October 11, 2005

This is the 2005 SCEC Progress Report for

3D Rupture Dynamics Code Validation 2005 SCEC Workshop

Co-Principal Investigators:
Ruth Harris (USGS) and **Ralph Archuleta (UCSB)**

This progress report is for the SCEC 3D Rupture Dynamics Code Validation workshop that was held on September 11, 2005 in Palm Springs, California.

The goal of the workshop was to compare and better understand the computer codes that are currently being used by SCEC scientists to simulate earthquake rupture dynamics. The results have significant ramifications for research findings in the SCEC science groups Earthquake Source Physics, Ground Motions, Fault Systems, Fault and Rock Mechanics, in the SCEC NGA project, and in the SCEC ITR projects Pathway3, TeraShake and Cybershake because all of these projects rely on the assumption that the numerical simulations are working correctly.

60 people, including SCEC students and junior and senior researchers attended the September SCEC code validation workshop. The list of attendees is Table 1.

Workshop speakers included the co-organizers introducing the workshop and presenting the comparisons, a SCEC graduate student presenting his new code, a SCEC PI showing a detailed inter-code comparison, and a SCEC PI introducing the new web interface that we hope to use in the future. There was also a SCEC/USGS PI presentation on formatting issues. The workshop schedule and list of presenters is Table 2.

In preparation for the September 2005 workshop, 13 SCEC researchers tackled our fourth and fifth benchmarks, The Problem, Version 4 (TPV4) and The Problem, Version 5 (TPV5). The definitions of these benchmarks and instructions to the modelers are attached as Appendix I.

The workshop modelers included 14 people (13 SCEC scientists, and 1 scientist from Japan) who used 14 different computer codes to numerically simulate earthquakes in the code-validation exercise. In some cases a modeler used more than one code and in some cases modelers worked as a team, using one code. Included among the modelers were SCEC students, postdocs, faculty, USGS researchers, and 2 researchers who originally started participating in code validation while at SCEC U.S. institutions last year but who are now working for free, outside of the U.S., a researcher at ETH, in Switzerland, and a researcher at AIST, in Japan. These 2 researchers sent their results in electronically, but were not able to attend the workshop. The ETH researcher is also working to bring our entire exercise to interested scientists in the EU. The list of modelers and their codes is Table 3.

The benchmarks tackled for the 2005 workshop were 3D simulations of spontaneous rupture propagation on a vertical strike-slip fault in a homogeneous medium, with heterogeneous initial stress conditions. We examined the case of rupture on the heterogeneously stressed fault, set in a wholespace (The Problem, Version 4, see Appendix I), and set in a halfspace (The Problem, Version 5, see Appendix I). The wholespace problem was done since it is rigorously simulated for Boundary Integral formulations and thereby allows for critical comparisons with the other codes. The halfspace problem was done since it includes the all-important earth's surface and allows for synthetic seismograms to be produced at the earth's surface.

Results:

At the workshop we learned that most of the computer programs produced similar results (rupture front times and synthetic seismograms) if the grid node spacing or element size was sufficiently small to resolve the friction breakdown distance. For TPV4 and TPV5, this required grid spacing on the order of 100 m for the 30 km long fault (with nucleation in the middle of the fault).

Figure 1a shows the station location for the synthetic seismogram comparisons in Figure 1b and 2. This station is not close to the nucleation region, and therefore is a challenging test since the rupture had to travel further than say to, the epicenter. (In other words, we could instead present synthetic seismograms for the station at the epicenter and the reader would be quite impressed, but instead we aim to challenge our simulation capabilities.)

Figure 1b shows comparisons using 100 m node spacing. The match among most of the codes is pretty good.

Figure 1c shows comparisons using 300 m node spacing. The match among most of the codes is not very good, as expected.

We found that much large element or node sizes on the order of 300 m led to comparisons that were not as satisfying (Figure 1c). Figure 1c's synthetic seismograms are from the same station (Figure 1a) as Figure 1b's synthetic seismograms, a station that is not close to the nucleation region, and therefore is a challenging test since the rupture had to travel farther than say to, the epicenter. Therefore we learn from this exercise that 100 m spacing was a more appropriate element size/node-spacing to resolve the friction parameters.

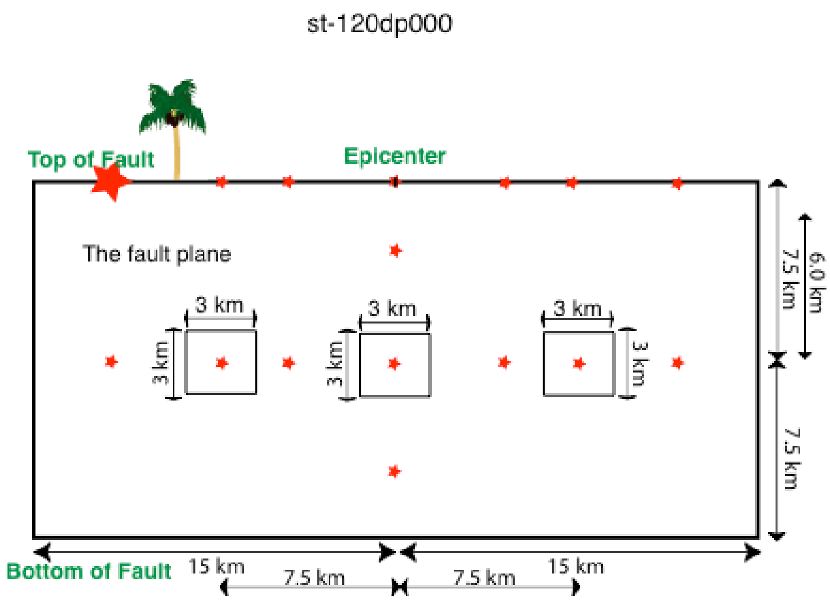

Figure 1a. Station location (large red star) for benchmark TPV5 used to simulate synthetic seismograms shown in Figure 1b and 1c. Small red stars indicate other stations the modelers also simulated seismograms for - those station's results were examined for the workshop, but aren't shown in this summary report.

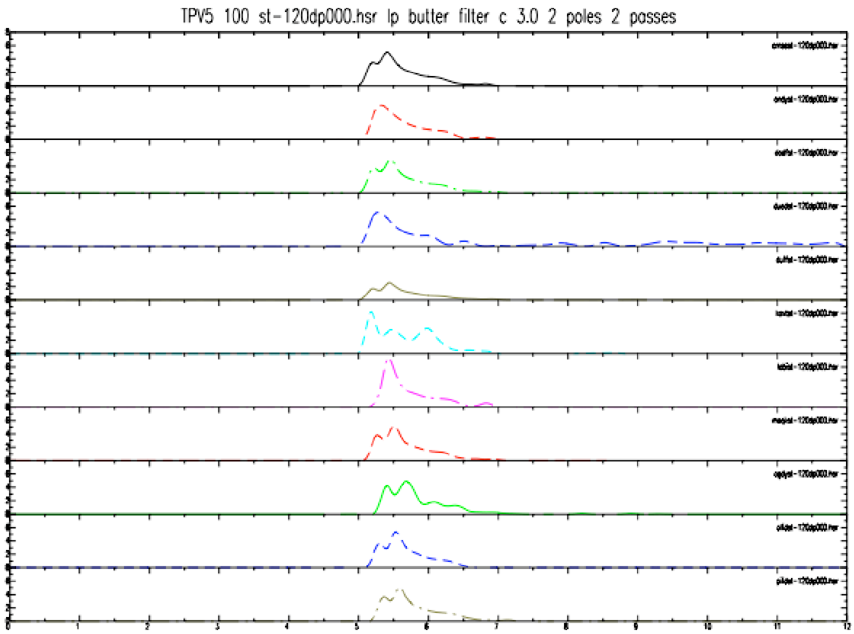

Figure 1b. Synthetic seismograms (horizontal slip-rates) for 100 m element size/node spacing (filtered seismograms). The synthetics match fairly well for many of the codes.

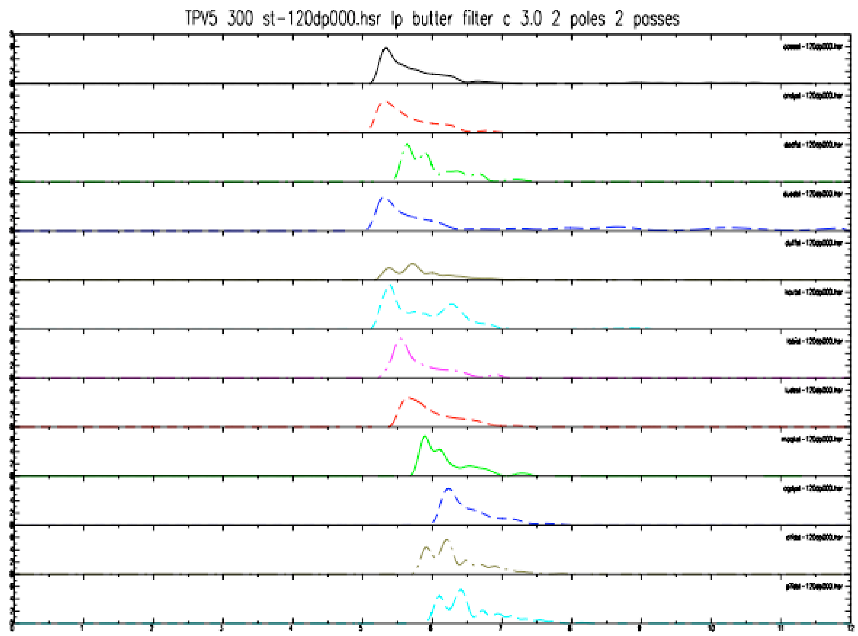

Figure 1c. Synthetic seismograms (horizontal slip-rates) for 300 m element size/node spacing (filtered seismograms). The synthetics do not match very well for many of the codes, indicating that the 300 m spacing was not adequate to resolve the friction's breakdown zone. Figure 1b, with the finer grid spacing of 100 m produces synthetic seismograms that match much better. This is a lesson in how we choose a grid spacing that resolves the assumed friction parameters (and shows that for this benchmark we needed to choose a grid spacing smaller than 300 m).

At the workshop we learned that a few codes still are not quite matching the results of the others, for either of the assigned node spacing/element sizes. This has been an important lesson at each workshop to date - each workshop has been an opportunity for the modelers to either abandon codes that do not appear as promising as others, in favor of codes that are matching well, or if possible an opportunity for the modelers to learn how to fix the codes that do not match very well.

Most of the codes in the spontaneous rupture exercise use a 'split-node' formulation for the fault plane, but a few do not. A past lesson (e.g., Dalguer, L.A. and S.M. Day, EOS, 2004) has been that the offset grid codes using a 'fat fault' approximation do not match either the rupture front times or the synthetic seismograms of the codes that use co-located 'split-nodes' for the fault plane.

Although this might be thought of as different views of fault mechanics, i.e. that faults are fat vs. skinny, instead this is a numerical issue, resulting purely from the computational methodology rather than resulting from a physical basis. Since the assumed physics is the same, the results produced by the 'fat fault' and 'split-node fault' formulations should be the same. But instead the results differ.

To address this problem, a new methodology that uses a 'stress glut' has recently been adopted in the SCEC codes that formerly used the 'fat fault' approximation. A comparison of the 'fat fault', 'stress glut' and 'split node' methods is shown in Figure 2 (figure courtesy of Steve Day and Luis Dalguer). It is seen that the 'stress glut' method is an improvement over the 'fat fault' method, however, the 'stress glut' method is still not performing ideally.

Since the split-node formulation has already favorably compared with the analytically rigorous boundary integral method [Day, Dalguer, Lapusta, Liu, JGR, accepted], the differences between the fat-fault or stress-glut methods and the split-node methods indicate

1) 'Fat fault' codes are unlikely to be satisfactory for SCEC spontaneous rupture simulations, including Terashake, Pathway 3, and NGA simulations, and

2) it is likely that the 'stress glut' codes also need further improvement.

In the future, a different fault formulation may be required in these offset grid dynamic rupture codes.

<u>Post Workshop Update November 14, 2005</u>
A fix has been found for the former 'stress glut' vs. 'thick fault' vs 'split node' problem in the offset grid codes. This is a SCEC Code Collaboration Success Story. Without our code comparison effort the dissimilarities among the methods might not have been noticed, or, fixed.

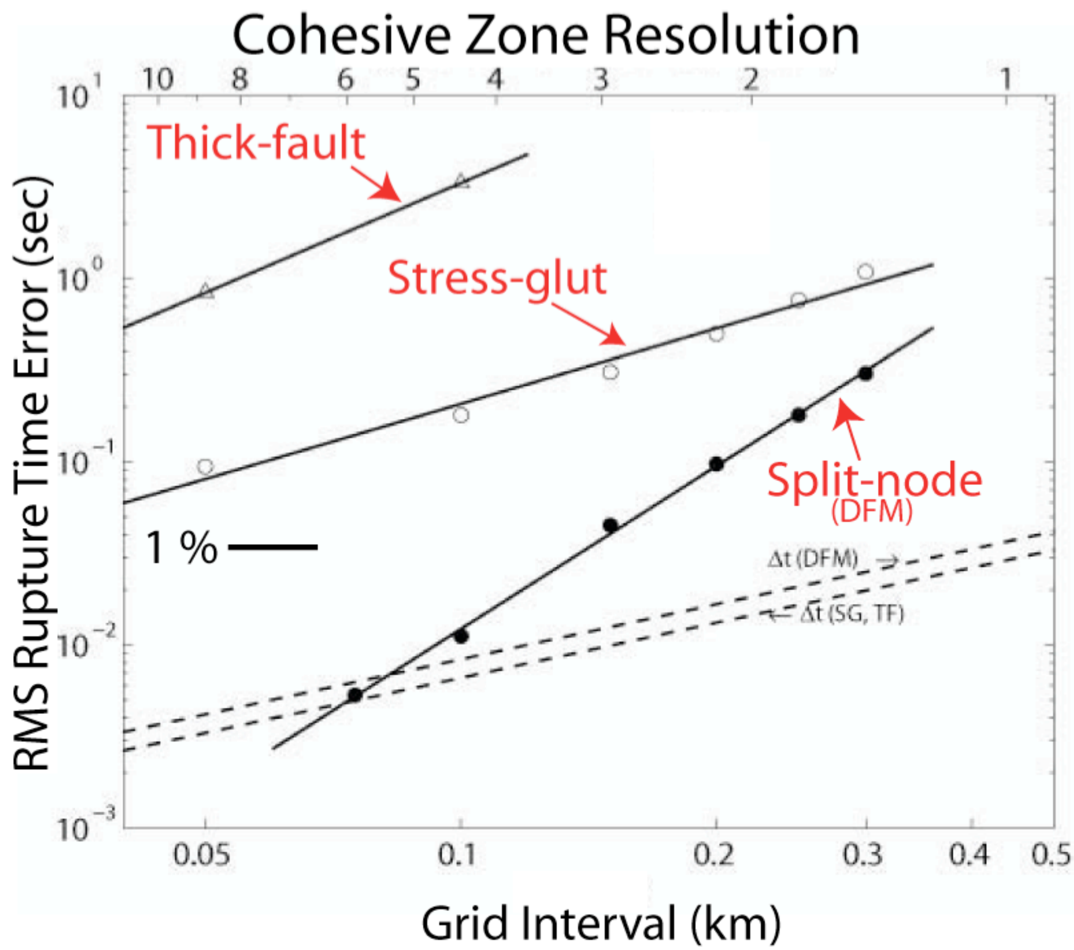

Figure 2. Comparison between computer codes that use the offset grid 'fat fault' method, the 'stress-glut' method and the more common 'split-node' method for the fault plane. The test uses a Code Validation benchmark and shows that neither the fat fault nor the stress-glut method approach the resolution limit of the time-step, delta-t. The split-node method does approach this limit, between a grid interval (i.e. finite-difference code node-spacing) of 100 m and 50 m. Therefore, even if offset grid codes use either the fat fault or stress glut method with finer node spacing, the friction breakdown process still may not be resolved adequately. The end result is simulated ruptures that propagate differently from those simulated by split-node or boundary integral methods.
Figure courtesy of Steve Day and Luis Dalguer.

To date the workshops have tackled problems that are vertical faults set in a homogeneous medium. The added complexity for this September 11, 2005 workshop was to examine the effects of multiple stress inhomogeneity on the fault plane. The assigned problems to date of a vertical fault set in a homogeneous off-fault medium has been so that all of the codes can do the benchmark problems, which they won't be able to as soon as we move on to dipping faults or material/stress inhomogeneities off-fault. However, in the very near future, i.e. for the next workshop, we do plan to add material complexity to the benchmark. We are aiming in this direction since this information is needed to address the repeatability and accuracy of TeraShake and Pathway3 simulations that use spontaneous rupture propagation set in the 'real' Southern California community velocity model.

The workshops serve a key function, to gather SCEC researchers who either already use a spontaneous rupture code for their research or who want to understand the process of rupture dynamics simulations, and to allow for a constructive critical dialogue among the researchers on this specific topic. The workshops serve as a venue for code comparison and thereby improvement of the methodology. In addition to the workshops, in 2004 and 2005 SCEC has also funded a few of the code developers to improve their methodology. One of these SCEC codes is going forward as the ultimate choice for TeraShake simulations, a finite-element code that will be fully documented by its developer. Each (working) code in the SCEC comparison/validation exercise has its own advantages and pitfalls. The type of scientific problem to be solved determines the most efficient type of computer code to use. For example, earthquake simulations on complicated fault geometry set in a complicated mountainous velocity structure/density structure requires a finite-element code. Efficient computations of simpler fault geometry are most easily accomplished with a finite-difference code. Multi-cycle simulations with complex friction formulations are most efficiently achieved with a boundary integral code.

References:

Dalguer, L.A. and S.M. Day (2004), Split Nodes and Fault Zone Models for Dynamic Rupture Simulation, *Eos Trans. AGU, 85*(47), Fall Meet. Suppl., Abstract S41A-0944.

Day, S. M., L. A. Dalguer, N. Lapusta, and Y. Liu, (2005). Comparison of finite difference and boundary integral solutions to three-dimensional spontaneous rupture, *Journal of Geophysical Research*, accepted.

2005 SCEC Publication directly related to this SCEC collaborative exercise:

Day, S. M., L. A. Dalguer, N. Lapusta, and Y. Liu, (2005). Comparison of finite difference and boundary integral solutions to three-dimensional spontaneous rupture, submitted to *Journal of Geophysical Research*, May, 2005

Table 1.

2005 SCEC 3D Rupture Dynamics Code Validation Workshop
Sunday September 11, 2005 at the SCEC Meeting Hotel in Palm Springs

60 WORKSHOP ATTENDEES (who signed up for the workshop):

Ruth Harris
Ralph Archuleta
Aagaard, Brad
Akullian, Kristy
Ando, Ryosuke
Andrews, Dudley Joe
Anooshehpoor, Rasool
Benesh, Nathan
Bhat, Harsha
Brune, James
Casteel, John
Clark, Julia
Cui, Yifeng
Custodio, Susana
Dalguer, Luis
Day, Steven
Dmowska, Renata
Duan, Benchun
Ely, Geoffrey
Faerman, Marcio
Fang, Zijun
Graves, Robert
Haqque, Ifraz
Heaton, Thomas
Herrera, Daniela
Ichinose, Gene
Ji, Chen
Jimenez, Rosa
Jordan, Thomas
Kaneko, Yoshihiro
Klose, Christian
Lapusta, Nadia
Lavallee, Daniel
Liu, Yi
Ma, Shuo
Ma, Kuo-Fong
Maechling, Philip
McRaney, John
Minster, Bernard

Oglesby, David
Olsen, Kim
Page, Morgan
Pitarka, Arben
Prakash, Vikas
Purvance, Matthew
Ramirez-Guzman, Leonardo
Rice, James
Robertson, Randy
Rojas, Otilio
Shi, Zheqiang
Sleep, Norman
Somerville, Paul
Squibb, Melinda
Templeton, Elizabeth
Teng, Ta-liang
Tullis, Terry
Vredevoogd, Michael
Yang, Wenzheng
Zechar, Jeremy
Zeng, Yuehua

Table 2.

AGENDA

2005 SCEC 3D Rupture Dynamics Code Validation Workshop

Sunday September 11, 2005 at the SCEC Meeting Hotel in Palm Springs

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8:30-8:55	**Workshop Introduction** *(Ruth Harris/Ralph Archuleta)*
9:00-9:20	**Comparison of Two Spontaneous Rupture Methods** **(***Steve Day /Luis Dalguer /Nadia Lapusta /Yi Liu)*
9:25-9:45	**EQdyna: An explicit dynamic finite element code for modeling spontaneous rupture on a geometrically complex fault** *(Benchun Duan)*
9:50-10:10	**Break**
10:10-11:30	**The Problem Versions 4+5 Comparisons/Discussion** (*Ruth/Ralph/All)*
11:30-12:30	**Lunch**
12:30-12:50	**A New SCEC IT Visualization Tool** (*Kim Olsen)*
12:55-1:15	**The Reference Earthquakes Digital Library Rupture Model Format** (*Brad Aagaard)*
1:20-2:00	**General Discussion and Future Plans** (*All)*

Table 3. Codes and Code Users for The September 11, 2005 Workshop

The Problem, Versions 4, 5 **(July – September 2005)**

Code Abbreviation	Code User	Spacing (m)	Code Description
*labi	Lapusta/Liu	both TPV4, TPV5 100 300	Lapusta Spectral Bounday Integral
*duff	Dunham	both TPV4, TPV5 100 300	Favreau Finite Difference with No Rake Rotation
*dadf	Dalguer/Day	both TPV4, TPV5 100 300	Day/Dalguer Finite Difference
*kavt	Kase	both TPV4, TPV5 100 300	Kase Finite Difference
*pifd	Pitarka	both TPV4, TPV5 100 300	Pitarka Finite Difference Finite Fault Zone Width?
*olfd	Olsen	both TPV4, TPV5 100 300	Olsen Finite Difference Finite Fault Zone Width
*lude	Dalguer	both TPV4, TPV5 300	Dalguer Discrete Element Split Nodes
*aaes	Aagaard	both TPV4, TPV5 300	Aagaard Finite Element
*maqk	Ma	both TPV4, TPV5 100 300	Ma Finite Element
*ogdy	Oglesby	both TPV4, TPV5 150 300	Oglesby Finite Element
*dued	Duan	both TPV4, TPV5 100 300	Duan Finite Element
*andy (150m) *Andy(300m)	Andrews	TPV4=300 TPV5=150,300	Andrews Finite Element
*dumd	Dunham	TPV4=150, 300 no TPV5	Dunham Spectral Bounday Integral with Rake Rotation
amse	Ampuero	TPV4=100 no TPV5	Ampuero Spectral Element with Kelvin-Voigt viscosity

Appendix 1. 14 Page letter sent to modelers describing the benchmarks.

July 21, 2005

Dear SCEC Spontaneous Rupture Modeler,

We are now tackling The Problem, Versions 4 and 5 for our upcoming spontaneous rupture code-validation (modelers) workshop. This first workshop of 2005 will be held on **Sunday September 11, 2005 in the SCEC Annual Meeting Hotel in Palm Springs.** I am envisioning a 9:00 a.m. start time.

Please register for the workshop and for the Annual Meeting on the SCEC website. Please also contact John McRaney or Dana Coyle if you need help with plane tix, hotel, and travel reimbursement information. Most likely you will want to stay over at the meeting hotel Saturday night.

The specific goal for this meeting is to see if we can get a (comparative) handle on the The Problem, Version 4 (TPV4) and The Problem, Version 5 (TPV5).

For this workshop the only code-description presentations will be by modelers whose codes were not previously presented in a code-validation workshop, or whose codes have had significant modifications. Please let me know if you'll be using a new or greatly modified code. We can also discuss new insights into how the codes work differently, if these differences are affecting our comparison exercise.

The next pages have the description of The Problem, Versions 4 and 5.
TPV4 and TPV5 use the same nucleation process as TPV3, but add 2 new stress patches along strike.
TPV4 is for a fullspace, and TPV5 is for a halfspace.

For TPV4 and TPV5 we will be starting a new system whereby modelers still provide to Ruth the word, ascii and eps results, as has been done previously, but modelers also provide their results to Kim Olsen's new IT website. (Hopefully by our November workshop we will have mastered this process so that everything just goes to Kim's website). Information will be coming shortly about how to send material to Kim, but in the meantime please do not be shy about sending your code results to Ruth.

*The deadline for sending results to Ruth is **August 23, 2005.***

This will allow for Ruth and Ralph to show a comparison of the results at the workshop.

Thanks!

Ruth and Ralph

Part I. Some definitions:

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

Velocity = Absolute motion with respect to time.

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

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

Rupture Front = 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 IIa. MODEL DESCRIPTION - THE PROBLEM, VERSION 4 (August 4, 2005)

Please note that this is **THE 3D** model that we are investigating for TPV4. Although variations are of course interesting, our goal is to follow the description precisely. If the code you're using will not run with Version 4's parameters, please contact Ruth ASAP. *Please feel free to point out to me as soon as possible, if I have omitted some critical details that you and others may need to run the simulations, or if there are any mistakes in the descriptions/requests.*
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 resides in a **fullspace**.

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

4) The top and bottom boundaries of the allowed 30000m x 15000m rupture area are 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 because the initial shear stress in a 3000 m x 3000 m square nucleation patch is set to be higher than the initial static yield stress in that patch. Failure occurs everywhere on the fault plane, including in the nucleation patch, following a linear slip-weakening fracture criterion. 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 81.6 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) = 81.6 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) = 81.6 MPa – (0.525 x 120 MPa) = 18.6 Mpa
Slip-weakening critical distance = 0.40 m

8) Halfway between the nucleation patch's center and the **right** end of the fault, there is a square patch of lower initial shear stress. The square patch has a side-length of 3000m. This patch has the same depth as the nucleation patch and is centered on a point 7.5 km along-strike distance from the center of the nucleation patch, so that the new patch's center is at along-strike, along-depth coordinates (+7.5, 7.5).
Friction is governed by the linear slip-weakening fracture criterion.
The initial shear stress in this square area is equal to **62.0 MPa**.

Within the entire 3000 m x 3000 m right 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) = 62.0 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) = 62.0 MPa – (0.525 x 120 MPa) = -1.0 MPa
Slip-weakening critical distance = 0.40 m

9) Halfway between the nucleation patch's center and the **left** end of the fault, there is a square patch of higher initial shear stress. The square patch has a side-length of 3000m. This patch has the same depth as the nucleation patch and is centered on a point 7.5 km along-strike distance from the center of the nucleation patch, so that the new patch's center is at along-strike, along-depth coordinates (-7.5, 7.5).
Friction is governed by the linear slip-weakening fracture criterion.
The initial shear stress in this square area is equal to **78.0 MPa**.

Within the entire 3000 m x 3000 left 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) = 78.0 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) = 78.0 MPa – (0.525 x 120 MPa) = 15.0 MPa
Slip-weakening critical distance = 0.40 m

10) Outside of the nucleation patch, and the right and left patches, friction is governed by the linear slip-weakening fracture criterion, but the initial shear stress is once again different (but the same as for TPV3, **70 MPa**).

Within the 30000 m x 15000 m faulting area, but outside of the 3000 m x 3000 m nucleation patch, right patch, and left 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 = 0.40 m

11) *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 = 0.40 m

End of TPV4 Description

Part IIb. MODEL DESCRIPTION - THE PROBLEM, VERSION 5 (August 4, 2005)

Please note that this is **THE 3D** model that we are investigating for TPV5. Although variations are of course interesting, our goal is to follow the description precisely. If the code you're using will not run with Version 5's parameters, please contact Ruth ASAP. *Please feel free to point out to me as soon as possible, if I have omitted some critical details that you and others may need to run the simulations, or if there are any mistakes in the descriptions/requests.*
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 resides in a **halfspace**. The fault reaches 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 because the initial shear stress in a 3000 m x 3000 m square nucleation patch is set to be higher than the initial static yield stress in that patch. Failure occurs everywhere on the fault plane, including in the nucleation patch, following a linear slip-weakening fracture criterion. 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 81.6 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) = 81.6 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) = 81.6 MPa – (0.525 x 120 MPa) = 18.6 Mpa
Slip-weakening critical distance = 0.40 m

8) Halfway between the nucleation patch's center and the **<u>right</u>** end of the fault, there is a square patch of lower initial shear stress. The square patch has a side-length of 3000m. This patch has the same depth as the nucleation patch and is centered on a point 7.5 km along-strike distance from the center of the nucleation patch, so that the new patch's center is at along-strike, along-depth coordinates (+7.5, 7.5).
Friction is governed by the linear slip-weakening fracture criterion.
<u>The initial shear stress in this square area is equal to **62.0 MPa.**</u>

Within the entire 3000 m x 3000 m right 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) = <u>62.0 MPa</u>
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) = <u>62.0 MPa</u> – (0.525 x 120 MPa) = <u>-1.0 MPa</u>
Slip-weakening critical distance = 0.40 m

9) Halfway between the nucleation patch's center and the **<u>left</u>** end of the fault, there is a square patch of higher initial shear stress. The square patch has a side-length of 3000m. This patch has the same depth as the nucleation patch and is centered on a point 7.5 km along-strike distance from the center of the nucleation patch, so that the new patch's center is at along-strike, along-depth coordinates (-7.5, 7.5).
Friction is governed by the linear slip-weakening fracture criterion.
<u>The initial shear stress in this square area is equal to **78.0 MPa**</u>.

Within the entire 3000 m x 3000 left 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) = <u>78.0 MPa</u>
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) = <u>78.0 MPa</u> – (0.525 x 120 MPa) = <u>15.0 MPa</u>
Slip-weakening critical distance = 0.40 m

TPV5 Description, continued

10) Outside of the nucleation patch, and the right and left patches, friction is governed by the linear slip-weakening fracture criterion, but the initial shear stress is once again different (but the same as for TPV3, **70 MPa**).

Within the 30000 m x 15000 m faulting area, but outside of the 3000 m x 3000 m nucleation patch, right patch, and left 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 = 0.40 m

11) *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 = 0.40 m

End of TPV5 Description
(stunningly similar to TPV4 except that this is for a halfspace and the fault reaches the earth's surface)

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

(Please send results to Ruth on or before August 23, 2005)

Note 1.

The requested output files are:

1) Time-series files in ascii format. (see pages 11-12 for specific formatting directions.)
Please provide the results in raw form (no filtering). Don't worry about oscillations.

2) A rupture time contour plot in Adobe Illustrator format. If this is not possible, then encapsulated postscript format is o.k. Please send the contour plot twice – one plot with the contours labeled, and one plot without the contours labeled.
***The scale for the rupture time contour plots is* 1 km = 0.25 inches**
Please do use this scale - it saves me a lot of time. Thanks.

Note 2.

Computations should be run using the following element-size/node-spacings
(please provide a complete output-file set for each of these):
100m, 300m

If the code you are using cannot run with 100m spacing, due to memory/processor constraints, please run using 150m instead and please note that you used 150m in the files and accompanying information that you send me.

Results to provide (on or before August 23, 2005):

<u>Please provide the results for TPV4 and the results for TPV5 separately (e.g. in different folders).</u>

For Versions 4 and 5 all output requests are for points on the fault plane.

1) The time that the entire 30 km x 15 km fault has stopped slipping, as indicated by the entire fault having a slip-rate of <1 mm/sec (or information that it hasn't stopped slipping by xx seconds).

2) The time that the hypocenter has stopped slipping, as indicated by the hypocenter having a slip-rate of <1 mm/sec (or information that it hasn't stopped slipping by xx seconds).

3) 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 0.5 second intervals. This plot should be in adobe illustrator or eps format. Please send it 2x, once with the contours labeled, once with no contour labels.

4) ASCII Time Series Files (see pages 11 & 12 for specific formatting directions)

For the times 0.0 to 12.0 seconds after nucleation:

*Horizontal Right-Lateral Slip (m) vs. time (s)
*Horizontal Right-Lateral Slip-rate (m/s) vs. time (s)
*Horizontal Right-Lateral Shear stress (MPa) vs. time (s)
*Vertical Up-Dip Slip (m) vs. time (s)
*Vertical Up-Dip Slip-rate (m/s) vs. time (s)
*Vertical Up-Dip Shear Stress (MPa) vs. time (s)

a1) For TPV4:
At these <u>7</u> points along the fault, all 1.5 km below the <u>fault's</u> <u>top</u> <u>edge</u>:
Directly above the hypocenter, and at +/-4.5, +/-7.5 km and +/-12.0 km along-strike distance from the hypocenter (7 points total)

a2) For TPV5:
At these <u>7</u> points along the fault, all on the <u>fault's</u> <u>top</u> <u>edge/earth's</u> <u>surface</u>:
At the epicenter, and at +/-4.5, +/-7.5 km and +/-12.0 km along-strike distance from the epicenter (7 points total)

b) For TPV4 and TPV5:
At these <u>9</u> points along the fault:
At the hypocenter, and at +/-4.5, +/-7.5, and +/-12.0 km along-strike distance from the hypocenter,
and at +/- 4.5 km down-dip distance from the hypocenter:

Part IV. TIME-SERIES FILE FORMAT AND FILE NAMING CONVENTION
(Please send results to Ruth on or before August 23, 2005)

Here's the naming convention for those many The Problem, Version 4 and The Problem, Version 5 time-series output files that are requested on page 10.

Please send all files (except for the requested plotted figure) in ascii format.

Time series Filename convention: **aabb**faultst**ccc**dp**ddd**.dat

Note, the format for ccc was changed slightly as of Aug. 1, 2005, see below.

The fixed parts of the label are: fault=on the fault plane, st=strike, dp=depth

The variable parts of the label are:
aa = 2 lowercase letters designating author (1st 2 letters of last name)
bb = 2 lowercase letters designating code used in simulation (any 2 letters)
ccc = distance (to the right) along strike from the hypocenter in km * 10
ddd = distance down-dip from top of the fault in km * 10

Each data file contains the time history for 1 (station) location on the fault in ASCII format.

The file header contains 16 lines, each beginning with a # sign and includes:
author,
date,
code,
code version (if desired),
node spacing or element size,
time step,
number of time steps in file,
station location
descriptions of data columns (8 lines)

The line (row) for each time step is 7 columns wide in 14.6E or 14.6e floating point format*.
The columns are:
(1) time in seconds,
(2) horizontal right-lateral slip (m),
(3) horizontal right-lateral slip-rate (m/s),
(4) horizontal right-lateral shear stress (MPa),
(5) vertical up-dip slip (m),
(6) vertical up-dip slip-rate (m/s)
(7) vertical up-dip shear stress* (MPa)

Please see example files namyfaultst045dp075.dat, namyfaultst-045dp075.dat, next page.

the file namyfaultst045dp075.dat:
(note, this is an invented file, not from a TPV4 run)

```
# author=MyLastName (na)
# date=2005/07/09
# code=MyCode (my)
# code_version=3.7
# element_size=100  m
# time_step=0.02
# num_time_steps=5
# location= +4.5km along strike from the hypocenter and 7.5km down-dip from fault's top edge
# Time series in 7 column of E14.6:
# Column #1 = Time (s)
# Column #2 = horizontal right-lateral slip (m),
# Column #3 = horizontal right-lateral slip-rate (m/s),
# Column #4 = horizontal right-lateral shear stress (MPa),
# Column #5 = vertical up-dip slip (m),
# Column #6 = vertical up-dip slip-rate (m/s)
# Column #7 = vertical up-dip shear stress (MPa)
 0.000000E+00 -0.000000E+00 -0.000000E+00  7.000000E+01  0.000000E+00  0.000000E+00  0.000000E+00
 5.000000E-02 -0.000000E+00 -0.000000E+00  7.000000E+01  0.000000E+00  0.000000E+00  0.000000E+00
 1.000000E-01 -0.000000E+00 -0.000000E+00  7.000003E+01  0.000000E+00  0.000000E+00 -3.077084E-05
 1.500000E-01 -0.000000E+00 -0.000000E+00  7.000011E+01  0.000000E+00  0.000000E+00 -5.298069E-04
 2.000000E-01 -0.000000E+00 -0.000000E+00  7.000332E+01  0.000000E+00  0.000000E+00 -7.467587E-04
```

the file namyfaultst-045dp075.dat:
(note, this is an invented file, not from a TPV4 run)

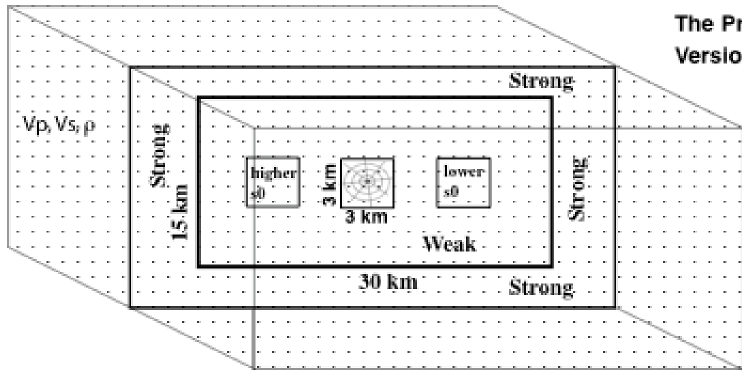
```
# author=MyLastName (na)
# date=2005/07/09
# code=MyCode (my)
# code_version=3.7
# element_size=100  m
# time_step=0.05
# num_time_steps=5
# location= -4.5km along strike from the hypocenter and 7.5km down-dip from fault's top edge
# Time series in 7 column of E14.6:
# Column #1 = Time (s)
# Column #2 = horizontal right-lateral slip (m),
# Column #3 = horizontal right-lateral slip-rate (m/s),
# Column #4 = horizontal right-lateral shear stress (MPa),
# Column #5 = vertical up-dip slip (m),
# Column #6 = vertical up-dip slip-rate (m/s)
# Column #7 = vertical up-dip shear stress (MPa)
 0.000000E+00 -0.000000E+00 -0.000000E+00  7.000000E+01  0.000000E+00  0.000000E+00  0.000000E+00
 5.000000E-02 -0.000000E+00 -0.000000E+00  7.000000E+01  0.000000E+00  0.000000E+00  0.000000E+00
 1.000000E-01 -0.000000E+00 -0.000000E+00  7.000003E+01  0.000000E+00  0.000000E+00 -3.077084E-05
 1.500000E-01 -0.000000E+00 -0.000000E+00  7.000011E+01  0.000000E+00  0.000000E+00 -5.298069E-04
 2.000000E-01 -0.000000E+00 -0.000000E+00  7.000332E+01  0.000000E+00  0.000000E+00 -7.467587E-04
```

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

Overall view:

July 21, 2005

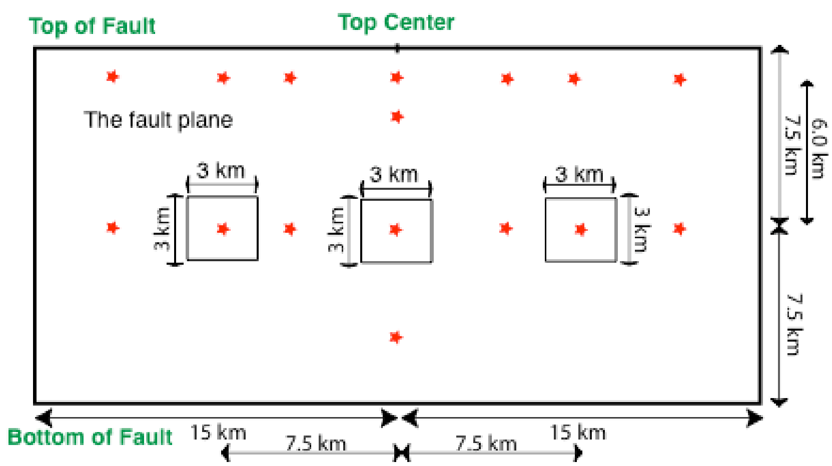
The Problem, Version 4



The fault plane (in a different scale from above), with stations indicated by stars:

Stations 1.5 km below the fault's top surface (depth=1.5 km) on the fault plane are at 0, +/-4.5, +/-7.5, and +/-12.0 km along-strike distance from the top center.

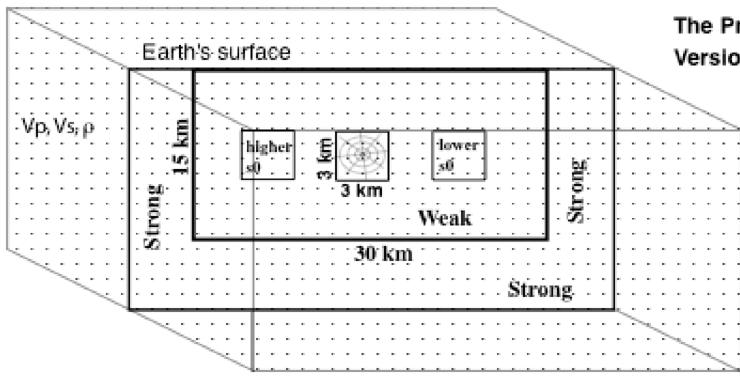
Stations deeper on the fault plane are at the hypocenter, and at +/-4.5, +/-7.5, and +/-12.0 km along-strike distance from the hypocenter, and at +/-4.5 km down-dip distance from the hypocenter



Overall view:

July 21, 2005

The Problem, Version 5



The fault plane (in a different scale from above), with stations indicated by stars:

Stations at the Earth's surface (depth=0 km) on the fault plane are at
0, +/-4.5, +/-7.5, and +/-12.0 km along-strike distance from the epicenter.

Stations deeper on the fault plane are at
the hypocenter, and at +/-4.5, +/-7.5, and +/-12.0 km along-strike distance from the hypocenter,
and at +/-4.5 km down-dip distance from the hypocenter