November 12, 2003

2003 Workshop Report submitted by Ruth Harris and Ralph Archuleta.

The SCEC Workshop **Numerical Simulations of Rupture Dynamics: Validation of the 3D Method** was held at USC on Monday November 10, 2003.

Co-conveners were Ruth Harris and Ralph Archuleta.

The purpose of the workshop was to bring together the SCEC spontaneous rupture community and compare the results generated by the computer programs that are currently being used to tackle earthquake rupture dynamics problems.

Attendance: 30 members of the SCEC Community attended and participated in the workshop that had 9 invited speakers. Included in the attendance, and among the speakers were SCEC scientists whose level of expertise on the topic ranged from very senior experts with decades of experience on the topic to graduate students with 1 or 2 years of rupture modeling experience. We also had attendance from the FARM community, from the Ground Motions Focus Group, from the SCEC ITR project, and from the Implementation Interface.

We started the code validation/comparison effort by casting as wide a net as possible to SCEC-affiliated scientists working in rupture dynamics. We sent out a problem (The Problem) for interested parties to tackle and gave those who chose to commit themselves to the effort 3 weeks to complete the exercise.

As in all of these types of validation exercises, we had a fairly continuous stream of communication while the researchers were performing the calculations, and the final communication about The Problem occurred just 3 days before the workshop.

At the end of this report are 7 attached documents. These documents show the original invitation to participate, the description of The Problem, and a series of Questions and Answers about The Problem. These documents are also available as pdf files on the SCEC website, http://epicenter.usc.edu/rdm, set up by SCEC IT specialist Phil Maechling.

At the workshop itself, we had the 9 SCEC modelers each spend 20-30 minutes explaining their codes to the audience and providing their results to The Problem. This was quite worthwhile since everyone was able to learn more about the individual methods.

At the workshop, following the individual presentations, we showed a comparison of a representative portion of the results from the computer simulations. Figures showing some of these results are also appended. The conclusion was that although there were some similarities in the results to The Problem, there were also considerable differences that need to be understood. Therefore, based on the success of the 2003 workshop, and the clear need for continued work to arrive at convergence among the simulations, we will be proposing follow-up work. This will involve a 2004 workshop proposal to fund the 2004 workshop itself, and a collaborative 2004 proposal to fund at least a fraction of the 2004 PI/student modeler salaries.

The schedule for the Nov. 10, 2003 workshop:

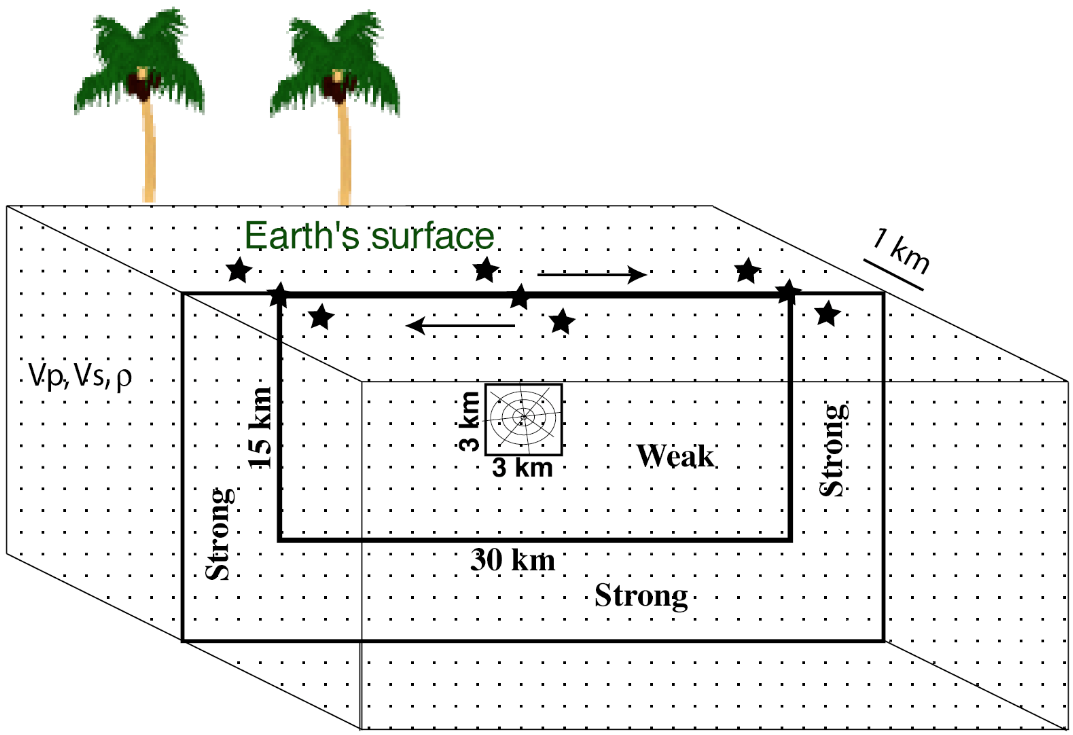
SCEC Workshop
Numerical Simulations of Rupture Dynamics: Validation of the 3D Method
November 10, 2003 in the SCEC Conference Room at USC

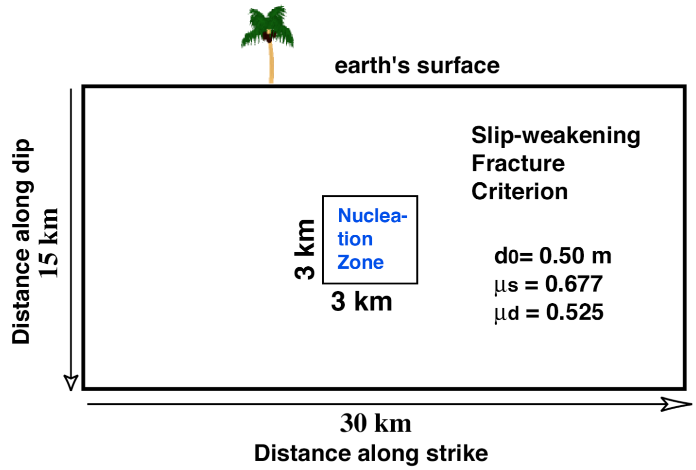
8:30-9:30	Coffee and muffins, etc.
9:30	Workshop Introduction (Ruth Harris/ Ralph Archuleta)
9:40-12:00	Presentations explaining the codes (15-20 minutes each)
9:40	David Oglesby
10:00	Shuo Ma
10:20	Jean Paul Ampuero
10:40	Brad Aagaard
11:00	Arben Pitarka
11:20	Kim Olsen
11:40	Geoff Ely/ Steve Day
12:00 -1:00	Lunch
1:00-1:40	Presentations explaining the codes (15-20 minutes each)
1:00	Eric Dunham/ Morgan Page
1:20	Joe Andrews
1:40-3:00	Comparison of Results using the range of codes (Ralph/Ruth)
3:00-3:30	Coffee/Snack Break
3:30-5:00	Discussion and plans for SCEC 2004
5:00	End

Attendees of the Nov. 10, 2003 SCEC workshop
(Co-conveners Ruth Harris and Ralph Archuleta)

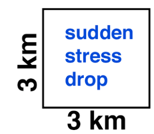
Brad Aagaard	USGS	baagaard@usgs.gov
Jean Paul Ampuero	Princeton	jampuero@princeton.edu
Joe Andrews	USGS	jandrews@usgs.gov
Ralph Archuleta	UCSB	Ralph@crustal.ucsb.edu
Nick Beeler	USGS	nbeeler@usgs.gov
Harsha Bhat	Harvard	bhat@esag.harvard.edu
Will Dalrymple	UCR	wmdal@yahoo.com
Steve Day	SDSU	day@moho.sdsu.edu
Benchun Duan	UCR	benchun@namazu.ucr.edu
Eric Dunham	UCSB	edunham@physics.ucsb.edu
Geoff Ely	UCSD	gely@ucsd.edu
Marcio Faerman	UCSD	mfaerman@sdsc.edu
Bill Foxall	LLNL	bfoxall@llnl.gov
Ruth Harris	USGS	harris@usgs.gov
Larry Hutchings	LLNL	hutchings2@llnl.gov
Nadia Lapusta	Caltech	lapusta@its.caltech.edu
Daniel Lavallee	UCSB	daniel@crustal.ucsb.edu
Pengcheng Liu	UCSB	pcliu@crustal.ucsb.edu
Shuo Ma	UCSB	sma@crustal.ucsb.edu
Phil Maechling	USC	maechlin@usc.edu
David Oglesby	UCR	doglesby@namazu.ucr.edu
Kim Olsen	UCSB	kbolsen@crustal.ucsb.edu
Morgan Page	UCSB	pagem@physics.ucsb.edu
Arben Pitarka	URS	arben_pitarka@urscorp.com
Paul Somerville	URS	Paul_Somerville@URSCorp.com
Seok Goo Song	Stanford	seisgoo@pangea.Stanford.edu
Julie Trotta	Brown	Julie_Trotta@brown.edu
Terry Tullis	Brown	Terry_Tullis@Brown.edu
Michael Vredevoogd	UCR	mikev@namazu.ucr.edu
Yuehua Zeng	UNR	zeng@seismo.unr.edu

A brief discussion of The Problem: Rupture was nucleated in the middle of a 30-km long right-lateral vertical strike-slip fault that extended from the earth's surface down to 15-km depth. The nucleation was a sudden stress drop in a 3-km x 3-km patch. The rest of the rupture occurred spontaneously, following a slip-weakening fracture criterion. The rupture stopped at the ends and bottom of the fault due to a strength barrier.





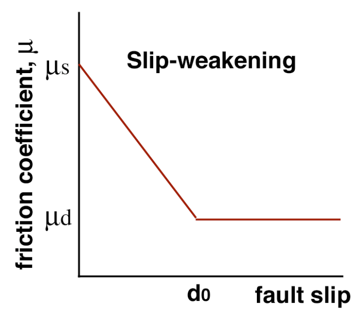
Nucleation Process:
At t=0, a sudden stress drop occurs over the entire 3 km x 3 km zone.
This stress drop is from the static yield strength of 81.24 MPa down to the dynamic friction stress of 63.00 MPa, for a total stress drop of 18.24 MPa.



Outside of the nucleation zone, the rupture is allowed to propagate spontaneously and friction follows a linear slip-weakening law.

Initial shear stress (t=0) = 70 MPa
Initial normal stress (t=0) = 120 MPa
Both the shear and normal stresses are time-dependent.
The friction coefficients are constant with
μ_s = 0.677 μ_d = 0.525
The slip-weakening critical distance, d_0, is constant with d_0 = 0.50 m

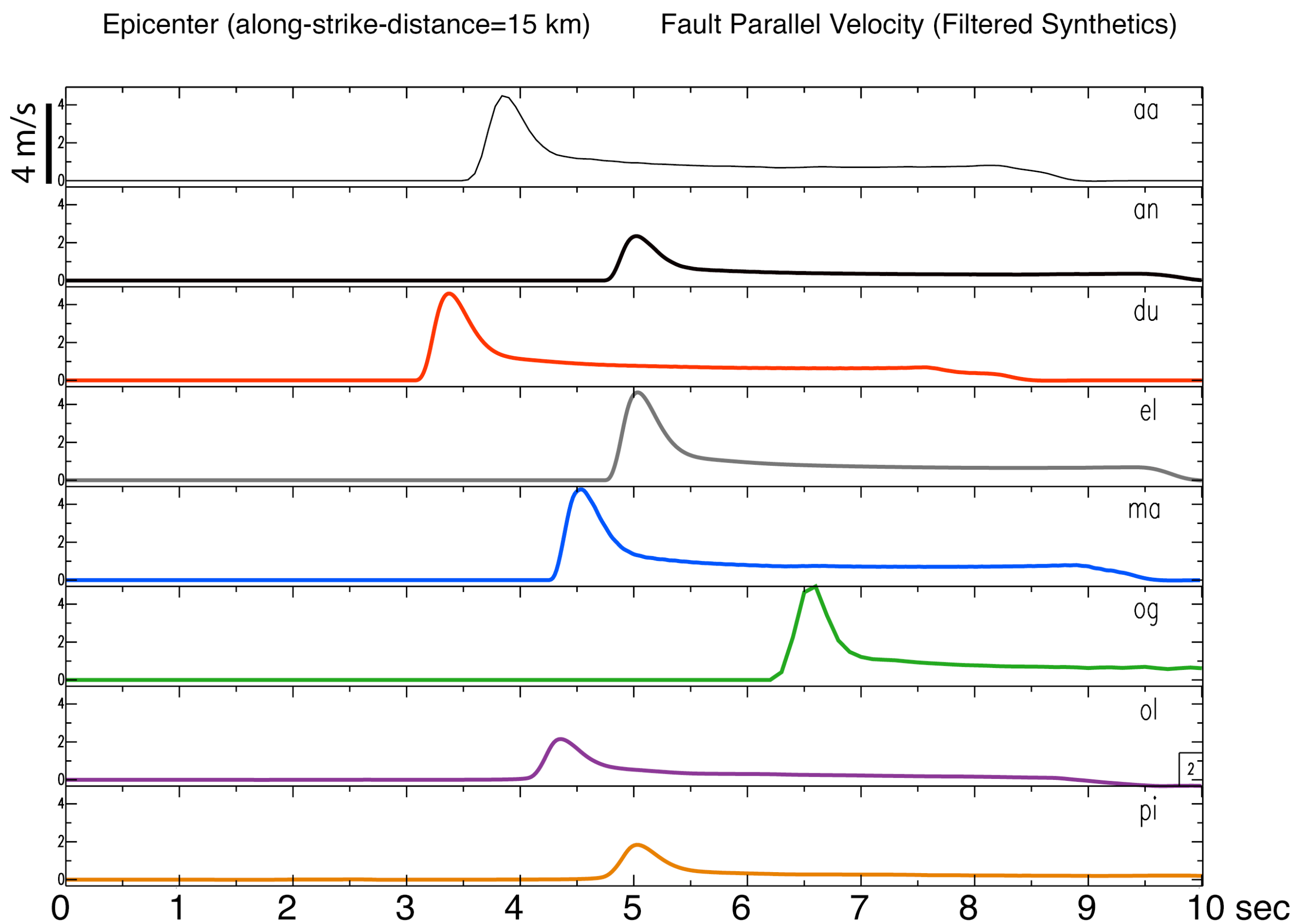
Following slip-weakening, failure occurs when & where shearstress (t) >= (μ(faultslip)) x (normalstress(t)).



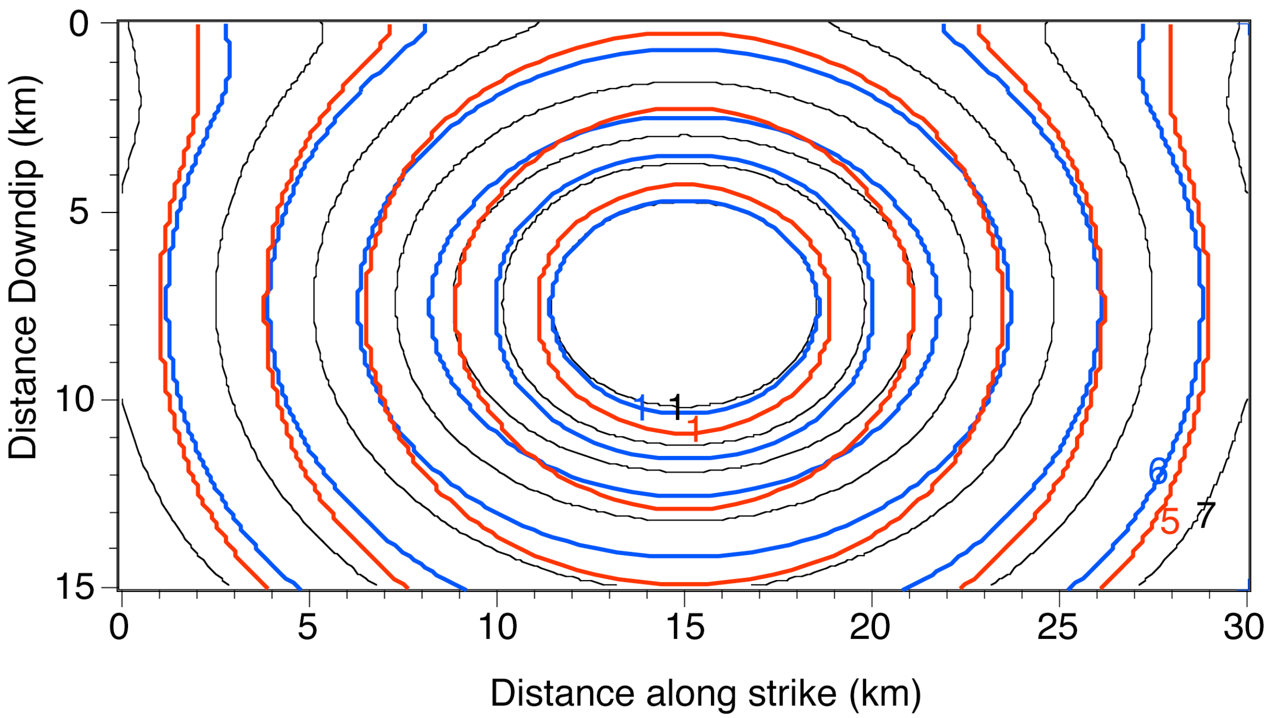
Outside of the 30km x 15 km rupture area,
the rupture stops at the 30km x 15 km boundaries of the fault plane because the static coefficient of friction is very high (strong material) on the plane beyond the 30 km x 15 km boundaries. μ_s = 10000.

Synthetic seismogram comparison (fault-parallel velocity) for The Problem, at the epicenter. Each colored seismogram was produced by a different computer program used to simulate rupture dynamics. The 2 letter labels identify the modeler/program.

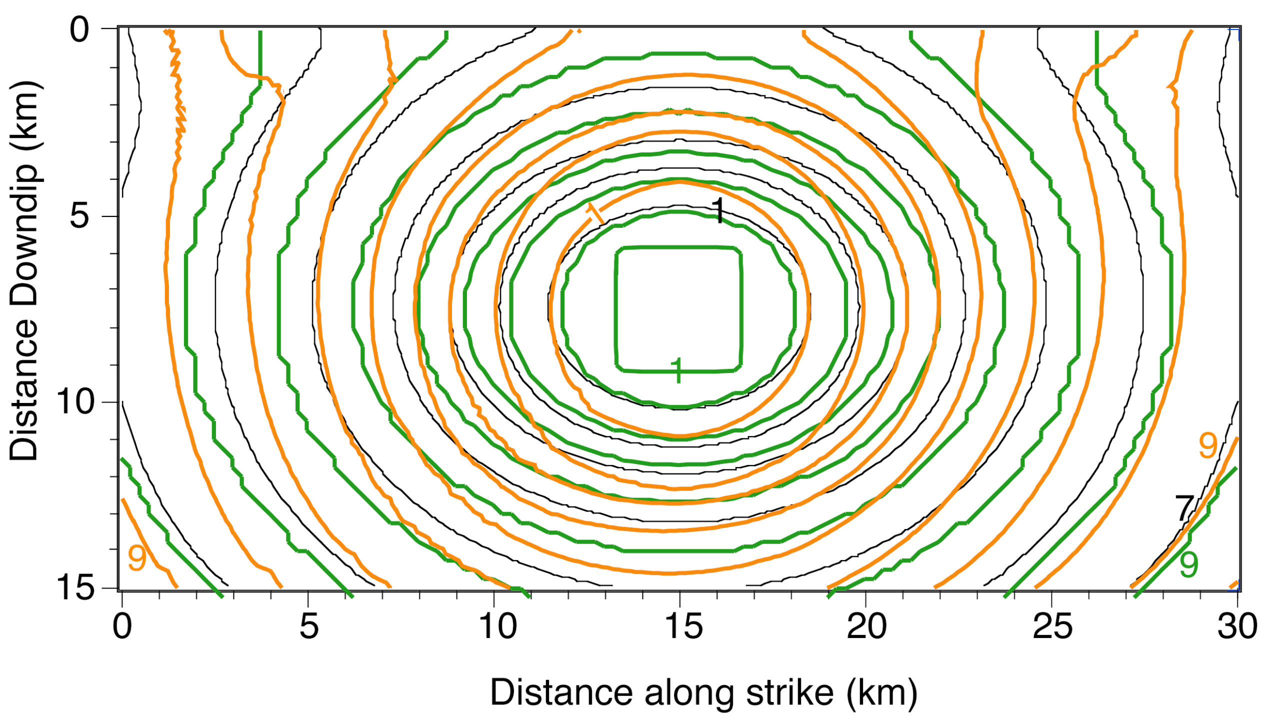
The seismograms are low-pass butterworth filtered with a corner at 1.5 Hz, 2 poles, 2 passes.



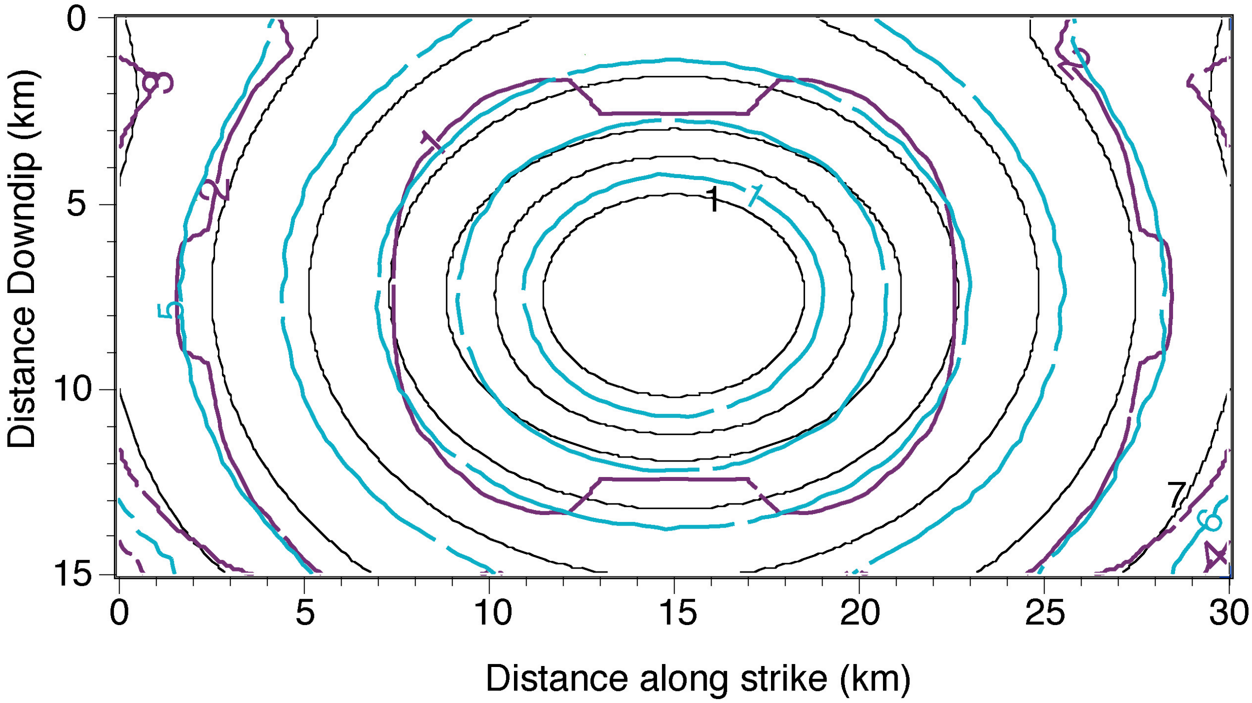
4 figures of Rupture Front time comparisons (2-3 methods/figure). The rupture front is shown at the time (contoured in seconds) that it first reaches 1 mm/second.



Black=An; Red=Du; Blue=Ma



Black=An; Green=Og: Orange=Pi



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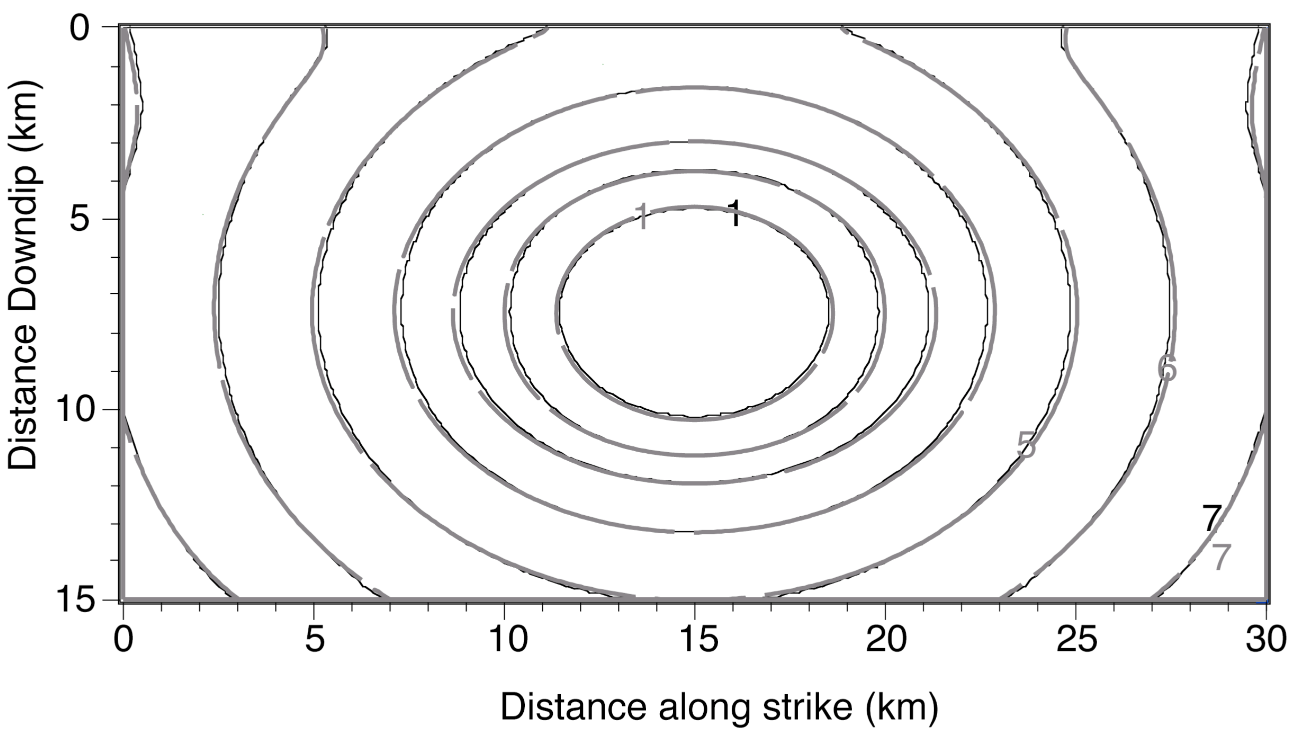


Black=An; Gray=El

7 communications (also available on the SCEC website http://epicenter.usc.edu/rdm/):

1) The original invitation to participate, describing The Problem
2) 1 page showing figure 1
3) 1 page showing figure 2
4) 1 page showing figure 3
5) Questions and Answers for October 2, 2003
6) Questions and Answers for October 8, 2003
7) Questions and Answers for October 17, 2003

October 1, 2003

Dear SCEC Spontaneous Rupture Modeler,

You are invited to participate in the SCEC workshop *"Numerical Simulations of Rupture Dynamics: Validation of the 3D Method"* to be held on **Monday November 10, 2003**.

This is a 1-day workshop that will run from 9:30 a.m. to 5:00 p.m.

Please RSVP as soon as possible to both harris@usgs.gov and mcraney@usc.edu to let us know if you will be participating in this workshop.

If you are traveling from a considerable distance and need to spend the night before (or after) in a hotel, or need other travel assistance, please contact John McRaney (mcraney@usc.edu) to make arrangements as soon as possible. This meeting will be held either at a hotel near LAX, or at USC. We will update you soon as to the exact location.

The objective of this workshop is to compare our methods of three-dimensional spontaneous rupture calculations. We welcome users and developers of 3-d finite-element, finite-difference, boundary integral/element, spectral element, and hybrid approaches.

We are starting our endeavor with a simply defined problem and will continue to more complex scenarios in future workshops.

For this workshop presenters will be providing explanations of their methodologies to the rest of the group, which will be eager to learn about each particular approach. A few members of the audience will likely be non dynamic-rupture modelers, so if presenters could tailor their presentations to include the critical details for the specialists, while still making the description understandable to the non-specialists, this would be very helpful. We will also be working with Phil Maechling, SCEC IT specialist, to make this effort as user friendly as possible.

> **Presenters will also be expected to provide to Ruth, 2 weeks before the workshop, by October 27, 2003, the results of their simulation efforts. These results will then be presented at the meeting.**

Part I. THE MODEL DESCRIPTION

Please note that this is **THE 3D** model that we are investigating. Although variations are of course interesting, our goal is to follow the description precisely.

Please feel free to point out to Ruth & Ralph (harris@usgs.gov, ralph@crustal.ucsb.edu), as soon as possible, if we have omitted some critical details that you and others may need to run the simulations, or if there are any mistakes in our descriptions/requests. This is just one perk of the collaboratory approach (!).

Note: All units are in MKS.

1) Material properties are homogeneous throughout the medium and set to:
   vp=6000. m/s
   vs=3464. m/s
   density=2670. kg/m3

2) The fault within the three-dimensional medium is a vertical right-lateral strike-slip planar fault that reaches up to the earth's surface.

3) The rupture is allowed within a rectangular area that is 30000 m long x 15000 m deep.

4) The bottom boundary of the allowed 30000m x 15000m rupture area is defined by a strength barrier*.

5) The right and left ends of the allowed 30000 m x 15000 m rupture area are defined by a strength barrier*.

6) The nucleation point is centered both along-dip and along-strike of the 30000m x 15000m rupture area, on the fault plane, at 15000m along-strike and 7500m depth.

7) Nucleation occurs by having an instantaneous stress drop, from the static yield stress down to the dynamic friction stress. This occurs at time = 0 seconds. This occurs over a square area (patch) on the fault plane. The square patch has a side-length of 3000m. The square nucleation patch is centered on the nucleation point. The initial shear stress in this square area is equal to the static yield stress; both are 81.24 MPa.

Within the entire 3000 m x 3000 m nucleation patch, at zero seconds:

Static coefficient of friction = 0.677
Dynamic coefficient of friction = 0.525
Initial shear stress in the along-strike-direction (at t = 0) = 81.24 MPa
Initial shear stress in the along-dip direction (at t = 0) = 0 MPa
Initial normal stress (at t = 0) = 120 MPa
Initial static yield stress (at t = 0) = 0.677 x 120 MPa = 81.24 MPa
Initial dynamic friction stress (at t = 0) = 0.525 x 120 MPa = 63.00 MPa
Initial stress drop (at t = 0) = 81.24 MPa – (0.525 x 120 MPa) = 18.24 MPa

8) Friction on the fault plane outside of the 3000 m x 3000 m nucleation patch is governed by the linear slip-weakening fracture criterion.

Within the 30000 m x 15000 m faulting area, but outside of the 3000 m x 3000 m nucleation patch:

Static coefficient of friction = μ_s = 0.677
Dynamic coefficient of friction = μ_d = 0.525
Initial shear stress in the along-strike-direction (at t = 0) = 70 MPa
Initial shear stress in the along-dip-direction (at t = 0) = 0 MPa
Initial normal stress (at t = 0) = 120 MPa
Initial static yield stress (at t = 0) = 0.677 x 120 MPa = 81.24 MPa
Initial dynamic friction stress (at t = 0) = 0.525 x 120 MPa = 63.00 MPa
Initial stress drop (at t = 0) = 70 MPa – (0.525 x 120 MPa) = 7.00 MPa
Slip-weakening critical distance = d_0 = 0.10 m

9) *On the fault plane, but outside of the 30000 m x 15000 m faulting area, there is a strength barrier.
This is accomplished by setting the static coefficient of friction to the high value of 10000. so that the rupture is not able to propagate on the fault plane beyond 30000 m x 15000 m:

Static coefficient of friction = μ_s = 10000.
Dynamic coefficient of friction = μ_d = 0.525
Initial shear stress in the along-strike direction (at t = 0) = 70 MPa
Initial shear stress in the along-dip direction (at t = 0) = 0 MPa
Initial normal stress (at t = 0) = 120 MPa
Slip-weakening critical distance = d_0 = 0.10 m

10) Some definitions:

<u>Displacement</u> = motion relative to its initial position. Since all of the calculations start with this position at zero, Displacement = Absolute motion.

<u>Velocity</u> = Absolute motion with respect to time.

<u>Slip</u> = Relative motion across the fault plane (e.g., for split nodes).

<u>Slip-Rate</u> = Relative motion across the fault plane (e.g., for split nodes), with respect to time.

<u>Rupture Front</u> = Location of the leading edge of the rupture. Here we define this region as where (and when) slip-rate first changes from zero to greater than 1 mm/s.

Part II. **RESULTS TO PROVIDE FOR THE WORKSHOP**

(Please send results to Ruth on or before Oct. 27, 2003)

Note 1.

ALL PLOTS ARE TO USE THE FOLLOWING SCALE TO ALLOW FOR EASY COMPARISONS.

1 km = 0.25 inches
1 m/s = 0.5 inch
1 m = 1 inch
1 second = 0.5 inches

Note 2.

Please provide contour plots in Adobe Illustrator format. If this is not possible, then encapsulated postscript format is o.k.

> **Time series should be provided in ascii format, one time series point per line. The first two lines of each file should give header information that describes the ascii file's contents.**
> **The first header line should give a short description. For example,**
> **v (m/s) at depth=0km, 30km along-strike, 0.5 km from fault, on left-moving block.**
> **The second line gives the total number of points, and the sample rate in seconds (dt).**

Please also create time-series plots, in Adobe Illustrator format. If this is not possible, then encapsulated postscript format is o.k.

Note 3.

Computations should be run FOR A MAXIMUM FREQUENCY OF 1.0 Hz.
Please provide the results in raw form (no filtering). Don't worry about oscillations.

Results to provide (on or before October 27, 2003):

1) The final (static) slip-distribution on the 30000m x 15000m fault plane, contoured in 1 meter intervals. Generate this contour plot for the single time, t, of 10 seconds after nucleation (nucleation occurs at t = 0 seconds), but please note if the fault is still slipping significantly after t = 10 seconds.

2) The final shear stress distribution on the 30000m x 15000m fault plane, contoured in 1 MPa intervals. Generate this contour plot for the single time of 10 seconds.

3) The final normal stress distribution on the 30000m x 15000m fault plane, contoured in 1 MPa intervals. Generate this contour plot for the single time of 10 seconds.

4) At these 9 points on the earth's surface (see Figure 1):

At the top left end, at the epicenter, and at the top right end of the 30000 m long fault (3 points total), These are along-strike distances of 0m, 15000m (epicenter), 30000m.

On 2 fictitious parallel faults that are 0.5 km (fault-perpendicular distance) from the main fault, 1 on the "right-moving" side of the right-lateral strike-slip fault, 1 on the "left-moving" side of the fault, at the same along-strike distances of 0m, 15000 m, 30000m. (6 points total)

a) The displacement (m) versus time (s)
   for time = 0-10 seconds after nucleation

b) The velocity (m/s) versus time (s)
   for time = 0-10 seconds after nucleation.

(*Note - For the fault plane itself (our first 3 points), we are really asking for slip (m) and slip-rate (m/s) as a function of time*)

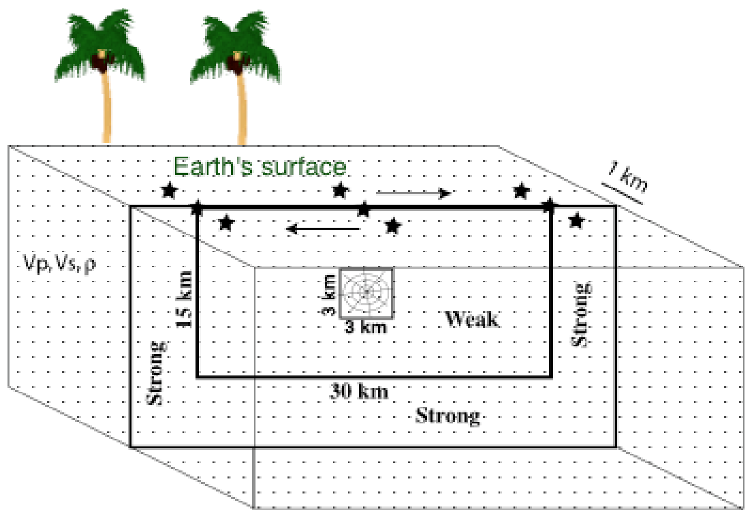
5) A plot of strike-parallel slip-rate (m/s) versus time (s),
for time = 0-10 seconds,
at the depths of 3 km and 12 km, at 2 km intervals along strike, from one end of the fault to the other (see Figure 2).

6) A 2D contour plot of the rupture front, as defined by the locations where (and when) fault slip-rate first changes from zero to greater than 1 mm/s, contoured at 1 second intervals.

We look forward to your participation in this effort!

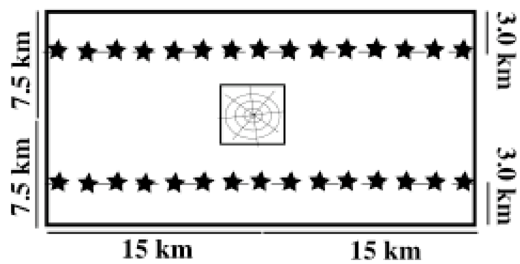
Sincerely,
Ruth Harris (harris@usgs.gov) and Ralph Archuleta (ralph@crustal.ucsb.edu)

FIGURE 1. THE MODEL AND LOCATIONS FOR EARTH'S SURFACE CALCULATIONS



★ denotes locations on the earth's surface for calculations of displacement(t), velocity(t):
Upper left end of fault, Epicenter, Upper right end of fault
Same distances along strike, but 0.5 km perpendicular to the fault plane,
on both sides of the fault

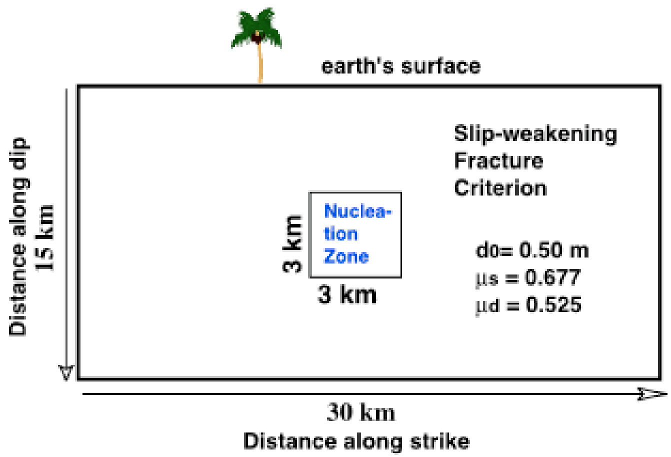
FIGURE 2.   LOCATIONS FOR ON-FAULT CALCULATIONS



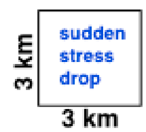
Plot the strike-parallel component of slip-rate on the fault plane at depths of 3 km and 12 km, in 2-km along-strike intervals from one end of the fault to the other.

Note added October 8, 2003:   These locations (stars) start 1-km along-strike-distance from the left & right edges of the 30-km-long rupture area, so that calculations are at along-strike distances of
1,3,5,7,9,11,13,15 (nucleation center's along-strike-distance),17,19,21,23,25,27,29 km.
The left edge of the 30-km-long fault rupture plane is at 0-km along-strike distance.

FIGURE 3. DETAILS OF THE FAULT PLANE AND FRICTION



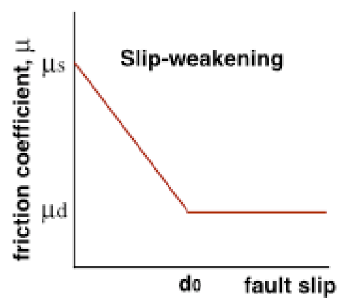
Nucleation Process:
At t=0, a sudden stress drop occurs over the entire 3 km x 3 km zone.
This stress drop is from the static yield strength of 81.24 MPa down to the dynamic friction stress of 63.00 MPa, for a total stress drop of 18.24 MPa.



Outside of the nucleation zone, the rupture is allowed to propagate spontaneously and friction follows a linear slip-weakening law.

Initial shear stress (t=0) = 70 MPa
Initial normal stress (t=0) = 120 MPa
Both the shear and normal stresses are time-dependent.
The friction coefficients are constant with
μ_s = 0.677 μ_d = 0.525
The slip-weakening critical distance, d_0, is constant with d_0 = 0.50 m
NOTE, as of Oct. 8, d_0 = 0.50 m

Following slip-weakening, failure occurs when & where shearstress (t) >= (μ(faultslip)) x (normalstress(t)).



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. μ_s = 10000.

Date: Thu, 2 Oct 2003 16:26:12 -0700
To:
From: Ruth A Harris <harris@usgs.gov>
Subject: Q&A - SCEC Spontaneous Rupture Workshop, PC pdf

Dear Colleague,

In case the first version of the RuthRalph letter introducing the SCEC Spontaneous Rupture code validation workshop did not come across well, here is an improved pdf version.

The figure attachments should be in your previous email, and hopefully these did come across o.k. Please let me know if you can't read any of the 3 attachments.

We hope that you can participate in this code exercise and look forward to hearing from you. Please send RSVP's to
harris@usgs.gov &
mcraney@usc.edu

Answers to Questions asked about THE Problem:
(Please feel free to ask more questions - they are very helpful)

Friction:

It is pure slip-weakening, so there is No healing. Friction stays at the dynamic level forever after...

Nucleation:

Yes, the nucleation process may be a bit sudden, but it is also an attempt at the same size nucleation area for all of the codes, and an examination of how the codes handle nucleation.

If the code you're using isn't happy with sudden nucleation, this is fine - all of the codes will eventually have difficulty dealing with some aspect of the problems that we will be tackling, this is just part of our learning process. In the near future we will also be implementing a smoother nucleation process. This will be THE 2nd Problem.

If the code that you're using absolutely cannot do THE Problem, with sudden nucleation, please write soon to harris@usgs.gov, and we will also send to everyone the nucleation process for THE 2nd Problem.

Thanks,
Ruth

Date: Wed, 8 Oct 2003 12:04:48 -0700
To:
Subject: SCEC Spontaneous Rupture, New Parameter, Q&A

Oct. 8, 2003

Hello Everyone,

If you would not like to receive anymore of these workshop/code validation workshop updates, please let me know and I will remove you from the email distribution list. Please inform me at harris@usgs.gov

If you would like to attend the workshop or participate in the code comparison exercise or both and have not yet RSVP'd to me & John McRaney, please do so now, by sending email to harris@usgs.gov and mcraney@usc.edu

If you are a modeler or workshop attendee or both and already have RSVP'd, thanks!

Officially RSVP'd attendees as of today:
Aagaard, Ampuero, Andrews, Archuleta, Beeler, Day, Duan, Dunham
Harris, Ma, Maechling, Oglesby, Page, Pitarka, Trotta, Tullis

****
You Have Questions, We Have Answers October 8, 2003
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Question 1:
Wouldn't it be better to have a bigger slip-weakening critical distance so that it can be resolved, even out to the end of the fault rupture plane, at 15 km?

Answer 1:
Yes, good idea. Although we don't plan on changing the rest of the variables, the slip-weakening critical distance is now 0.50 m.

NOTE- ONE FRICTION PARAMETER HAS BEEN CHANGED IN THE PROBLEM.
THE SLIP-WEAKENING CRITICAL DISTANCE IS NOW 0.50 METERS.

Question 2:
Where is the end of the slippable part of the fault plane? For those using nodes (finite-difference method), can the edges of the 30-km-long by 15-km-deep rupture plane also slip? Or are these edges the start of the locked (very strong) parts of the fault plane?

Answer 2:
In a finite-difference grid, the nodes that are 15-km along-strike from the hypocenter still have the rest of the rupture plane's friction values and therefore can slip. Just outside of this boundary the fault plane is locked (courtesy of high friction).

Question 3:
Where exactly should the time-series points on the fault plane be located, relative to the along-strike distance of the nucleation's center point? Do they start mid-strike and work outward, at 2-km-intervals along-strike, or do they start at the edges and

work inward, across the fault plane.

Answer 3:
The time-series points should start mid-strike and work outwards, in 2-km intervals along strike.
If the left edge of the fault rupture surface is at 0 km along-strike, the nucleation's center point is at 15 km along-strike, and the right edge of the rupture surface is at 30 km-along-strike, then the time series should be at
1,3,5,7,9,11,13,15,17,19,21,23,25,27,29 km distance-along-strike.

Question 4:
Were the dimensions (meters**3) of the entire 3D volume assigned for
The Problem?

Answer 4:
No, they weren't assigned. We leave the volume size at the discretion of each modeler. This is because different codes may have different methods for preventing waves reflected/refracted off of the outer boundaries of the model from returning to the regions of interest.

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More questions are very welcome! We all learn from them.

Please send questions to harris@usgs.gov and ralph@crustal.ucsb.edu

Sincerely,
Ruth

October 17, 2003

Dear SCEC spontaneous rupture modelers and other interested colleagues,

----
This week's You have Questions, We have Answers

Question:
I tried using the 50 cm slip-weakening critical distance and the rupture wouldn't propagate far beyond the nucleation patch. What happened?

Answer:
Please ensure that the nucleation area is the specified 3-km x 3-km area. If the nucleation area is smaller the rupture either won't propagate, or will take forever (i.e. >10 seconds) to do so.

Question:
What node spacing or element size should I use in my simulations?

Answer:
If possible, please use whatever spacing/size will enable resolution of the of the slip-weakening critical distance. This turns out to be a more stringent constraint than our originally posed '1 Hz' request.

For The Problem, which uses the 50 cm slip-weakening critical distance, a calculation by Joe Andrews shows that the slip-weakening critical distance can be resolved, even when the rupture is reaching the edge of the fault plane, if a node spacing (or element size) of <=150 m is used. His calculation produces a cohesion zone width of 344 m at 15000m propagation distance (assuming the 7 MPa stress drop), and he is assuming that resolution is achieved if the cohesive zone is 2-3 nodes wide. So it looks like 100-150 m element size/ node spacing is a target value, if it is doable.

Please feel free to ask more questions - we all learn from them.

Also, for the modelers, that deadline of Oct. 27 is quickly approaching, so it would be handy to discover the need for any additional info. (e.g., that we inadvertently forgot to provide) before then...

We look forward to seeing more of your questions/comments!

Thanks,
Ruth

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