit assumptions and a critical review on SOC see *Carlson and Doyle*, 1999; *Zhou and Carlson*, 2000; *Carlson and Doyle*, 2002]. Earthquakes are interpreted as manifestations of a self organized critical system because the GR statistics describing the frequency of occurrence of seismicity averaged over large spatial and temporal scales follows a power-law.

Related to the cellular automaton model class, but with a more direct relevance to simulating the behavior of earthquake faults, are slider block models [*Main*, 1996; *Rundle et al.*, 2003, and references therein]. They can be interpreted as cellular automaton models that have been adopted and modified to the seismogenic problem, such that the energy transfer across the numerical grid changed from simple nearest-neighbor rules to more realistic physical interactions like stress transfer based on dislocation theory. This class of models is referred to as Burridge-Knopoff (BK) type, based on the original paper from 1967 [*Burridge and Knopoff*, 1967]. Hence, to investigate earthquake related processes and in particular the genesis of power-law frequency-magnitude statistics with computational methods results are required to be grid independent.

Work presented in this thesis approaches the complexity problem from two different perspectives. First, the role of fluids in the Earth's crust on slip evolution is discussed. The second approach is assumed to be more fundamental, focusing on the degree of heterogeneity required to produce realistic response patterns. In the present framework, "realistic" refers to the similarity of synthetic slip maps and earthquake catalogs compared to related properties of natural seismicity. Although the two concepts differ, the associated numerical implementations are very similar (see Appendix), which allows the direct comparison of efficiency in generating observed phenomena, without taking particulars of the numerical procedure into account.

The thesis is organized such that the first two chapters investigate the effect of fluids on complex slip evolution, and in particular the role of slip hardening mechanisms in undrained faults. Chapters 3 and 4 neglect possible hydro-mechanical interactions and focus on the role of heterogeneity related to geometrical structure of fault systems. Finally, Chapter 5 presents an application in calculating strong ground-motions based on synthetic slip maps produced by physical mechanisms explored in previous chapters.

The motivation that leads to studies presented in Chapter 1 and 2 is the occurrence of fluids in the Earth's crust and its associated mechanical implications in the earthquake process, since it is a well-documented but still not well-understood phenomenon. Numerous studies identified the potential importance of fluid migration following a main shock in producing aftershock sequences [e. g., *Nur and Booker*, 1972; *Bosl and Nur*, 2002; *Miller et al.*, 2004; *Piombo et al.*, 2005, and references therein]. Free fluids are also expected to be involved in seismic swarm activity [*Waite and Smith*, 2002] and remotely triggered earthquakes in geothermal and volcanic areas [*Husen et al.*, 2004]. Stabilizing and weakening fluid related mechanisms during rapid seismic slip, such as dilatant hardening and pore fluid expansion due to shear heating, respectively, are assumed to alter rupture and slip propagation of large earthquakes [*Taylor and Rice*, 1998; *Garagash and Rudnicki*, 2003a,b]. A number of laboratory and field observations suggest the formation and maintenance of low-permeability seals between fault gouge and the host rock [*Sibson*, 1994], that effectively trap pore fluids hence leading to the formation of a conduit in the fault's core [*Moore et al.*, 1994; *Zhang and Tullis*, 1998; *Zhang et al.*, 1999, 2001]. Porosity reducing mechanisms that can lead to overpressured fluid states are plastic pore closure, stress induced dissolution and crack healing and sealing [*Walder and Nur*, 1984; *Nur and Walder*, 1992; *Sleep and Blanpied*, 1992; *Blanpied et al.*, 1998a; *Lockner and Byerlee*, 1994].

To address the question leading to Chapter 1: "Are hydro-mechanical interactions in a fluid infiltrated fault zone with homogeneous properties capable of producing complex seismicity patterns?", we investigate the effect of dilatant hardening mechanisms on a wet fault zone with homogeneous hydraulic properties along the fault. The model extends the 1-D spring block model by *Segall and Rice* [1995] to a 2-D fault zone, using the 3-D elastic framework by *Rice* [1993]. The 3-D approach is essential in trying to find an answer to the introductory question, since interactions on a fault with homogeneous parameter distributions are investigated with respect to their sufficiency in producing nonuniform slip pattern.

We focus on variations of three hydraulic parameters in controlling the system's response: Effective hydraulic diffusivity, the degree of overpressurization and a dilatancy coefficient. Diffusivity measures the ability of pore pressure states in- and outside the fault zone to be equilibrated, defining drained and undrained faults. Overpressurization describes pore pressure in excess of hydrostatic, and the dilatancy coefficient parameterizes the efficiency of dilatant hardening. As outlined by *Segall and Rice* [1995] dilatant hardening is the crucial physical mechanism in this study. It describes the increasing pore space due to accelerated slip in the fault gouge. This increase in pore space is accompanied by a decrease in pore pressure, which in turn increases the effective normal stress, hence prohibiting further unstable slip. However, this 'clamping' effect might be counteracted by fluid expansion due to shear heating, a mechanism which is not incorporated in the present simulations [*Taylor and Rice*, 1998]. The parameters define a multi-dimensional phase space, where regions of unstable and stable response types are separated by diffuse transition zones. Emerging response pattern can be explained by the system's position in the phase space. Drained systems develop the standard periodic repeat of system wide instabilities. Contrary, undrained systems that are located at or near transition zones show nonuniform slip pattern that do not coincide with the classic stick-slip or creeping behavior. Since these models do not represent extreme cases it is likely that dilatant hardening is a dominating mechanism in controlling slip evolution in sealed fault zones.

While the investigation presented in Chapter 1 explores the effect of both drained and undrained fault systems, Chapter 2 focuses on sealed faults in trying to answer: "What effects have heterogeneous distributions of pore pressure on a sealed fault on the seismic response?" The concept of sealed and overpressured faults with areas of potential variable pore pressure is based on the observation that the San Andreas fault shows no aberrant heat flow signal. It is accompanied by borehole stress measurements showing a nearly 90° angle between the fault's strike and the maximum compressive stress [*Lachenbruch and Sass*, 1980; *Hickman*, 1991], indicating the fault's strength is anomalously low. An explanation are elevated pore pressures reducing sufficiently the frictional strength [*Rice*, 1992]. Heterogeneous fault zone material exposed to the above mentioned pore compacting mechanisms are assumed to cause different pore pressure regimes in a fault zone. Based on this mechanisms *Lockner and Byerlee* [1995] and *Miller et al.* [1996] conducted a numerical study of a 1-D and a 3-D BK-type fault model, respectively, where most of the shear stress is supported by a small number of compartments where pore pressure is relatively low. We adopt this conceptual model and investigate in a systematic parameter space study of a 3-D continuous model modified from Chapter 1 effects of variable fluid pressures trapped in a sealed fault zone on seismicity pattern. The approach presented in this study aims to investigate qualitatively the nucleation, propagation and arrest of slip instabilities in a sealed and thus overpressured fluid infiltrated fault. We show that regions of low pressure act as asperities, responding in an unstable manner, and regions of elevated pressure tend to slip aseismically. Statistics of model seismicity show a GR type behavior for moderate and large events, but a decreased frequency of occurrence of small slip instabilities. Details of the results depend on the efficiency of dilatant mechanisms, consistent with observations in Chapter 1. Hypocenters correlate with regions of low pore pressure. Temporal evolution of variables as a function of pressure demonstrate the interdependence among the variables, and characteristic response types for high or low degrees of overpressurization.

The conceptual model in Chapter 3 and 4 focuses on elastic interactions of model faults with heterogeneous frictional properties. There are two view points in trying to explain nonuniform slip pattern—which are an indicator of complex system evolution—in purely elastic, continuous models. The first one seeks to produce heterogeneous slip pattern as a result of the governing physical laws in (elasto-dynamic) models with homogeneous frictional properties. Previous models using RS friction [e. g., *Rice*, 1993; *Ben-Zion and Rice*, 1997; *Tullis*, 1996; *Lapusta et al.*, 2000] employed only lab-based depth-variations of the frictional scaling parameters a and b that produce transitions between stable velocity-strengthening and unstable velocity-weakening regimes. Dynamical models using constitutive laws other than rate and state friction are e. g. *Carlson and Langer* [1989a,b] and *Shaw* [1994]. It is implicitly assumed that intrinsic properties of the mathematical description of the physical slip weakening laws (carried out numerically) are sufficient to produce subtle heterogeneities along the system's evolution, and that these physically based impurities cause system wide perturbations due to the nonlinearity of the problem. However, *Ben-Zion* [2001] pointed out that simulations of dynamic ruptures are highly sensitive to subtle features of the assumed constitutive laws and their implementation in a numerical procedure. Hence, after more than ten years of research, no definite positive example has been put forward, since slip complexity produced with homogeneous properties by various simulations can be explained by more or less hidden heterogeneities originating in the model implementation [*Ben-Zion and Rice*, 1995; *Lapusta et al.*, 2000].

The alternative view is that fault heterogeneity probably plays the dominant role in producing the observed earthquake complexities. Modeling studies found that strong geometrical and material heterogeneity on planar faults can produce complex spatio-temporal patterns of seismicity including fractal distributions, spatio-temporal clustering and other observed features of natural seismicity [*Ben-Zion and Sammis*, 2003]. The simplest way of parameterizing geometric heterogeneity is a cellular automaton, where numerical 'cells' capable of failing independent of their neighbors are interpreted as fault sections that are part of a larger fault system. In this context, failure of single cells is equivalent to small earthquakes, and cascades of failures represent moderate and large earthquakes. As has been discussed, these discrete models are of limited use for the investigation of heterogeneous frictional parameters. Because of the failure of continuous models with homogeneous frictional properties and the efficiency of heterogeneous models to generate complexity, it is desired to study the effect of fault heterogeneity independent of numerical resolution.

Several studies used different variables such as stress drop or linear slip weakening distance to parameterize heterogeneity [e. g., *Ben-Zion*, 1996; *Ben-Zion et al.*, 2003a; *Zöller et al.*, 2005a,b,c]. The RS critical slip distance L for the evolution of the friction coefficient is shown to correlate with the width of the gouge zone [*Marone*, 1998, and references therein], and it scales with the dominant wavelength that characterizes the roughness of the sliding surfaces [*Ohnaka*, 2003, and references therein]. We therefore use physically plausible spatial variations of the critical slip distance to parameterize geometrical disorder in a continuous approach. This realization thus bridges the gap between previous works associated with inherently-discrete and smooth-continuum models.

Focusing on spatial variations of L, the question we ask related to Chapter 3 is: "Are spatial variations of the critical slip distance in a continuous model sufficient to produce complex seismicity?" We impose a range of L values constrained by computational limits on grid size and width of the seismogenic zone at the lower and upper bound, respectively, leading to 2.5 orders of magnitude in L variability. We show that simple chessboard type distributions are sufficient to produce slip events with sizes spanning 4.5 orders of magnitude, and having statistical properties comparable to those of natural seismicity. Details of the statistics of generic earthquake catalogs and stress states depend on the number of patches in the chessboard models and hence on the degree of heterogeneity. Our results indicate a correlation between hypocenter locations and regions of small L values on the fault. Visual similarity of final slip maps of earthquake models to slip distributions compiled from real earthquakes indicates the applicability of the chosen approach to study mechanisms responsible for observed features of natural seismicity. The positive correlation between magnitude and average L value at the hypocenter for a certain magnitude range suggests the dependence of earthquake magnitude on nucleation size.

Chapter 3 reveals that the parameterization of fault heterogeneity with 2-D L distributions in the continuum limit is a powerful, consistent tool to investigate the origin of complexity. Asking: "Which tuning parameter is most efficient to control seismicity pattern associated with evolving fault structure?", leads to Chapter 4, which extends the approach introduced in Chapter 3 to the investigation of the evolution of fault zone structure and associated seismic response type. While Chapter 3 investigated the efficiency of heterogeneity *per se* in generating complex seismicity pattern, Chapter 4 focuses on different degrees of geometric disorder, depending on fault zone maturity. A large number of multi-disciplinary observations and various theoretical frameworks, summarized by *Ben-Zion and Sammis* [2003], indicate that faults evolve toward structural simplicity and increasing regularity of the associated seismic response [e. g., *Tchalenko*, 1970; *Wesnousky*, 1994; *Stirling et al.*, 1996; *Lyakhovsky et al.*, 2001]. Immature fault zones appear to be formed as highly disordered structures associated with wide range of size scales and short correlation lengths of structural features. Continuing deformation seems to lead to progressive regularization manifested by coalescence and reduction in the range of size scales of fault segments accompanied by development of larger correlation lengths [*Ben-Zion and Sammis*, 2003, and references therein]. In this work we perform a parameter space study of the seismic response of structures with different degrees of maturity. To approximate fault zones at different evolutionary stages we use a family of 2-D heterogeneous, correlated L maps to explore the relative efficiency of the tuning parameters range of size scales, correlation length and Hurst exponent. Our parameter space study examines systematically the response of model realizations associated with different sets of those parameters using a number of seismicity and stress response functions.

Comparing model responses depending on different sets of parameters we find that the range of size scales is the most effective tuning parameter. More specifically, for certain correlation lengths and Hurst exponents, respectively, the seismic response is controlled by the range of L values used in the 2-D distributions. The efficiency in controlling the response is most significant in the resulting frequency-magnitude distributions, where immature faults show a GR type statistics, whereas mature faults develop a characteristic event type seismicity. This classification can also be seen in the evolution of stress functions, seismicity evolution and associated coefficient of variation which is a measure for temporal earthquake clustering. We find that small earthquakes cluster in time, moderate ones occur approximately random and large events show a variable degree of periodicity, depending on specific parameter constellations. In this study we extend the correlation of hypocenters with physical properties at their location to a larger set. We test dependencies of earthquake nucleation on the original L map, an effective nucleation size, seismic coupling and its spatial gradient. In agreement with results presented in Chapter 3, most instabilities develop in regions where L and thus the effective nucleation size is small. This is a universal feature, and deviations from it are due to less realistic parameter choices. Contrary, the correlation with coupling and its gradient does not reveal a positive dependence, which indicates that in our model earthquake nucleation is controlled by stationary physical properties and not by evolving properties. This study confirms the increase of average nucleation size—as a function of L—with magnitude for small and moderate earthquakes, suggesting different mechanisms at the onset of smaller and large earthquakes. Although we observe this trend to be persistent for a variety of simulations it needs to be reevaluated using different concepts of earthquake nucleation. Hence, using heterogeneous distributions of the frictional parameter L on a numerically efficient planar fault representation is shown to be a powerful tool to investigate seismicity patterns associated with fault zones with different degrees of maturity.

Synthetic slip maps produced by models discussed in Chapters 2, 3, and 4 show remarkable similarity to finite-source rupture models obtained for past earthquakes. In Chapter 5, the synthetic maps, generated by the physically consistent rate and state earthquake model, are used to investigate source-scaling relations of earthquake rupture by comparing them to observations, taken both from literature and the source-model database. Such scaling relations between observable quantities may help to understand underlying, but difficult to assess, physical mechanisms [e. g., *Scholz*, 1982; *Romanowicz*, 1992; *Scholz*, 1994; *Bodin and Brune*, 1996; *Yin and Rogers*, 1996; *Matsuura and Sato*, 1997; *Mai and Beroza*, 2000; *Shaw and Scholz*, 2001; *Miller*, 2002]. Generated seismicity is intended to contribute to a long-lasting controversy in seismology concerning the scaling of large strike-slip earthquakes. Two models exists that describe seismic moment to be proportional to the rupture length ($M_o \propto L^2$ or $M_o \propto L$), but none has been shown to explain several data compilations consistently better. In the light of the ongoing discussion we address earthquake scaling properties using a combined, yet diverse data compilation. We use a set of simulated earthquake models obtained by quasi-dynamic seismicity simulations with spatial variations of the critical slip distance discussed in Chapters 3 and 4. To assess to what extent this type of simulations generate earthquake catalogs whose source parameters are comparable to seismic observables, we deploy a recent compilation of displacement-length measurements [*Manighetti et al.*, 1990]. It is used together with data from the above cited online database to compare various "bulk" properties of earthquakes as well as the specific features of distributed slip on a fault plane. We find that the catalog of simulated events reproduces essentially all aspects of measurable properties of natural seismicity. Hence, we can use this large data set to try to shed light onto some fundamental issues in earthquake source mechanics, namely the scaling of large strike-slip earthquake.

The last aspect of this thesis addresses the problem of near-source ground-motion prediction. While standard empirical attenuation models are easy to apply, they can only serve as a general reference that hardly includes the aspects of diversity of the dynamic rupture process. Dynamic rupture modeling for a large set of scenario earthquakes, on the other hand, is desirable, but it inherently lacks the information on stress fields that result from tectonic loading on previously ruptured faults. As has been discussed, quasi-dynamic rupture models of studies presented in Chapters 3 and 4 are a natural consequence of previous seismic activity on the model fault and present a self-consistent model for earthquake source complexity. We extract a random series of rupture models from the synthetic catalog. Using a pseudo-dynamic source characterization [*Guatteri et al.*, 2003, 2004] we compute near-source ground-motions with a specific geometry that is meant to illustrate potential ruptures on the Main Marmara fault (NW Turkey) and the expected ground shaking in the Istanbul metropolitan area.