November 17, 2004

This is the 2004 Annual Progress Report for

A Collaborative Project:
3D Rupture Dynamics, Validation of the Numerical Simulation Method
Coordinating Principal Investigator:
Ruth Harris (USGS)
Co-Principal Investigators:
Ralph Archuleta (UCSB)
Brad Aagaard (USGS)
Dudley Joe Andrews (USGS)
Steven Day (SDSU)
Eric Dunham (UCSB)
Nadia Lapusta (Caltech)
David Oglesby (UCR)
Kim Olsen (SDSU)
Arben Pitarka (URS)
Allan Rubin/Jean Paul Ampuero (Princeton)

AND FOR

3D Rupture Dynamics Code Validation 2004 Workshop
Co-Principal Investigators:
Ruth Harris (USGS) and Ralph Archuleta (UCSB)

This progress report is for the collaborative spontaneous-rupture-dynamics code validation exercise, and for the related two workshops that were held on September 19, 2004 and November 8, 2004. In 2004 the code-validation efforts were funded in 2 separate proposals, 1 proposal for the workshop(s), and 1 proposal for modeler salary support (mostly to support the students/postdocs). In 2004, 16 SCEC researchers numerically simulated earthquakes in the code-validation exercise, including the 7 SCEC-funded Principal Investigators, the 3 USGS Principal Investigators, 1 SCEC-institution visiting researcher from Japan, 2 SCEC institution postdocs, and 4 SCEC institution students.

The benchmarks tackled in 2004 were 3D simulations of spontaneous rupture propagation on a vertical strike-slip fault in a homogeneous medium. This simple scenario was the basis of our comparisons since it enabled the most types of codes (finite-difference, finite-element, boundary integral, spectral-element) to be included. Future efforts, with more complex parameterizations, will only be doable by a subset of these methodologies. In 2004 we tackled two benchmarks, The Problem, Version 2 (TPV2), and The Problem, Version 3 (TPV3). TPV2 is a slight modification of the instantaneous-nucleation The Problem, Version 1, that was simulated for the November 2003 SCEC workshop. TPV2 is the case of spontaneous rupture following slip-weakening nucleation on a vertical strike-slip fault in a homogeneous half-space (see figure 1). The objective was for each SCEC researcher's code to produce matching synthetic seismograms both on the synthetic earth's surface and at depth on the fault plane, in addition to matching rupture behavior. TPV3 (see figure 2) is a slight modification of TPV2 in that it has the same parameters as TPV2, except that it occurs in a fullspace rather than in the halfspace of TPV2.

During the summer and fall of 2004, 6 new codes came to the table and were implemented to tackle the benchmarks. These included the Boundary Integral code by Nadia Lapusta (TPV2 and TPV3), the spectral-element code by Jean-Paul Ampuero (TPV2), a discrete element code by Steve Day's postdoc Luis Dalguer, (TPV2 and TPV3), a finite-difference code by visiting Japanese researcher Yuko Kase (TPV2 and TPV3), and 2 variations of a boundary integral code by Eric Dunham (TPV3).

A discovery during 2004 is that the "fat fault" formulations may not lead to the same results as the "thin fault" or split-node fault approximations used by most of the other codes. Tests are being performed by Luis Dalguer to determine if there is a possibility of convergence between the "fat" and "thin" fault approximations if the nodes in the "fat fault" are brought close together, relative to the rest of the node spacing in the finite-difference grids. In 2005 we hope to arrive at convergence on this issue since otherwise it appears that the 2 types of codes produce divergent results, and thereby different synthetic seismograms.

During the September 2004 workshop we observed that many of the split-node codes are producing similar results, at least for the simple vertical strike-slip fault case of The Problem, Version 2. At our November 2004 workshop we compared our findings of the fullspace case (TPV3) with those of "rigorous" BIM simulations (the code of Nadia Lapusta), and also tested the effect of different node-spacings/element-sizes in the models. At the November workshop we found that for 100 m element-size/node-spacing, many of the codes agreed, whereas for coarser element-size/node-spacing, there was less of a convergence. It was decided that the differences might be due to how the element-size/node-spacings related to the slip-weakening breakdown distance, but this issue was not fully resolved.

During the September 2004 workshop Rasool Anooshehpoor and Jim Brune presented the Rasool/Matt/Jim results from foam rubber simulations that we were thinking of using as a validation exercise. (To this date we have been involved in comparison, rather than validation.) Discussion among the modelers and audience members at the September workshop proposed that our simulation of the foam rubber exercise might not be a new step forward for us since we would just be showing that we could match the Day and Ely [BSSA, 2002] studies of rupture in foam rubber, thereby demonstrating that we could match Steve's code's simulations of rupture. This discussion did move forward to the possibility that perhaps we could instead compare our simulations with new lab experiments on dynamic rupture in rock, such as is currently being undertaken by the Beeler/Junger/Tullis group. We will consider this issue further in 2005, including discussion with the SCEC ground motions and implementation interface groups about which would be our optimal validation test.

Part of the November 2004 workshop also consisted of discussion of FY05 problems to tackle (discussed in detail in the FY05 collaborative and workshop proposals). These will include rupture of an asperity away from the nucleation zone, a topic of specific interest to the ground motion modelers, and rupture of a weak patch. We also plan to tackle the sub-shear to supershear transition, to understand its physics better and see if it looks the same in all of the codes. The subshear/supershear topic is under more discussion in the seismological community than in the past, now that supershear rupture has been clearly inferred for a number of worldwide large earthquakes.

IT items that we plan to work on in 2005 include a better way to do the actual comparisons, and a place to host the simulations. Now that we have a large number of simulations being performed (see Table 1), there needs to be a better way to compare the results, which are currently undertaken by the coordinating-PI (RAH). This topic will be investigated by one of our co-PI's in the collaborative proposal for FY05.

2004 SCEC Publications directly related to this SCEC collaborative exercise:

EOS Article:

Harris, R.A., and R.J. Archuleta, Earthquake Rupture Dynamics: Comparing the Numerical Simulation Methods, EOS, vol. 85, No. 34, page 321, August 24, 2004.

Abstract for 2004 Fall AGU meeting:

Harris, R.A., R. Archuleta, B. Aagaard, J. P. Ampuero, D.J. Andrews, L. Dalguer, S. Day, E. Dunham, G. Ely, Y. Kase, N. Lapusta, Y. Liu, S. Ma, D. Oglesby, K. Olsen, A. Pitarka, The Source Physics of Large Earthquakes – Validating Spontaneous Rupture Methods, AGU Fall 2004 abstracts meeting volume.

AGENDA

2004 SCEC 3D Rupture Dynamics Code Validation Workshop

Sunday September 19, 2004 at the SCEC Meeting Hotel in Palm Springs

8:00-8:15	Coffee, etc.
8:20	**Workshop Introduction** (*Ruth Harris/ Ralph Archuleta*)
8:40-12:00	**Presentations explaining the codes**
8:40	*David Oglesby*
9:00	*Shuo Ma*
9:20	*Brad Aagaard*
9:40	*Jean Paul Ampuero*
10:00	Break
10:30	*Nadia Lapusta / Yi Liu*
10:50	*Arben Pitarka*
11:10	*Kim Olsen*
11:30	*Luis Dalguer/ Steve Day*
11:50	*Eric Dunham/ Morgan Page*
12:10 -1:30	Lunch
1:30-1:50	**Presentations explaining the codes**
1:30	*Yuko Kase*
1:50-2:10	**Presentation showing lab experiments to simulate**
1:50	*Rasool Anooshehpoor/Matt Purvance/Jim Brune*
2:10-3:00	**The Problem, Version 2 Comparisons** *(Ruth/Ralph)*
3:00-3:15	Break
3:15-4:30	**Group Discussion (Everyone)**

2004 SCEC 3D Rupture Dynamics Code Validation Workshop

Sunday September 19, 2004 at the SCEC Meeting Hotel in Palm Springs

52 WORKSHOP ATTENDEES:

Ruth Harris
Ralph Archuleta
Brad Aagaard
Jean-Paul Ampuero
Rasool Anooshehpoor
Annemarie Baltay
Yehuda Ben-Zion
Greg Beroza
Harsha Bhat
Jacobo Bielak
Julia Brinkman
Jim Brune
Susana Custodio
Luis Dalguer
Paul Davis
Steve Day
Derek Desens
Benchun Duan
Eric Dunham
Geoff Ely
Marcio Faerman
Karl Fuchs
Tom Heaton
Carlos Huerta-Lopez
Larry Hutchings
Tom Jordan
Yuko Kase
Nadia Lapusta
Daniel Lavallee
Guoqing Lin
Pengcheng Liu
Shuo Ma
Phil Maechling
Martin Mai
John McRaney
Bernard Minster
Thomas Morbitzer
David Oglesby
Kim Olsen
Morgan Page
Brandee Pierce
Arben Pitarka
Matt Purvance
Leonardo Ramirez-Guzman
Jim Rice
Zheqiang Shi
Seok Goo Song
Elizabeth Templeton
Terry Tullis
Jack Tung
Nicholas Vaughn
Michael Vredevoogd

AGENDA

2004 SCEC 3D Rupture Dynamics Code Validation Workshop

Monday November 8, 2004 at SCEC/USC

10:30 Workshop Introduction *(Ruth Harris/Ralph Archuleta)*

10:40-11:40 Presentations Explaining Codes
10:40 *Elizabeth Templeton*
11:00 *Leo Ramirez-Guzman*
11:20 *Geoff Ely*

11:40 Presentation Demonstrating new IT Visualization Tool
11:40 *Kim Olsen*

12:00-1:00 Lunch

1:00-2:15 The Problem, Version 3 Comparisons (*Ruth*/*Ralph*)

2:15-2:30 Break

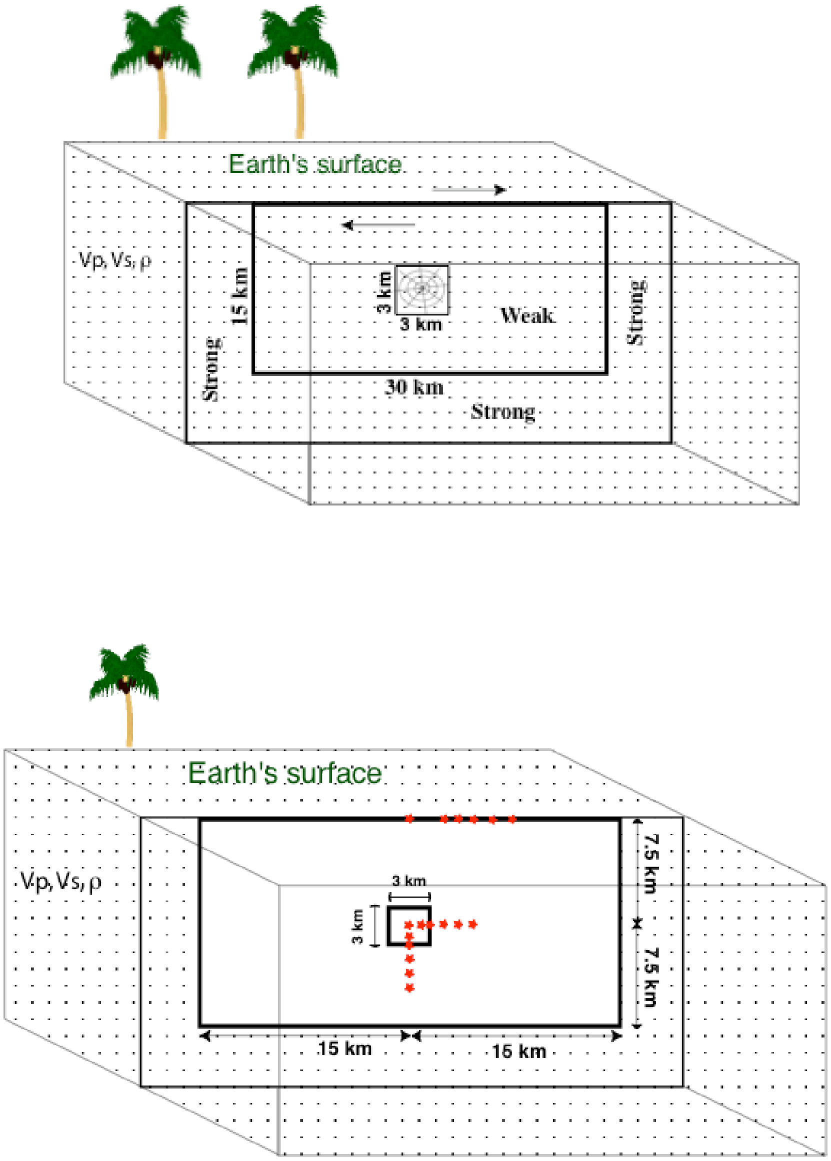
2:30-4:30 Group Discussion, Plans for FY05 Proposal (*Everyone*)

----

21 WORKSHOP ATTENDEES:

Ruth Harris
Ralph Archuleta
Brad Aagaard
Jean Paul Ampuero
Luis Dalguer
Steve Day
Eric Dunham
Geoff Ely
Yuko Kase
Nadia Lapusta
Daniel Lavallee
Pengcheng Liu
Yi Liu
Shuo Ma
David Oglesby
Kim Olsen
Morgan Page
Arben Pitarka
Leonardo Ramirez-Guzman
Otilio Rojas
Elizabeth Templeton

Figure 1a showing setting of The Problem, Version 2 (TPV2), the case of rupture on a vertical strike-slip fault in a homogeneous halfspace (top), and the locations of the stations for the synthetic seismograms (bottom).

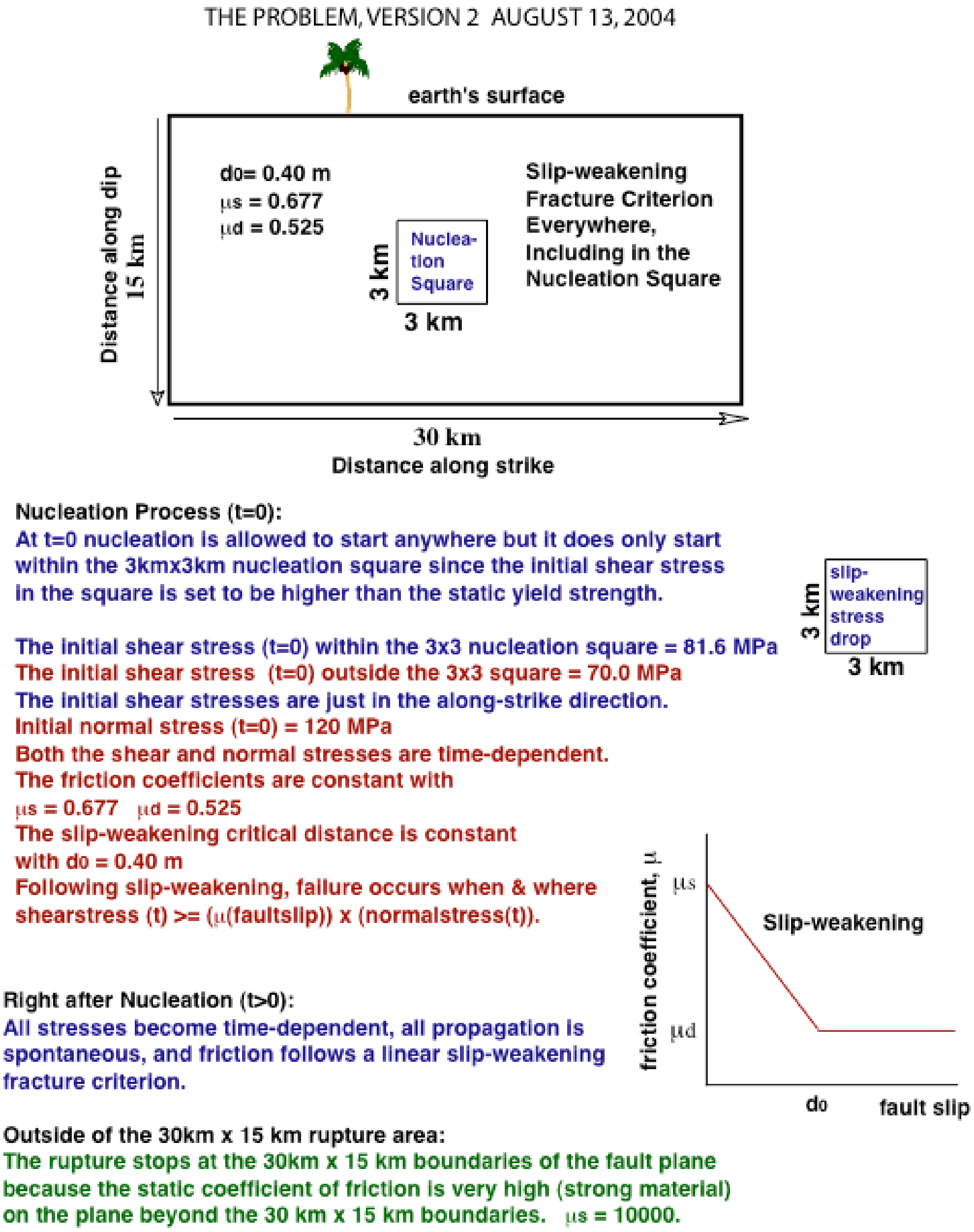


Station Locations

Earth's surface: epicenter, 2.5, 3.5, 4.5, 6.0, 7.5 km along strike from the epicenter

Deeper: hypocenter, 1.0, 1.5, 2.5, 3.5, 4.5 km along-strike from the hypocenter,
1.0, 1.5, 2.5, 3.5, 4.5 km down-dip from the hypocenter

Figure 1b showing physics for The Problem, Version 2 (TPV2)



Nucleation Process (t=0):

At t=0 nucleation is allowed to start anywhere but it does only start within the 3kmx3km nucleation square since the initial shear stress in the square is set to be higher than the static yield strength.

The initial shear stress (t=0) within the 3x3 nucleation square = 81.6 MPa
The initial shear stress (t=0) outside the 3x3 square = 70.0 MPa
The initial shear stresses are just in the along-strike direction.
Initial normal stress (t=0) = 120 MPa
Both the shear and normal stresses are time-dependent.
The friction coefficients are constant with
$\mu_s = 0.677$ $\mu_d = 0.525$
The slip-weakening critical distance is constant with $d_0 = 0.40$ m
Following slip-weakening, failure occurs when & where shearstress (t) >= (μ(faultslip)) x (normalstress(t)).

Right after Nucleation (t>0):

All stresses become time-dependent, all propagation is spontaneous, and friction follows a linear slip-weakening fracture criterion.

Outside of the 30km x 15 km rupture area:

The rupture stops at the 30km x 15 km boundaries of the fault plane because the static coefficient of friction is very high (strong material) on the plane beyond the 30 km x 15 km boundaries. $\mu_s = 10000$.

Figure 1c showing some results for The Problem, Version 2 (TPV2) at 1 station

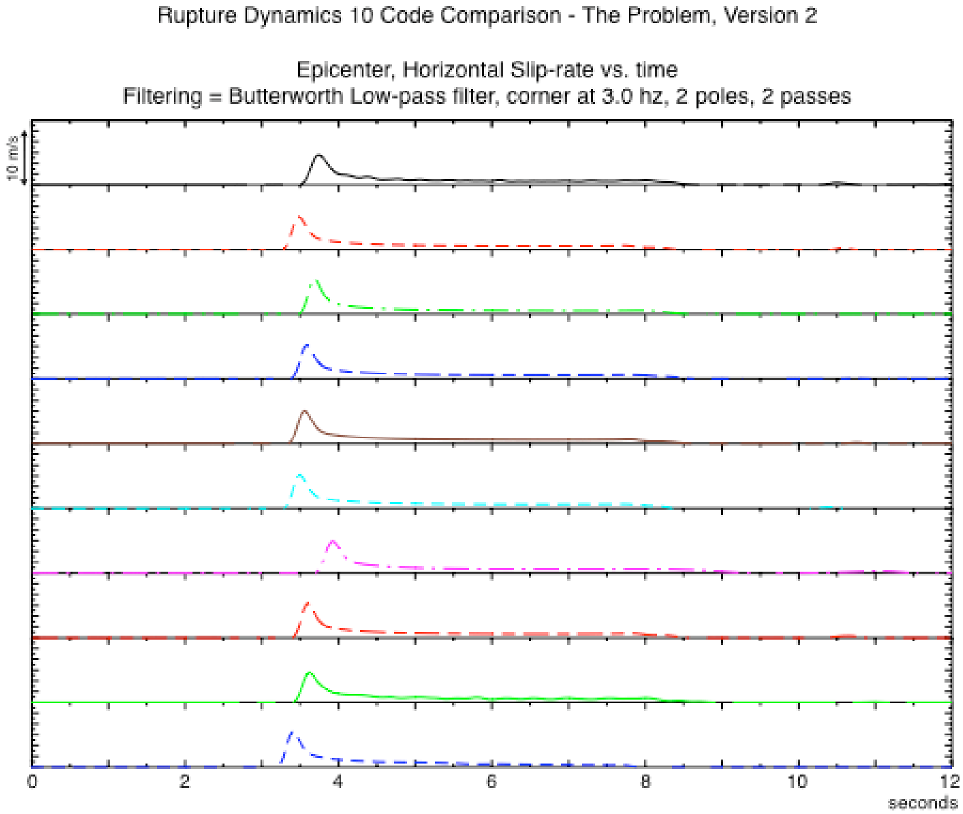
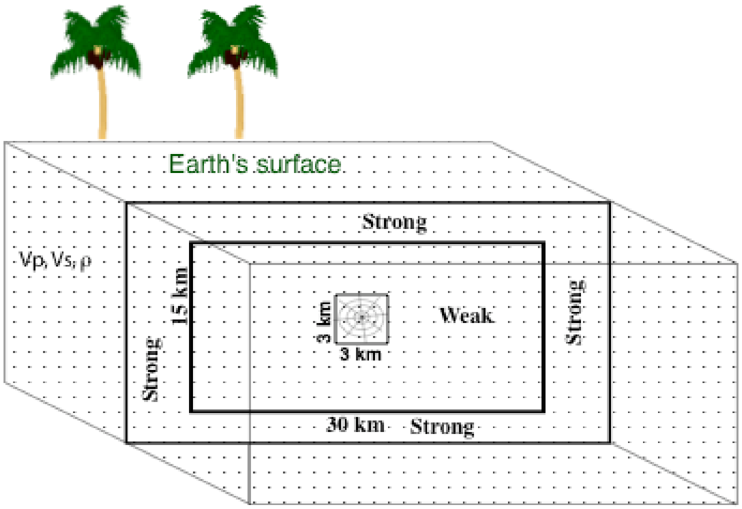


Figure 2a showing setting of The Problem, Version 3 (TPV3), the case of rupture on a vertical strike-slip fault in a homogeneous fullspace (top) and the locations of the stations for the synthetic seismograms (bottom).



10 Stations

0, 4.5, 7.5, and 12.0 km along-strike from the top center, 1.5 km down-dip from the top of the fault,
0, 4.5, 7.5, and 12.0 km along-strike from the top center, 7.5 km down-dip from the top of the fault,
0 km along-strike from the top center, 12.0 km down-dip from the top of the fault,
0 km along-strike from the top center, 13.5 km down-dip from the top of the fault

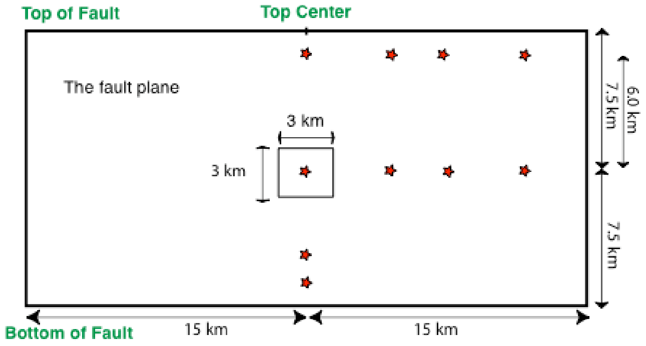
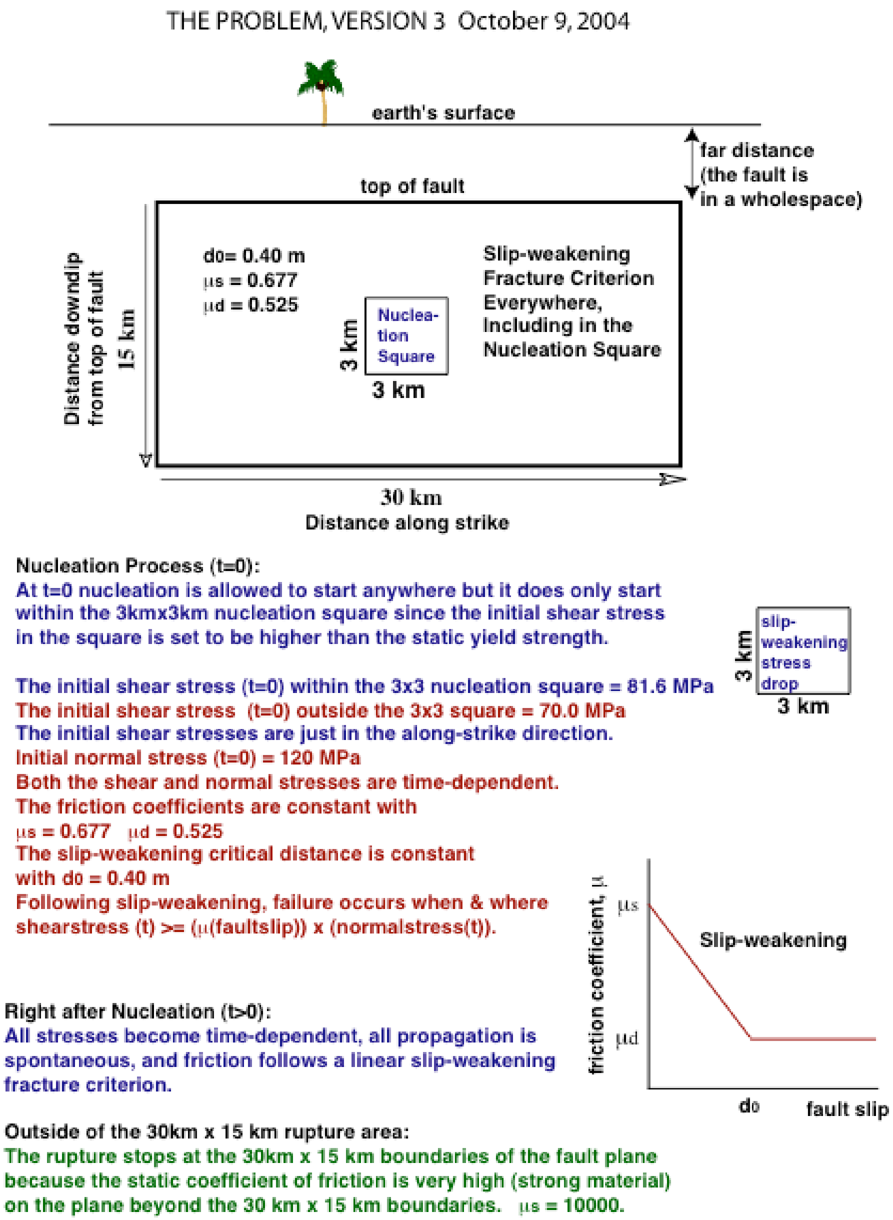


Figure 2b showing physics for The Problem, Version 3 (TPV3)



Nucleation Process (t=0):

At t=0 nucleation is allowed to start anywhere but it does only start within the 3kmx3km nucleation square since the initial shear stress in the square is set to be higher than the static yield strength.

The initial shear stress (t=0) within the 3x3 nucleation square = 81.6 MPa
The initial shear stress (t=0) outside the 3x3 square = 70.0 MPa
The initial shear stresses are just in the along-strike direction.
Initial normal stress (t=0) = 120 MPa
Both the shear and normal stresses are time-dependent.
The friction coefficients are constant with
μs = 0.677 μd = 0.525
The slip-weakening critical distance is constant
with d0 = 0.40 m
Following slip-weakening, failure occurs when & where
shearstress (t) >= (μ(faultslip)) x (normalstress(t)).

Right after Nucleation (t>0):

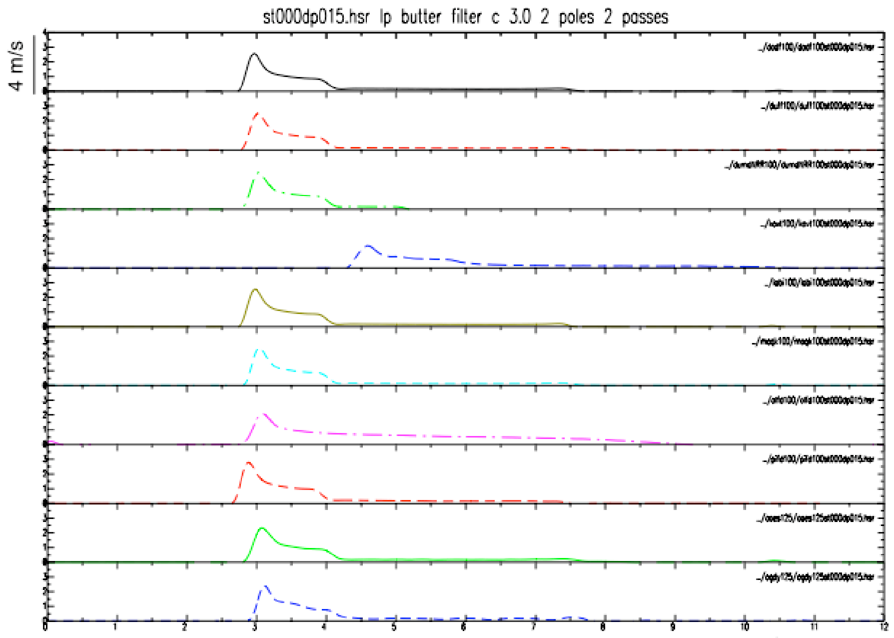
All stresses become time-dependent, all propagation is spontaneous, and friction follows a linear slip-weakening fracture criterion.

Outside of the 30km x 15 km rupture area:

The rupture stops at the 30km x 15 km boundaries of the fault plane because the static coefficient of friction is very high (strong material) on the plane beyond the 30 km x 15 km boundaries. μs = 10000.

Figure 2c showing some results from The Problem, Version 3 (TPV3) at 1 station.

Synthetic seismogram (relative horizontal velocity vs. time) Results from10 codes and The Problem, Version 3
The station is 6 km above the Hypocenter



Codes used 100 m (top 8) or 125 m (bottom 2) node-spacing/element-size

Table 1 showing the number of simulations done for The Problem, Version 3. Each calculation listed below was done for all of the stations depicted in Figure 2a.

The Problem, Version 3 Simulations (Oct. – Nov. 2004)

Code Abbreviation	Code User	Element/Node Spacing (m)	Code Description
labi	Lapusta/Liu	100	Lapusta Spectral Bounday Integral
		250	
		300	
maqk	Ma	100	Ma Finite Element
		250	
		300	
kavt	Kase	100	Kase Finite Difference
		250	
		300	
dadf	Dalguer	100	Day Finite Difference
		250	
		300	
duff	Dunham	100	Favreau Finite Difference No Rake Rotation
		150	
		300	
dumdNRR	Dunham	100	Dunham Spectral Bounday Integral No Rake Rotation
		150	
		300	
pifd	Pitarka	100	Pitarka Finite Difference Finite Fault Zone Width
		250	
		300	
olfd	Olsen	50	Olsen Finite Difference Finite Fault Zone Width
		100	
ogdy	Oglesby	125	Oglesby Finite Element
		167	
		250	
		300	
aaes	Aagaard	125	Aagaard Finite Element
		250	
		300	
lude	Dalguer	250	Dalguer Discrete Element Finite Fault Zone Width
		300	
dumdRR	Dunham	300	Dunham Spectral Bounday Integral Rake Rotation