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ABSTRACTS
DYNAMIC RUPTURE WITH THE SPECTRAL ELEMENT METHOD:
WHERE DO WE STAND?

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The Spectral Element Method (SEM) is a modern high order method that has been applied with success to wave propagation problems. Among its advantages are its low dispersion (5 nodes per minimum wavelength), its natural account for boundary conditions (e.g. free surface) and its flexibility in describing realistic geometries (topography, irregular layers). More recently the SEM has been applied to the modeling of earthquake source dynamics. We report on our most recent advances in this last topic, that includes our first 3D implementation and different techniques to control high frequency spurious oscillations near the source. A special attention will be given to nucleation and supershear transition problems. We will show results of comparative tests with the finite difference method and the spectral integral equation method. The issue of high frequency noise is common to all methods discretizing the bulk, such as SEM and FDM: it inevitably arises from the inability of the discrete mesh to radiate high frequency waves out of the fault (unresolvable wavelengths). We will show numerical experiments illustrating novel ideas to cope with this issue: high/low frequency decompositions, treated consistently by hybrid methods, and selective PML absorbing conditions near the fault.
DYNAMIC SIMULATIONS TO EXAMINE EFFECTS OF FOCAL MECHANISM ON RADIATED ENERGY

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The mechanism-dependence of radiated seismic energy generated by earthquakes is investigated by modeling dynamic ruptures for three different faulting mechanisms in two dimensions: a 30° dipping reverse fault, a 60° dipping normal fault and a vertical strike-slip fault. All three faults have the same down-dip width and are subjected to the same homogeneous stress conditions in a homogeneous half-space. Except for the geometry and the mechanism, all other conditions are identical. Following the work of Favreau and Archuleta (2003) both the energy distribution on the fault and the work done by seismic waves against distant surfaces enclosing the source for the three different mechanisms are calculated using a low-order finite element method. The apparent stress is 0.45 MPa, 0.29 MPa and 0.31 MPa for the reverse fault, normal fault and strike-slip fault, respectively. This is in contrast to the literature which finds strike-slip apparent stress 5-10 times larger than that for compressional or normal faulting, which are about the same. By looking at the energy distribution at the distant surface we find most energy is confined near the surface, i.e., most radiated energy propagates out as surface waves. The energy going out of the bottom of the distant surface, i.e., energy that goes to teleseismic distance, is very small. The major question is how well does averaging over the teleseismic energy represent the true seismic energy. We will explore this question with results from 3D simulations that will be presented at the workshop.
DYNAMIC RUPTURE IN STRUCTURES
WITH MATERIAL INTERFACES

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In a linear isotropic homogeneous solid, slip does not change the normal stress on the rupture plane. However, if the fault separates different solids, the normal stress is proportional to spatial derivative of in–plane slip. Analytical and numerical works (Weertman, 80; Andrews and Ben–Zion, 97) indicate that rupture along a material interface occurs as a narrow wrinkle–like pulse with: 1. strong correlation between changes of normal stress and slip, 2. asymmetric motion across the fault, 3. uni-directional propagation in the direction of slip in the more compliant solid, and 4. self–sharpening with propagation distance. These characteristics are consistent with lab data and seismological studies. Adams (95) found that rupture along a material interface governed by Coulomb friction is unstable to perturbations for a wide range of parameters. Ranjith and Rice (01) and Cochard and Rice (00) showed that the problem can be regularized by a Prakash–Clifton friction, where the response to abrupt change of normal stress is gradual strength evolution. Ben-Zion and Huang (02) found that the parameters of the regularized friction have to be fine–tuned to produce apparent stability for a given propagation distance. This creates difficulties for a parameter-space study. A more convenient regularization of the Adams instability can be done with a Kelvin–Voigt viscosity that produces, like the regularized friction, gradual response to abrupt changes of normal stress. We now use finite-difference calculations of dynamic rupture in models with several media and multiple possible rupture planes governed by Coulomb friction and Kelvin–Voigt viscosity to examine the conditions for which ruptures tend to migrate spontaneously to material interfaces (Brietzke and Ben–Zion, 03).
A FINITE DIFFERENCE ALGORITHM TO MODEL A FULLY 3D DYNAMIC RUPTURE GOVERNED BY DIFFERENT CONSTITUTIVE LAWS

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In the last decades large effort has been expended to realize numerical algorithms for solving the fundamental elastodynamic equation to model earthquake ruptures. Two class of methods have been extensively implemented and used: the Boundary Integral Equation (BIE) and the Finite Difference (FD) approaches. In Bizzarri et al. (2001) we have compared 2 D in plane solutions to discuss the main differences existing between these two different numerical strategies.

In this work we present a new FD numerical method to solve the fully dynamic spontaneous problem for a truly 3 - D rupture on planar faults. We implement the Traction at Split Nodes of Andrews (1999) fault boundary condition for a system of faults, either vertical or oblique. For each fault we can assume different constitutive laws: we can use a slip weakening law to prescribe the traction evolution within the breakdown zone or a rate and state dependent friction law, which involve the choice of a governing relation for the state variable. We have implemented a 3D version of the Rosembrock Stiff Integration, generalizing that previously used in our 2D model, and we have included the free surface effect.

In our numerical procedure the initial shear stress is not necessarily imposed in only one spatial direction and the two components of slip, slip velocity and traction can vary during the dynamic crack propagation. Such components are coupled together in order to satisfy, in norm, the adopted governing law, and therefore they allow for dynamically controlled rake variations. We can also model faults with spatially heterogeneous distributions of constitutive parameters in order to simulate crack arrest and the healing of slip.
EARTHQUAKE RUPTURE VELOCITY:
SOME OBSERVATIONS AND IMPLICATIONS

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Near-fault recordings of ground motion show that the speed at which a fault ruptures during an earthquake varies from event to event and that it also varies spatially during an earthquake. In particular, recent well–recorded earthquakes show that rupture can propagate at high supershear speeds on part of a fault while it propagates at sub-Rayleigh velocity on other parts of the fault. As rupture velocity is related to the strength of a fault, these variations may help understand the stress conditions under which a fault ruptures. As rupture velocity is also related to the seismic energy radiated by the rupturing fault, these variations have also important consequences for seismic risk. We will review the observations and we will discuss possible physical parameters of the fault which may control the rupture velocity.
EXAMINING TENDENCIES OF IN-PLANE RUPTURE TO MIGRATE TO MATERIAL INTERFACES

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Recent works indicated that rupture along a material interface has remarkable dynamic properties, which may be relevant to a number of geophysical problems, and that material interfaces are mechanically favoured locations for rupture propagation. Here we examine tendencies of 2D in-plane rupture to migrate spontaneously to material interfaces by performing a numerical parameter-space study in a model consisting of 3 media with 9 possible faults, 2 of which are material interfaces (Figure 1). The calculations employ a generalized version of the second-order finite-difference code used by Andrews (1973) and Andrews & Ben-Zion (1997). The faults are governed by Coulomb friction, and in some cases also Kelvin-Voigt viscosity. In general, a rupture along a material interface governed by Coulomb friction does not have a continuum limit (e.g., Adams, 1995; Ranjith & Rice, 2001). A Kelvin-Voigt viscosity provides regularization of the problem for a limited range of propagation distances and grid-refinements. Ruptures in our work are nucleated by a symmetric bilateral expanding pore pressure source, and may then continue to propagate (or not) along one or more faults. Using different nucleation locations (fault 1-9), different rheological parameters and initial stress, and different velocity contrasts, we examine the range of conditions for which ruptures migrate spontaneously to material interfaces and continue to propagate there in a self-sustaining manner.

Fig. 1. A model for studying migration of in-plane dynamic rupture among 9 frictional interfaces within 3 different elastic solids (a fast block, a slow block and a low velocity layer).
MODELING THE DYNAMIC TRACTION EVOLUTION DURING THE PROPAGATION OF AN EARTHQUAKE RUPTURE: CAN WE INFER THE FAULT CONSTITUTIVE LAW?

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Several recent investigations examine the mechanical conditions of faults before and during a large earthquake with the ambition to constrain the fault constitutive behavior and to retrieve the dynamic traction evolution during the rupture propagation. The definition of the dynamic traction as a function of time or slip is commonly used to prescribe its evolution within the breakdown zone through a constitutive law. However, it is still a matter of debate the full understanding of the physical mechanisms controlling the breakdown process. The analysis of dynamic traction as a function of slip allows the estimate of the critical slip weakening distance ($D_c$). Several methods have been proposed to measure $D_c$. The most recent suggests evaluating $D_c$ as the slip value at the peak slip velocity, assuming that the latter occurs when the traction is at its minimum (i.e., the frictional stress level). The inferred values of the critical slip weakening distance can be extremely large (of the order of several meters), they seems to be correlated with the final slip and cover a wide interval of values (from few percent to 80% of the total slip). In this study we investigate the dynamic traction evolution either by modeling the spontaneous propagation of a crack through 2–D and 3–D dynamic algorithms or by using the rupture history on the fault plane as a boundary condition to constrain the instantaneous traction. We aim to discuss the variability of $D_c$ estimates and the existing biases that limit its calculation. In particular, we will show that the possibility to estimate $D_c$ from the slip velocity peak depends on the adopted constitutive law and on the assumed dynamic parameters.
WHAT CAN ROTATIONAL MEASUREMENTS TEACH US ABOUT EARTHQUAKE RUPTURE HISTORIES?

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The general motion of a deformable body is uniquely specified by 3 components of displacement (those measured by classical seismometers), 6 components of strain, and 3 components of rotation. While it is standard to observe translational motions, and quite usual to measure strain, rotations had little attention, partly because rotational effects generated by earthquakes were thought to be small (e.g., Bouchon and Aki, 1982), and partly because no instruments existed which directly measured absolute rotations.

Recently, there has been a revival of interest for rotations due to a growing body of observational evidence that, at least in some cases, rotational motions are indeed strong (Takeo and Ito, 1997, Takeo, 1998), while, at the same time, very precise instruments are becoming available.

Here, we numerically study the effects of various kinematic scenarios on rotations. In some cases, the effects on rotations appear much more marked than those on translations, i.e., rupture histories with very similar translational seismograms show pronounced differences in the collocated rotational motions. This is the case, e.g., for a circular crack rupture with constant slip velocity on the one hand, and a more realistic inverse square root singularity Kostrov-like slip-velocity profile on the other hand. We also report effect on rotations of fault segmentation and variation of rupture velocity.

We anticipate that taking into account rotational measurements will help constraining inversions of kinematic rupture histories.
Nonplanar Dynamic Rupture
In Finite Difference Modeling

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We use a recently proposed four-order staggered-grid finite-difference (FD) scheme to model in-plane (mode II) fracture propagation in 2-D faults with any pre-established geometry. In contrast with the classical 2-D staggered grid elementary cell (Madariaga, 1976), the stencil used here defines the velocity and stress fields respectively at a unique node in two separate grids. These grids are shifted by half the grid step in each Cartesian direction. The new wavefield discretization permits a suitable treatment of boundary conditions to impose the shear stress drop in the nodes where the stress tensor is located.

The source is defined as a set of stress-grid points placed in the middle of the grid. Clusters of such points named numerical cells must be considered to well discretize the fault geometry. There exists a scaling relation that assures the equivalence between different numerical cell configurations. Configurations with more stress–grid points allow more accurate simulations. To quantify the slip over the rupture surface, we define a slip function which depends on the displacement field around every numerical cell but not in the local fault plane orientation. Spontaneous rupture simulations with the standard slip–weakening constitutive law are presented. Accurate stress field singularities near the crack tip are found for planar faults with any orientation and fit Kostrov theoretical predictions for the self–similar case. Because we deal with a regular FD mesh, the problem of discretizing planar geometries with any orientation, or nonplanar geometries, is equivalent. Thus, modeling of complex source geometries is justified and ultimately performed within an arbitrary heterogeneous media to test the methodology in realistic conditions.
The generation of tensile cracks that propagate during the shear dynamic rupture process of shallow earthquakes is proposed. The main assumption is that the dynamic tensile stress created during shear rupture process would be dominant over the background stress near the free–surface. The simple slip–weakening model was used as the friction law for shear rupture propagation. For tensile cracks, fracture follows classical Griffith theory when the critical value for tensile fracture surface energy is reached. Our proposed model (Dalguer et al., 2003, JGR, 108-B3) is able to simulate the mechanism of flower like–structure surrounding the shear fault and near the free–surface. The results show that when the asperity is located at less than a certain depth, the flower structure that originates from the top of the fault reaches the free–surface. The proposed model was applied to study the fracture zones found after the 2000 Tottori (Japan) earthquake in which we attempt to explain that some of these cracks were originated as a consequence of the dynamic tensile stress during the shear rupture (Dalguer et al., 2003, BSSA, in press). The results show that the cracks grow from the two sides of the fault forming fractures as a complex flower structure. The cracks grow mainly from the asperity zone and top of the fault. Some of the cracks are associated with the aftershock distribution, suggesting that some of these cracks could be zones of potential aftershocks. It could be plausible because these zones of tensile cracks (opened during the dynamic rupture) are closed (locked) by the pre-stress immediately after finish the dynamic process and remain as weakness planes. Then, after a certain time when stress is accumulated along these weakness planes shear slip can occurs.
DYNAMIC RUPTURE THROUGH FAULT BARRIERS:
ENERGY CONCENTRATION AND SUPERSHEAR BURSTS

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We numerically investigate the rupture process of circular high strength barriers and low prestress anti–asperities. The rupture front, initially straight with mode II symmetry and moving at sub–Rayleigh velocity, locally decelerates upon encountering the obstacle. The rupture front partially or totally encircles the obstacle, focusing energy into its center. Subsequent failure of the obstacle generates large slip velocities, particularly for barriers, where the increased yield stress replaces the initial stress as the stress drop determining the maximum slip velocity. This creates local slip velocities over an order of magnitude larger than at the unperturbed rupture front. Strong elastic waves are emitted that manifest as slip pulses on the fracture surface, for which an analytical solution is given. Energy focusing is much less pronounced for anti–asperities, and the rupture process differs considerably between barriers and anti–asperities, even for those that take the same amount of time to break. For barriers above a critical strength, the energy concentration triggers a transient burst of supershear propagation, during which the rupture front can overtake its unperturbed position. Even unbreakable obstacles can trigger a supershear burst when the split rupture fronts encircle the obstacle and collide on the far side. For a narrow range of barrier strengths, the supershear burst, triggered by the convergence of the split fronts, is resonantly enhanced by a slip pulse traveling at the P–wave speed emitted upon failure of the barrier. Scaling laws based on non–dimensional parameters are given for the time required to encircle or break an obstacle. Synthetic seismograms showing distinctive wave arrivals from the obstacle are discussed.
RECI Procity Method in Seismology

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This talk applies the reciprocity to assess the seismic site and path effects at a chosen location of interest. To do this, we show that the reciprocity theorem is valid for this application, and develop a technique to represent velocity models of sedimentary basins. Using these tools we test the accuracy of synthetic seismograms computed for southern California. Finally, we apply the reciprocity technique to evaluate the site and path effects for three selected sites in southern California.

The first part describes the reciprocity method for simulating seismograms due to multiple earthquake sources at a site of interest. We show the practical implementation and accuracy for the finite-difference technique. The numerical tests show that the reciprocal simulations can be performed with the same level of accuracy as the forward calculations.

The second part of the talk shows a new methodology to represent models of sedimentary basins with extremely low near surface velocities by replacing these velocities with equivalent medium parameters for a finite frequency signal. The new model has a higher minimum velocity, which makes the numerical simulations feasible, and minimizes the difference between the seismograms from the original and new model.

The third part of the talk validates the velocity model by comparing synthetics and data. It applies the reciprocity method and compares the full waveform synthetic seismograms with a large number of weak motion data. The discrepancies between the predicted waveforms and the data are interpreted by analyzing the attributes of seismograms to find regions of the model that are in error.

Finally the reciprocity technique is applied to calculate site and path effects in the Los Angeles area for three selected sites by simulating 75 source scenarios on 5 major southern California faults. The largest amplitudes at the selected sites are obtained from earthquakes on local faults rather than an earthquake on the San Andreas fault.
INITIATION AND RUPTURE PROPAGATION
COMPUTED WITH HIGH SPATIAL ORDER FINITE DIFFERENCES

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Physically, a fault of negligible thickness needs only be defined locally by a dis-
placement discontinuity in an intact (elastic) body. To compute wave phenomena in a
finite differences velocity-stress scheme, one usually takes advantage of high spatial
order first derivatives. However, the presence of a fault implies discontinuities of the
displacement and stress fields at all orders across the fault. Therefore, we choose to
implement the fault as a perturbation, which consists in a set of degrees of freedom
corresponding to those discontinuities. The lacking equations to solve these degrees
of freedom are the elastodynamic equations. Here we present our preliminary results
with this method.
MODELING MULTIPLE EVENTS USING EMPIRICAL GREEN FUNCTIONS

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Some events of the year-2000 earthquake swarm occurred in NW-Bohemia, Czech Republic, display complex waveforms indicating a complicated rupture process. The method of empirical Green function deconvolution has shown that relative source time functions of these microearthquakes consist of several single events whose origin times and perhaps also other source parameters may differ. To find the parameters of individual single events, which build up the multiple event, a new method of modeling the waveforms of complex events with the use of empirical Green functions was designed. The waveform of a complex event is considered as a sum of waveforms of several single events with different sizes, origin times and hypocenter coordinates. For modeling single events a waveform of a near small event with a short source time function is used. Assuming similar focal mechanisms, the method searches for coordinates and origin times of individual single events and for their relative seismic moments. Application of the method to the waveforms of the 2000–swarm indicated also its capability to estimate the rupture area of multiple events and the velocity and azimuth of rupture propagation.
NON-PLANAR FAULT GEOMETRY AND STRESS FIELD AROUND THE FAULT

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The distribution of asperities (i.e. large slip area during an earthquake) should be correlated with the initial shear stress distribution (or possible stress drops during the earthquake). If the surrounding stress field around the fault is known and rather uniform, initial shear stress distribution on the fault could be controlled by its fault geometry. This suggests that in order to detect the distribution of asperity prior to the earthquake, estimation of initial tectonic stress field applied to the fault becomes important.

In this study, we examine if the final slip distribution can constrain the initial stress field when the constitutive relation on the fault and fault geometry are provided. We used a boundary integral equation method for triangular elements, which allows us to model an arbitrary shaped fault system with curvatures, branches and jogs. First, using a fault model with a complicated geometry and homogeneous constitutive law, we tried to invert the final slip distribution for the principal initial stress direction and its stress ratio (R) by a grid search method. This numerical test suggests that the principal stress direction can be estimated within an error of 5 degrees, but stress ratio R cannot be well constrained. Then we applied this technique to the 2000 western Tottori earthquake (Mw 6.6). The principal stress direction of the surrounding stress has already been estimated using a stress tensor inversion of aftershock moment tensors, the fault geometry is estimated using relocated aftershock distribution by double difference method, and the constitutive relations are estimated from the slip rate function estimated by a waveform inversion. Using this model, we conducted a forward modeling to examine the initial stress field. We found that the principal stress direction obtained by the stress tensor inversion is the easiest angle for the dynamic rupture to propagate and we think this initial stress distribution is constrained by the fault geometry of this earthquake.
SLIP COMPLEXITY CONTROLLED BY FAULT ZONE HYDRAULICS AND RATE/STATE FRICTION: RESULTS OF A 3-D HYDRO-MECHANICAL FAULT MODEL

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Numerous models have been developed to investigate mechanisms responsible for complex slip distributions observed for large earthquakes over several seismic cycles. The general conclusion from these studies is that a large degree of heterogeneity is required to generate complex slip distributions, GR-statistics, and non-periodic repeat times. The source of the heterogeneity can be frictional properties, geometric irregularities or lithologic variations. Here we pursue the hypothesis that spatio-temporal variations in fault zone hydraulics play a dominant role in the rupture process. To test this, we couple the models of Rice (1993) and Segall & Rice (1995) to a planar, vertical strike-slip fault. The model includes rate- and state-dependent friction (e.g. Dieterich, 1979), and an evolutionary model of pore compaction and dilatancy (Marone et al., 1990) to determine the fluid pressure. We show that the physically plausible scenario of variations in fault zone diffusivity (which controls pore pressure evolution) plays a major role in generating and maintaining complex rupture patterns and slip distributions along the fault. This occurs because pore pressure controls the critical stiffness and thus the seismic behavior of the fault plane. Non-smooth ruptures are controlled by the size and spatial distribution of drained (high diffusivity) and undrained (low diffusivity) regions on the fault. In the continuum limit, high frequency variations in hydraulic properties produce uniform rupture of the entire fault (like those observed in purely elastic models) because the overall system stiffness is not affected by the perturbations. Conversely, above a certain patch size, the effects of drained vs. undrained rock properties significantly affect the system stiffness and thus the rupture dynamics. Significant complexity is generated in the continuum limit, so this model provides a basis for intensive investigations of observed irregular slip distributions at different scales throughout a number of seismic cycles.
We have understood that strong ground motion is relevant to slip heterogeneity on the fault rather than the entire rupture area from source rupture processes inverted with strong motion data. Asperities are characterized as regions that have large slip relative to the average slip on the rupture area, based on slip distributions estimated from the source inversion and those asperity areas as well as total rupture areas scale with seismic moment (Somerville et al., 1999). We examined that strong motion generation areas approximately coincide with the asperity areas where stresses are released (Miyake et al., 2001). A source model satisfying such characteristics is expressed as a dynamically-constrained multi-asperity model that is an extension of a single-asperity model proposed by Das and Kostrov (1986). The source model for predicting strong ground motions is characterized by two kinds of parameters, outer and inner fault parameters. The outer fault parameters are defined as entire rupture area and total seismic moment. The inner fault parameters are defined as slip heterogeneity inside the source, area of asperities, and stress drop on each asperity. We have examined the validity of the earthquake sources constructed above, by comparing simulated and observed ground motions for recent large earthquakes, e.g., the 1995 Kobe, 2000 Tottori, and 1946 Nankai-trough earthquakes.
CHARACTERIZATION OF DYNAMIC SOURCE PARAMETERS FOR STRONG MOTION PREDICTION

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Heterogeneous slip characterization of inland crustal earthquakes ($M_s$ 5.4 – 7.6) shows a scaling relation between total area of asperity, which has rather larger slip than the total area, and seismic moment from source inversion results using strong motion data (e.g. Somerville et al., 1999; Miyakoshi et al., 2002). Irikura and Miyake (2001) proposed characterized source model based on this scaling relation for strong motion prediction. The availability of the characterized source models has been proved through the strong motion simulation in near-source area in the broadband frequency band (BB) for e.g., the 1995 Kobe (Kamae and Irikura, 1997) and for the 2000 Tottoriken-Seibu (Ikeda et al., 2002), Japan, earthquakes. In those simulations, they assumed stress drops only for the asperities by forward simulation of the high frequency contents of the records. When constructing a characterized source model for BB strong motion, we need rules to set stress parameters of the characterized source model. We examine dynamic source parameters by mapping method of spatio-temporal shear-stress distribution on the fault plane from a spatio-temporal slip distribution from kinematic waveform inversion (Bouchon, 1997). The dynamic source parameters averaged over on- and off-asperity areas are estimated. Average effective stress values of on- and off-asperity areas are estimated as 10-20MPa and about 5MPa for the 1995 Kobe, 1999 Chichi, Taiwan, and the 2000 Tottoriken–Seibu earthquakes. Stress parameters on the asperities are slightly increasing with asperity depth. Stress parameters on the asperities coincide with the ones that were used for forward ground motion modelings. Characterization of stress parameters contributes the development of characterized source model.
SIMULATION OF DYNAMIC RUPTURE PROCESSES
ON ACTIVE FAULTS WITHIN HETEROGENEOUS STRESS FIELD

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Laterally heterogeneous stress field is introduced into dynamic rupture simulation for realistic modeling of future earthquakes. We estimated heterogeneous stress fields from distributions of average geological uplift rates (Sekiguchi et al., in this workshop) and simulated spontaneous rupture processes that resulted heterogeneous slip distribution. We show rupture processes on the Uemachi fault system, an intraplate active fault in central Japan.

We assume that the heterogeneous stress field is caused by heterogeneity of horizontal principal stresses. On the Uemachi fault system, there are two peaks of the static stress drop, which corresponds to the along fault strike distribution of uplift rate. The portion between the two peaks, where strength excess is larger and stress drop is smaller, works as a barrier. An initial crack is set at a region with small strength excess and large stress drop.

The fault traces show that the Uemachi fault system extends about 45 km and consists of two thrust fault segments. Since the segments may connect in a deep portion, we consider two fault models: one has a segment and the other has two overlapping segments.

The rupture process depends on fault segmentation and hypocenter location. The rupture area of 1-segment model is larger than that of 2-segment model, because the static stress drop is larger on the overlapping region. The rupture starting from the larger peak of stress drop terminates at the barrier for a time, and eventually propagates across it. The rupture starting from the smaller peak cannot propagate across the barrier. The calculation shows heterogeneous rupture propagation and slip distribution corresponding to the uplift rate.
SOURCE PARAMETERS COMPUTATION IN FRIULI (NORTH-EASTERN ITALY) AND SURROUNDING AREAS - PRELIMINARY RESULTS

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We computed source parameters for seismic events with local magnitude ranging between 2.0 and 5.7, occurred in the Friuli Venezia Giulia region and Slovenia from 1995 to 2002, and recorded by the local Seismometric Network of the Istituto Nazionale di Oceanografia e Geofisica Sperimentale-OGS.

Seismic moment, source dimensions, Brune stress drop, seismic energy and apparent stress were computed according to the Brune model (Brune, 1970) and to the spectral theory developed by Boatwright (1980).

We used the Fourier Amplitude Spectrum of a time window starting at the S—wave arrival. Recorded spectra were corrected for attenuation effects, considering geometrical spreading, scattering and anelastic attenuation.

The spectral decay parameter $k$, first introduced by Anderson and Hough (1984) was used to describe the high frequency behaviour of the acceleration spectrum. Recorded spectra up to 62.5 Hz were available to this aim, thus allowing for reliable estimation of the $k$ parameter.

The hypocentral distances distribution (ranging from 10 to 60 km) allows stable $k$ versus distance regression, thus providing a model for anelastic attenuation correction of the recorded spectra.

Concerning the resulting source parameters, the analyzed events show seismic moments ranging approximately from 1.E+19 to 1.E+24 dyne . cm, Brune stress drop from 0.3 to 100 bar and apparent stress from 0.1 to 70.0 bar; average values for the Brune stress drop and the apparent stress are 11 and 7 bar respectively.

As expected, the corner frequency decreases when the seismic moment increases with values ranging from 0.5 to 9.6 Hz. The relation

$$\log E_s = 1.48 \cdot \log M_0 - 14.94$$

has been found relating radiated energy to seismic moment.


SOME OUTSTANDING PROBLEMS IN EARTHQUAKE DYNAMICS

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Recent dynamic models and inversions of earthquakes have put in evidence several general features that seem to be common to all these studies:

1. Self-healing rupture mode (Heaton pulses),
2. Complex slip = distributions down to the shortest resolved scales,
3. Energy release rates \( (G_c) \) that = are of the same order of magnitude as the radiated energy per unit surface \( (E_s/S) \),
4. Slip weakening distances \( (D_c) \) that are a substantial fraction of static slip \( (D_{max}) \),
5. Local control of the rupture process by stress and friction heterogeneities so that earthquakes are almost always either on the verge of stopping or jumping to supershear speeds,
6. Very large variations of stress change, so that the notion of stress drop needs to be reassessed.

I will critically examine the evidence and discuss possible alternative explanations for some of these observations. What appears is that earthquakes occur as almost critically damped oscillators where radiation controls rupture propagation in a detailed balance. I suggest that seismic radiation at higher frequencies may contain information about fault thermodynamics that has not yet been integrated in current kinematic or dynamic models.
RUPTURE NUCLEATION IN FINITE-SOURCE RUPTURE MODELS

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For moderate or large earthquakes, the position of the hypocenter with respect to regions of large slip has important implications for the generation of strong ground motion. However, in standard strong-motion simulations the hypocenter location is chosen randomly. In spontaneous dynamic rupture calculations based on randomized stress distributions and hypocenters, ruptures often stop prematurely because the energy supplied during the initial rupture process is too low to sustain a large earthquake. We investigate the correlation between hypocenter location and regions of large slip or stress drop by applying statistical tests and Monte-Carlo simulations to a database of 80+ finite-source rupture models for more than 50 earthquakes ($M_w = 4.1 - 8.1$). For strike-slip earthquakes we find a tendency for ruptures to nucleate in the deeper portion of a fault. Ratios of average or maximum slip with respect to hypocentral slip show that rupture can start at any level of slip. However, while only 31% of the events analyzed started on an asperity, most earthquakes nucleate outside or on the edge of an asperity (69%). For the latter population of events we find that ruptures nucleate close to "weak" asperities and will encounter a "strong" asperity within the first half of the maximum rupture distance. The position of the hypocenter with respect to regions of high slip can be understood by considering the energy balance during earthquake rupture. While such energy-budget calculations may be useful to constrain the point of rupture nucleation in spontaneous rupture models, our statistical results can be used to confine the hypocenter location in earthquake simulations for strong ground motion prediction.
THE DYNAMIC RUPTURE PROCESS
OF THE 2001 GEIYO, JAPAN, EARTHQUAKE

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We studied the dynamic rupture process of the 2001 Geiyo earthquake ($M_w = 6.7$). Firstly, the kinematic model inversion using the nearfield strong ground motion data and the farfield seismic waveform data has been carried out. The source process is characterized by a unilateral rupture propagation. The rupture mainly propagated 20 km to the south. Two asperities are identified. The maximum dislocation is about 1.9 m. Then, we have constructed a dynamic rupture model of the earthquake that is consistent with the above kinematic slip model. In dynamic simulation, the finite difference method was used to construct a dynamic rupture model from the kinematic model. The kinematic parameters necessary for the dynamic analysis are the slip amount and the rupture start time of each subfault.

Firstly, the static stress drop distribution is calculated by using Okada’s Green function. Next, we applied dynamic model to the earthquake. We used a fourth-order staggered-grid, finite-difference scheme to the three-dimensional equation of motion. Our scheme includes absorbing boundary conditions and the slip-weakening model on the fault plane. In the process, the dynamic final slip distribution and fracture energy distribution were obtained. The maximum stress corresponding to the maximum slip reaches 30MPa and is located near the hypocenter. The maximum fracture energy of about is also located near the hypocenter. We also found that if we choose the critical slip displacement of more than 75cm the second asperity would not rupture.
3D FINITE-DIFFERENCE AND FINITE-ELEMENT MODELING OF SEISMIC MOTION IN HETEROGENEOUS VISCOELASTIC MEDIA

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The finite-difference (FD) and finite-element (FE) methods are direct numerical methods for solving differential equations. Both methods are powerful tools in numerical modeling of seismic wave propagation and earthquake motion because they are applicable to complex media. A proper combination of both methods can eliminate or significantly reduce disadvantages of the methods. One natural approach is to cover a part of the computational region by the FE mesh while the rest of the region is solved by the FD method. A good example is a free surface topography or a rupturing fault surface.

Moczo, Kristek, Vavrycuk, Archuleta & Halada (2002) addressed a problem of justification and construction of heterogeneous elastic FD schemes and developed a robust FD scheme with volume harmonic averaging of torsion and bulk moduli, and volume arithmetic averaging of density in proper positions in the staggered grid. Numerical tests showed that the scheme is more accurate than standard staggered-grid FD schemes. A planar free surface is simulated using the technique based on adjusted 4th-order accurate FD approximations at grid points at and near free surface (Kristek, Moczo & Archuleta, 2002) and considerably more accurate/efficient than the standard stress-imaging. A new definition of the anelastic functions (independent of material parameters) and their new coarse spatial distribution (Kristek & Moczo, in press) enabled to incorporate realistic attenuation (based on rheology of the Generalized Maxwell Body) with sufficient accuracy and efficiency.

The attenuation based on the GMB rheology and new definition of the anelastic functions has also been incorporated in the FE scheme.

The consistency of the viscoelastic model of the medium in the FD and FE schemes enables to combine them for simulation of seismic motion. We have developed a 3D hybrid FD-FE scheme and computer code in which the 2nd-order FE scheme is applied to a part of the computational region (with a free-surface topography and/or rupturing fault surface), and the rest of the region is solved by the 4th-order staggered-grid FD scheme.
THE STOPPING DYNAMICS OF LARGE EARTHQUAKES

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The question of earthquake stopping can be quantified by evaluating the energy dissipated at the tip of a propagating earthquake. The earthquake stops when it encounters a region with fracture energy $G$ larger than that available from the advancing fracture. According to a simple crack model, stress drop and asperity dimensions can be estimated for a given earthquake, in order to derive the minimum strength of the barriers in terms of fracture energy (Aki, 1979). However, the energy balance at the propagating fracture tip can change by orders of magnitude depending on the rupture time history. In particular, it can be shown theoretically that the energy dissipated at the tip of a narrow fracture pulse is much smaller than that dissipated in the case of a large crack. We discuss the implications of such a model and we propose a natural mechanism for arresting earthquakes without invoking huge barriers at fault boundaries. For a realistic earthquake scenario, the complexity is such that the energy balance should be performed numerically. For dynamic numerical models based on the Chi Chi 1999 Earthquake, we find that the barrier strength can be at least ten times weaker in the case of a narrow fracture pulse.
THREE-DIMENSIONAL DYNAMIC MODELS
OF THE 2002 DENALI, ALASKA, EARTHQUAKE

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The 2002 Denali, Alaska, earthquake took place on a geometrically complex fault system. Rupture nucleated on a previously-unmapped thrust fault, proceeded to the Denali fault, and continued eastward. At a fault branch on the eastern side of the slip zone, rupture abandoned the Denali fault in favor of the Totschunda fault. We perform three-dimensional dynamic models of this event, in conjunction with kinematic strong-motion slip inversions, in order to elucidate the physical reasons for the complex faulting behaviors observed in this event. We find that the propagation of rupture to the Totschunda fault can be explained by its more favorable orientation with respect to the regional tectonic stress field. However, such a simple stress field does not adequately explain the slip patterns seen in this earthquake. We also show that under reasonable assumptions about the fault friction and stress field, discontinuous (jumping) rupture propagation naturally arises at the intersection between the Denali and Totschunda faults. Such behavior, while not definitively required by the data, helps to explain certain puzzles about this event, such as the apparently high rupture velocity on the relatively unfavorable main Denali segment. The results help to show how dynamic stress interactions can affect both the rupture path and the amount of slip in geometrically complex fault systems.
Understanding the generation process of earthquakes is now entering a new phase of development. We are now beginning to understand the earthquake generation process, including the nucleation and the dynamic rupture propagation, quantitatively in terms of the underlying physics. In order for the physics of earthquakes to aim at a branch of exact science, however, the governing law for the earthquake rupture must be formulated as a constitutive law that has scaling property in itself, because some of the physical quantities inherent in the rupture are scale-dependent. Otherwise, scale-dependent physical quantities inherent in the rupture over a broad scale range cannot be scaled quantitatively and self-consistently in terms of a single constitutive law. It has been found with recent laboratory experiments that fundamental cause of the scaling property lies at the characteristic length scale defined as the predominant wavelength contained in geometric irregularity of the rupturing surfaces. This means that the fault irregularity (inhomogeneity) plays a crucial role in physical scaling of the rupture, and that the predominant wavelength must be incorporated into the law as a scaling parameter that represents the scaling property. In addition, there are increasing amounts of commanding evidence that the earthquake rupture at shallow crustal depths is a mixed process between frictional slip failure on a pre-existing fault and shear fracture of initially intact rock, such as asperity fracture. It thus follows that the constitutive law must also be formulated as a unifying law that governs both frictional slip failure and shear fracture. To meet these requirements, the constitutive law needs to be formulated as a slip-dependent law into which the scaling property is properly incorporated, because the slip-dependent constitutive law is such a unifying law. With these in mind, the constitutive law for the earthquake rupture may be formulated as follows. The shear traction $\tau$ is primarily expressed as a function of the slip displacement $D$, and the constitutive relation between $\tau$ and $D$ (i.e., the transient response of $\tau$ to $D$) is affected by slip rate $\dot{D}$, scaling parameter $\lambda$, effective normal stress $\sigma_n^{\text{eff}}$, temperature $T$, and chemical effect of pore fluid pressure CE. However, the effects of $\dot{D}$, $\lambda$, $\sigma_n^{\text{eff}}$, $T$, and CE are secondary compared with the primary effect of $D$, and hence the law is referred to as slip-dependent law. The constitutive law may thus be written as:

$$
\tau = f(D; \dot{D}, \lambda, \sigma_n^{\text{eff}}, T, CE)
$$

(1)

The slip-dependent constitutive law spontaneously satisfies Griffith’s energy balance fracture criterion. In addition, the rate property and the scaling property are both incorporated into this law as follows:

$$
\tau_p = f(\sigma_n^{\text{eff}})[1 + c \log(\dot{D}/\dot{D}_0)]
$$

(2)

and

$$
D_c = a(\Delta \tau_p / \tau_p)^m \lambda_c
$$

(3)

where $\tau_p$ is the peak shear strength, $D_c$ is the breakdown displacement, $\Delta \tau_p$ is the breakdown stress drop, $\dot{D}_0$ is the reference slip rate, and $a$, $c$, and $m$ are
dimensionless constants. The slip-dependent constitutive law is thus a generalized, more universal, physical law than the Griffith fracture criterion. Scaling of scale-dependent physical quantities inherent in the rupture is commonly reduced to the scale-dependence of $D_c$. In fact, it has been demonstrated that such scale-dependent physical quantities as the length of nucleation zone and its duration, the slip acceleration, and the apparent fracture energy, scale with parameter $D_c$, which in turn scales with the scaling parameter $\lambda$, according to equation (3).
NONLINEAR DYNAMIC RUPTURE INVERSION
OF THE 2000 WESTERN TOTTORI, JAPAN, EARTHQUAKE

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The conventional procedure to infer information about the rupture history of large
earthquakes is a linear inversion for the slip history on the fault by matching recorded
and synthetic accelerograms. Such inversion has traditionally been carried out kine-
matically, which has some important limitations, in particular unphysical constraints
on the rupture velocity and the choice of source-time function. A more physically cor-
rect inversion would therefore take into account the dynamics of the rupture, i.e., the
stress, and friction parameters. While the radiated waves are highly sensitive to the
distribution of stress and friction parameters on the fault, an essential requirement
for the inversion to work, such inversion is highly complicated due to the strong non-
linearity of the dynamic problem. We have developed a fully systematic, nonlinear
inversion method to estimate dynamic rupture parameters using a Neighbourhood
algorithm and a finite-difference technique for the forward modeling. The method
provides an objective means of routinely estimating dynamic rupture parameters for
large earthquakes. We test the method by estimating the initial stress within 32 re-
gions on the causative fault for the 2000 M6.6 Western Tottori, Japan, earthquake.
The synthetics for the dynamic models with the smallest misfit provide a good fit to
0.5 Hz strong motion data recorded at 12 near-field stations. The dynamic models
with the smallest misfit agree with the slip distributions from conventional kinematic
analyses in the location of the largest asperity. In the surrounding areas on the fault,
where kinematic inversions generally produce only one, final model, our method pro-
vides an ensemble of nearly equally acceptable rupture models.
3D ELASTIC WAVE PROPAGATION MODELING USING A ROTATED STRESS-VELOCITY FINITE-DIFFERENCE SCHEME

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We apply a fourth-order staggered grid finite-difference method to solve the three-dimensional elastic wave equation. The technique is an extension of the 2D technique proposed by Cruz-Atienza et al., 2002. Our approach is based on rotated finite-difference operators that allow for defining the velocity and stress fields as well as media parameters in only two separate locations within the grid element. Although it requires a larger number of grids for achieving the same level of accuracy, the flexibility of the scheme for modeling rupture dynamics for non-planar faults with any orientation, and surface topography, is much higher than that of classic staggered grid schemes. We will show results of its accuracy tests using double-couple point sources, and discuss its potential use in modeling rupture dynamics.
PALEOSEISMOLOGICAL DATA HELP
CONSTRUCTING RUPTURE MODELS
FOR FUTURE EARTHQUAKES ON ACTIVE FAULTS

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We show here a method for estimating heterogeneous rupture models for scenario earthquakes from displacement distributions of past earthquakes measured along active faults. This is based on an assumption that long-wavelength components of heterogeneity in rupture process is stable over geological (10 10 E+6 yrs) time scale and so reflected in slip distribution of past earthquakes. Lindvall et al. (1989) and Sieh and Jahns (1984) have shown that displacement distributions on surface ruptures are always similar, which supports our assumption. First, we construct a static slip distribution model. We assume that static slip varies along fault strike in a similar way to coseismic displacement. In the downdip direction, we assume a distribution similar to those of recent, well-analyzed earthquakes. The slip gradually converges to zero at the bottom of the seismogenic zone. The static slip distribution is then converted to static stress change, using the formulation of Okada (1992). The static stress change is incorporated into the dynamic rupture simulation as a variation of initial stress (Kase et al., in this workshop). We apply this method to the Uemachi fault system, a 45 km long, reverse-type active fault system which lies beneath the Osaka Basin, Southwestern Japan. Only one measurement is available about coseismic displacement of past earthquakes, but average uplift rate is estimated at several points along this fault system from cumulative displacements. Therefore, we derive a static slip distribution model from the distribution of coseismic displacement and average uplift rate. If we assume a constant recurrence time along fault strike, we get two peaks in the static slip distribution model, which indicate asperities. If we assume rupture over the whole range in depth, the stress distribution has peaks near the bottom of the seismogenic zone, which indicates plausible locations for hypocenters. This heterogeneous static stress distribution together with the locations of hypocenters affects the rupture propagation significantly (Kase et al., in this workshop).
FROM MICROSCOPI TO MACROSCOPIC EARTHQUAKE PHYSICS

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The macroscopic approach to earthquake physics, based on the microscopic one is proposed. The microscopic model (Tectonophysics, 344, 37-60, 2002) is formulated in terms of slip and stress fields, while the macroscopic one relates seismic energy to seismic moment, and to other parameters that can be expressed as averages of microscopic variables.

The microscopic model assumes overdamped dynamics (i.e., instantaneous - in comparison to the slip movement rates - stress transmission), slip dependent friction, and tectonic loading applied from fault region sides. The tectonic loading expresses Reid's elastic rebound mechanism, modified by including interactions within the rupture area. Validity of the over damped dynamics approximation is considered jointly with the assumed slip dependent friction and the pulse like rupture style. The model is used to simulate seismic activity of heterogeneous seismic sources in time scales of single events, earthquake cycles, and the long-term fault behavior. Stable, accelerating, and dynamic rupture phases, delayed subevents, and non regular earthquake recurrence, are explained by heterogeneity of seismic sources and non locality of fault stability conditions.

The macroscopic model is based on the seismic energy rate formulation implied by the microscopic model, which leads to reinterpretation of the apparent stress as a measure of non uniformity - in time and space - of rupture processes, and to the scaling relationship for the apparent stress as a function of the seismic moment, the rupture area, and the mean slip acceleration. These results explain fluctuations and statistical trends of the apparent stress observed for real and simulated earthquake populations.
MAGNITUDE DEPENDENCE OF RADIATED ENERGY AND ENERGY SPECTRA

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Radiated energy and radiated energy spectra and their scaling with moment are important both from the point of view of earthquake hazard, and from the dependence on and insight into source dynamics they provide. Having to assume only a physics of tractions on the fault, we have been able to simulate sequences of elastodynamic events with a wide range of sizes, and measure the radiated energy and energy spectra of populations of events. Techniques for doing this, and the implications of the results, will be addressed.
DYNAMIC RUPTURE MODELING
OF THE 1995 KOBE EARTHQUAKE

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The 16 January 1995 Kobe earthquake ($M_w 6.9$) occurred near the city of Kobe in western Japan, causing a tremendous amount of damage. The focal mechanism indicates that it is a right–lateral strike slip event on nearly vertical faults. We investigate the dynamic rupture process of the Kobe earthquake by modeling spontaneous rupture of a 3–D dynamic shear crack guided by the slip distribution found from kinematic waveform inversion. We find that using the initial stress field obtained from the static stress drop distribution computed from the kinematic slip model and a uniform final stress field successfully generates a dynamic model with a slip and rupture time distribution consistent with the kinematic source inversion. Large surface rupture was generated from high local stress drop up to 50 bar beneath Awaji Island. Relatively small or negative stress drop with a large slip weakening distance beneath the city of Kobe might explain the lack of surface rupture in this area. Ide and Takeo (1997) suggest depth dependent slip weakening distances on the order of 0.5 - 1 m by analyzing the joint behavior of stress and slip inferred from their kinematic waveform inversion although they recognized that these values probably represent an upper bound. Mikumo et al. (2003) independently suggest similar upper bounds on the slip weakening distance to that found by Ide and Takeo (1997). Our dynamic analysis indicates a smaller slip weakening distance (0.1 - 0.5 m) is required in order for rupture to propagate spontaneously.
CAN WE LEARN ANYTHING ABOUT FAULT FRICTION FROM WAVE-FORM MODELING STRONG MOTION SEISMOGRAMS?

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The frequency–band limits of traditional wave-form modeling of strong motion data are typically so narrow that models derived from such studies place few constraints on the governing fault friction law. Given a kinematic slip model of an earthquake, it is possible to calculate stress change and to derive an apparent relation between frictional stress and slip. Guatteri and Spudich (BSSA, 2000) showed that the yield stress and the slip-weakening distance cannot be uniquely determined from a wave–form data set, although the derived fracture energy is more stably estimated. Even if it is assumed that the derived stress-slip relation is unique, Guatteri, Spudich, and Beroza (JGR, 2001) showed that such relations could be interpreted in terms of a wide range of rate-state length scales. A parameter $D_c'$ has been proposed which might be an easily calculated estimate of the slip–weakening distance. We calculated the $D_c'$ parameter for two slip models originally presented by Guatteri and Spudich (2000). These two models generate nearly identical seismograms in the 0 - 1 Hz band, but have different slip–weakening distances, about 0.3 and 0.8 m. To simulate the poor resolution of wave form inversion, we low-pass filtered the stress–slip curves from these two models with a 1.0 Hz corner frequency. $D_c'$ calculated from the filtered stress-slip curves is sometimes less than the actual $D_c$, and often is greater. $D_c'$ calculated for low-pass filtered stress-slip curves tends to be biased toward the total slip amount, and the filtering operation tends to introduce an artificial correlation of $D_c'$ with total slip. All of these resolution problems imply that we will have to expand our data set beyond 0-1 Hz bandpassed seismograms to understand fault friction during dynamic rupture.
NONLINEAR INTERACTION AMONG CHANGES
IN TEMPERATURE, PORE FLUID PRESSURE AND POROSITY
IN A POROUS FAULT ZONE AND ITS EFFECTS
ON THE DYNAMIC INITIATION OF FAULT SLIP

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Pore fluid is believed to play an important role in the occurrence of earthquakes. It will be a general view that frictional heating raises fluid pressure, which tends to enhance the rupture occurrence. However, we have to note the existence of intense nonlinear interaction among changes in fluid pressure, temperature and porosity in a porous fault zone saturated with pore-fluid, which may yield fault behavior that is not necessarily consistent with the above simple view. We theoretically investigate this interaction and its effect on fault slip assuming a 1–dimensional porous fault zone saturated with pore–fluid. We derive a system of equations based on the formulation of Biot. The bulk modulus and thermal expansion coefficient of the porous medium are assumed to be functions of porosity based on theoretical analyses. The slip velocity is assumed to depend on the fluid pressure based on the concept of the Terzaghi effective stress. Our calculation shows that the slip behavior is sensitive to the ratio of the thermal expansion coefficient of rock to that of pore–fluid. If it is small enough, the pore-fluid pressure increases with time for a while, and then decreases after attaining a maximum value. This implies that the fault slip shows slip-strengthening behavior in the range of fluid pressure decrease. On the other hand, if the ratio is sufficiently large, the fluid pressure is shown to increase monotonically with time and attains the lithostatic pressure. The fault slip shows only slip weakening behavior in this case. Our calculations also show significant dependence of the system behavior on the magnitude of the load applied at the fault zone boundary. Smaller magnitude of the applied load generally yields lower slip velocity and longer slip duration.
DYNAMIC TRACTION EVOLUTION
OBTAINED FROM KINEMATIC RUPTURE MODELS
WITH PRESCRIBED SOURCE TIME FUNCTIONS:
INFERENCE ON THE ESTIMATE
OF THE CRITICAL SLIP WEAKENING DISTANCE

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Earthquake source models describing the rupture history on the fault plane are currently obtained through the inversion of near-source strong motion records. These models have been used as input in 3D finite difference dynamic algorithms to infer the spatial distribution and the temporal evolution of the dynamic traction on the fault plane, which is also employed to measure the critical slip weakening distance. In this study we present the results of a sensitivity test to investigate how the slip-velocity time function adopted in kinematic models influences the calculation of dynamic parameters. We have used several kinematic source models, based on the rupture history of the Western Tottori (Japan) earthquake, to compute the traction evolution, the strength excess, the dynamic stress drop as well as the critical slip weakening distance. Our results show that the adopted source time functions affect the inferred values of dynamic parameters and their distribution on the fault plane. In particular, the retrieved critical slip weakening distance strongly depends on the function assumed to represent slip velocity: we have found that $D_c$ ranges between 30% and 80% of the total slip. This range of variability depends on the frequency content of the adopted source time function. We have found that the distribution of the breakdown stress drop (i.e., the difference between yield and frictional stress) on the fault plane is less dependent on the adopted source time function than the strength excess or the dynamic stress drop.
MODELLING OF SOURCE TIME FUNCTIONS
AND DIRECTIVITY EFFECT
OF THE 1999, KOCAELI EARTHQUAKE

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The 1999 $M_w = 7.4$ Kocaeli earthquake provided number of interesting near fault strong motion records. One of them, recorded at the station YPT consists of two, almost separated wave trains. In order to find out whether this separation results from the source process or is due to propagation we calculate relative source time functions for this site, first, by assuming a homogeneous Haskell slip model. Therefore, we use a ground motion synthesis program along with delta peaks instead of Green's functions. The results show that directivity is present, but don't explain the separation of the wave trains.

To show the influence of heterogeneous slip distribution typical for real earthquakes, we calculate also source time functions for the rupture/slip model of this earthquake derived by Bouchon et al. (2000).

We further calculated other relative source time functions at various azimuths, to demonstrate the directivity effect of this earthquake. These results show the importance of directivity for this earthquake especially at sites close to the fault.

Moreover, we tried to achieve the source time function by deconvolving the main event strong motion record from a small aftershock record, usually referred to as Empirical Greens function (EGF) deconvolution method. The result differs significantly from the source time function which we calculated directly, thus demonstrating that the EGF deconvolution method is not applicable in the near field, since the point source assumption doesn't hold there. The reason therefore is that the Green's functions from the different parts of the fault differ significantly very close to the fault, and, that perhaps nonlinear effects may be present, which cannot be accounted for by the (linear) EGF approach.
HOW TO DETERMINE THE PORE FLUID PRESSURE IN A FOCAL AREA?

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Pore fluid pressure is assumed to significantly influence the seismicity pattern and the type of faulting. It decreases the effective stress on faults, destabilizes faults and triggers earthquakes. Therefore, it is desirable to estimate its value and variation in time.

We propose a method which can setup limits for the fluid pressure in a focal area. The method utilizes non-DC components of moment tensors of small earthquakes and requires the fluid pressure to be sufficiently high to generate not only shear but also tensile faulting. If we detect shear as well as tensile earthquakes in the same focal area, but on faults with different orientations, we can estimate the fluid pressure as follows: The fluid pressure should attain a value such that the effective normal traction will be compressive on the faults with shear earthquakes but extensive on the faults with tensile earthquakes.

The method proposed was applied to earthquakes observed in West Bohemia, Czech Republic in January 1997. West Bohemia is a seismically active geothermal area, in which a high fluid pressure is a reasonably satisfied assumption. Analyzing moment tensors of 40 microearthquakes we found that some moment tensors display high non-DC components probably induced by tensile faulting. The tensile faulting was manifested by positive isotropic and compensated linear vector dipole components. We analyzed stress conditions from focal mechanisms of earthquakes under study. We estimated the lithostatic stress to be 250 MPa in the focal area and found that the fluid pressure should be less than the lithostatic stress by 5 MPa. The ratio of the fluid pressure to the maximum compressive stress is 0.7.
CRACK GROWTH RESISTANCE AND RUPTURE ARREST UNDER SLIP–DEPENDENT FRICTION

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The slip–strengthening behavior observed in fracture and friction experiments is considered as a candidate for crack growth resistance and dynamic rupture arrest. The peak shear stress and the strengthening slip play a role in the crack growth resistance. Depending on this resistance, the rupture may be stopped by a strengthening barrier. In such a case, we show that the residual shear stress at the end of the dynamic process is not grid-size dependent, suggesting that the shear stress does not exhibit any singularity at the crack tip. Hence, rupture arrest by a strengthening barrier is compatible with a criterion based on a finite shear stress threshold. Considering a finite weak zone bounded by two strengthening barriers, we investigate the modalities of rupture arrest. Despite the barriers, the final size of the rupture event is not controlled a priori, but rather depends on the strength of the barriers and on the seismic energy released in the weak zone. Two mechanisms for rupture arrest are pointed out. The first one is associated with a negative stress drop in the barrier, and is crack size independent. The second one is associated with a positive stress drop in the barrier, and is crack-size dependent. In both cases we show the existence of a crack arrest zone characterized by a small amount of slip and a shear stress concentration, and associated to a self healing slip pulse.
MIXED FINITE ELEMENT METHOD
FOR RUPTURE INITIATION ON A FAULT SYSTEM

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The antiplane shearing of a fault system under slip dependent friction in a 2D homogeneous elastic media is considered. A nonlinear spectral problem is deduced from the evolution problem, to investigate the stability of complex fault systems during the initiation phase of earthquakes. Spatial discretization is performed using a mixed finite element method with Lagrange multipliers and adaptive mesh refinement.

This spectral analysis leads to the computation of the most unstable modes of deformation arising in the initiation phase. A comparison is drawn with observed slip profiles in a population of active normal faults in the Afar, showing that fault interaction, together with other processes, may be responsible for frequently observed asymmetric profiles.

Computation of the dynamic slip instabilities is also performed in the time domain using a Newmark scheme. Domain decomposition is used to handle the non-linear boundary conditions on the fault. Results obtained using a finite difference scheme are successfully reproduced, with more flexibility to handle complex geometries.