

DYNAMIC SLIP TRANSFER FROM THE DENALI TO TOTSCHUNDA FAULTS, ALASKA: TESTING THEORY FOR FAULT BRANCHING

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ABSTRACT

We analyze the observed dynamic slip transfer from the Denali to Totschunda faults during the M_w 7.9, November 3, 2002, Denali, Alaska, earthquake. This study adopts the theory and methodology of Poliakov et al. [2002] and Kame et al. [2003], in which it was shown that the propensity of the rupture path to follow a fault branch is determined by the preexisting stress state, branch angle and incoming rupture velocity at the branch location. Here we check that theory on the Denali-Totschunda rupture process using 2D numerical simulations of processes in the vicinity of the branch junction.

The maximum compression direction with respect to the strike of the Denali fault near the junction has been estimated to range from approximately 73° to 80° . We use the values of 70° and 80° in our numerical simulations.

The rupture velocity at branching is not well constrained but has been estimated to average about $0.8c_s$ throughout the event. We use $0.6c_s$, $0.8c_s$, $0.9c_s$ and even $1.4c_s$ as parameters in our simulations.

We simulate slip transfer by a 2D elastodynamic boundary integral equation model of mode II slip-weakening rupture with self-chosen path along the branched fault system. All our simulations except for 70° and $0.9c_s$ predict that the rupture path branches off along the Totschunda fault without continuation along the Denali fault. In that exceptional case there is also continuation of rupture along the Denali fault at a speed slower than that along the Totschunda fault and with smaller slip.

INTRODUCTION

A M_w 7.9 earthquake struck central Alaska on November 3, 2002. The earthquake occurred along the Denali fault system and ruptured a total length of approximately 350 km. The last segment of rupture was along the Totschunda fault, which branches off from the Denali fault, with 68 km of observed surface rupture [Peter Haeussler, USGS, Anchorage; private communication, 2002]; see Figure 1a (epicenter: star in center left of the figure) [Figure courtesy: Alaska Division of Geological and Geophysical Surveys].

Beyond the branching location there was no surface rupture visible on the Denali fault for at least 25 km [Peter Haeussler, USGS, Anchorage; private communication, 2002].

Beyond the Denali-Totschunda branching location the aftershocks of the M_w 7.9 event occurred predominantly along the Totschunda fault segment; Figure 1b [Eberhart-Phillips et al., 2003]. Together with the lack of surface rupture along the continuation of the Denali fault, this indicates that after branching the rupture progressed exclusively along the Totschunda fault.

SUMMARY OF THEORY FOR FAULT BRANCHING

Following the concepts introduced by Poliakov et al. [2002] on factors governing fault branching, Kame et al. [2003] performed an extensive set of numerical simulations of branching. Those were done in the context of a 2D, mode II, rupture model with a slip-weakening friction coefficient, with strength during slip-weakening proportional to the instantaneous local normal stress. They involved a range of branching fault angles (ϕ) with the primary fault, rupture velocities (v_r) approaching the branching location, and maximum horizontal pre-stress inclinations (Ψ) with the main fault. See Figures 2-4 for their results which are most relevant for the present discussion; all results are shown for right-lateral rupture.

The results can be summarized as follows. For a given rupture velocity the most vulnerable branch orientations change from those on the compressional side ($\phi > 0$) to those on the extensional side ($\phi < 0$) with increasing orientation of the maximum horizontal stress with the main fault (as partly illustrated in Figures 2 and 3). The tendency of the rupture path to proceed exclusively on the branch also increases (and becomes more and more independent of rupture velocity) as one approaches limits of maximum stress inclinations (0° or 90° for exclusive propagation on compressional or extensional branches respectively). With increasing rupture velocity (keeping Ψ constant) the stress shadow effect of one fault on another, which is important for small branching angles, decreases; that makes the rupture path lie less exclusively either along the main fault or along the branched one (Figure 4). The parameter L_{stop}/R_0 in the figures refers to the distance, L_{stop} , beyond the branch junction at which propagation has stopped on either the branch or the main fault. It is normalized by R_0 , which is the length that the slip-weakening zone would occupy along the main fault in low speed propagation [Kame et al., 2003].

DETERMINATION OF PARAMETERS INFLUENCING BRANCHING FOR THE DENALI EVENT

Maximum Principal Stress Direction (Ψ)

Nakamura et al. [1980], have estimated the late Quaternary tectonic stress trajectories in the Aleutians and Alaska, using geologic indicators along continental Alaska. Their results show averaged directions of maximum horizontal compression. The principal stress

direction near to the Denali-Totschunda branching region would thus be estimated from their results to be approximately 75° with respect to the main fault. Estabrook and Jacob [1991] later provided a map of maximum horizontal compression-determined stress trajectories from a variety of sources, including seismic focal mechanisms, volcanic, geologic fault and borehole breakout data, for Alaska, the Aleutians, and the Bering Sea. This is based on the results of Nakamura et al. [1980], and Estabrook et al. [1988]. The principal stress direction nearest to the Denali-Totschunda branching region was again reported to be at approximately 75° , with respect to the strike of the Denali fault just before branching.

Azimuths of maximum and minimum horizontal compression, obtained using stress tensor inversion from focal mechanisms, were determined along different fault systems in central Alaska by Ratchkovski and Hansen [2002]. All of their regions were of the order 100 to 400 km west of the branching location, and most to the north too. The principal stress direction nearest to the Denali-Totschunda branching region was found to be approximately 73° (by extrapolating results from closest locations) with respect to the strike of the Denali fault just before branching.

Based on the more recent focal mechanism inversions of Ratchkovski [2003] it can be seen that as one traverses along the Denali fault to the east, from the epicenter, the direction of principal maximum stress, before the earthquake, rotates slightly in a clockwise sense from R1 to R2 and counter-clockwise from R2 to R3 (Figure 5). It can be roughly approximated, then, that the direction of principal maximum stress close to the Denali-Totschunda branching location was inclined at about 80° with respect to the Denali fault.

Given the range of values for Ψ we choose two values, 70° and 80° , to cover the range of observations. The latter better represents measurements near the branching junction; the former is an approximate lower bound based on the more regional stress studies. Based on the results of Kame et al. [2003], $\Psi=70^\circ$ is a conservative estimate for our simulations because, as it was noted earlier, the likelihood of the rupture taking the branch exclusively increases with increasing Ψ and becomes more and more independent of the rupture velocity when approaching the branching location. We will show that the rupture path is predicted to be captured exclusively by the branch in nearly all cases studied when $\Psi=70^\circ$ and in all cases when $\Psi=80^\circ$.

Rupture Velocity (v_r)

The average rupture velocity during the Denali event seems to be about 80% of the shear wave speed [Kikuchi and Yamanaka, 2002], although the velocity as the branch was approached is not yet constrained very well. Inversion of strong motion records by Eberhart-Phillips et al. [2003] revealed three sub events (Figure 1b) during the Denali event with the second and the third subevent occurring at about 125 km and 50 km to the west of the Denali-Totschunda branching location respectively. Best fitting inversion

required a high rupture velocity of about 3.5 km/s between sub events 2 and 3. Ellsworth et al. [2004] note that the rupture actually went super-shear near Pump Station 10 (PS10), whose location is much further to the west of the branching location and is very close to subevent 2. They also mention that the rupture velocity is around $0.8c_s$ for about 20 km east of PS10. We therefore carry out our numerical simulations for different values of rupture velocity when approaching the branching location, including super-shear rupture velocity. (Rousseau and Rosakis [2003] have extended branching concepts like in Poliakov et al. [2002] to the super-shear regime.)

Branching Angle (ϕ)

The Totschunda fault branches away from the Denali fault, to the extensional side, at an angle of approximately 15° . The angle was measured from a fault map of Central Alaska provided by Savage and Lisowski [1991].

Wallace et al. [2002] suggested that the northern part of the Totschunda fault system may consist of multiple discontinuous southeast striking strands and are locally connected by south-striking step-over faults. This may reflect the immaturity of the northern Totschunda system. The aim of our study is to do a first order analysis of the branching process by simplifying the geometry. Also, an aerial photograph [Peter Haeussler, private communication, 2002] of the branch location, possible because the earthquake shook snow off steep slopes, suggests that a simple branch geometry was followed at the start, like in our model.

NUMERICAL IMPLEMENTATION USING THE BOUNDARY INTEGRAL EQUATION (BIE) METHOD

Numerical implementation of the dynamic rupture propagation scheme was done using the 2D Boundary Integral Equation (BIE) method as described in Kame et al. [2003]. An important advantage of this method, besides others, is that the domain of calculations is confined to the fault geometry. Of course, a long running rupture, which is depth limited, like for the Denali fault event cannot be modeled in a 2D framework. However, following the theoretical concepts outlined in Poliakov et al. [2002], Kame et al. [2003] and Rousseau and Rosakis [2003], we can argue that the critical factor, other than the geometry and pre-stress, is the rupture speed as the branch is approached. This can be suitably simulated in 2D, with far greater grid refinement than in 3D simulations, by nucleating a 2D rupture at various distances from the branching location. Given the present computing capabilities, the 2D formulation allows adequate grid refinement to fully resolve the slip-weakening process, a feature which is not generally achieved in 3D simulations. Nevertheless, the rupture phenomenon is clearly a 3D one, and much has been learned about branching from such simulations by Aochi et al. [2000a, 2000b], Aochi and Fukuyama [2002], Oglesby et al. [2000a, 2000b] and Oglesby and Day [2001].

Following the discretized form of the dynamic representation theorem evaluated by Kame and Yamashita [1999a, 1999b, 2003], we obtain the following algebraic equation for the

change in shear traction on spatial cell l , at the end of time step n , due to the slip history up to that time:

$$\Delta\tau^{l,n} = \sum_{k=1}^n \sum_i V^{i,k} K^{l-i,n-k} \quad (1)$$

Here $V^{i,k}$ is the slip-velocity of cell i , during time step k and $K^{l-i,n-k}$ is the response to unit slip-velocity in cell i in time step k .

If we now choose the discretization parameters, cell size Δs and time step Δt , such that $c_p \Delta t / \Delta s = 0.5$ then equation (1) decouples (actually for all $c_p \Delta t / \Delta s < 1$) resulting in an explicit formulation as below (c_p is the P-wave speed of the medium).

$$\Delta\tau^{l,n} = V^{l,n} K^{0,0} + \sum_{k=1}^{n-1} \sum_i V^{i,k} K^{l-i,n-k} \quad (2)$$

where $K^{0,0}$ ($= -\mu/2c_s$) is the radiation damping term [Cochard and Madariaga, 1994]. This term represents the instantaneous contribution of the current slip-velocity to the shear stress at the same position (μ is the shear modulus of the medium and c_s is the shear wave speed of the medium). A similar expression applies for the change of normal stress on the fault, except that there is zero instantaneous contribution [Kame et al., 2003].

We use a slip-weakening friction law as originally proposed by Ida [1972] and Palmer and Rice [1973]. We formulate this in a Coulomb manner so that the fault strength is always proportional to the normal stress acting on the fault. Thus it is the friction coefficient that slip-weakens. According to this law, the strength of the fault, at constant compressive normal stress, decreases linearly from an initial peak strength, τ_p , to a residual strength, τ_r , up to a critical slip, $\Delta u = D_c$, and then remains constant at the residual level for any further slip. Thus

$$\begin{aligned} \tau &= \tau_r + (\tau_p - \tau_r)(1 - \Delta u / D_c)H(1 - \Delta u / D_c) \\ \tau_p &= \mu_s(-\sigma_n) ; \quad \tau_r = \mu_d(-\sigma_n) \end{aligned} \quad (3)$$

where $H(\cdot)$ is the Heaviside function, μ_s and μ_d are the static and dynamic coefficients of friction respectively and $(-\sigma_n)$ is the normal stress acting on the fault (we take stress as positive in tension). We use the same expression during general stress and slip histories, taking τ_p and τ_r to be proportional to the instantaneous effective normal stress as indicated. Andrews [1976] defined a parameter $S \left[= (\tau_p - \sigma_{yx}^0) / (\sigma_{yx}^0 - \tau_r) \right]$ associated with the slip-weakening law where σ_{yx}^0 is the initial shear stress on the fault. This parameter has a critical value (approximately 1.77) below which the rupture would

propagate with a speed that ultimately transitions to super-shear, at least for propagation paths that are long enough compared to the size of the nucleation zone.

All the parameters in our calculations are non-dimensionalized as follows:

- 1) Length, $X^* = X/R_0$
- 2) Time, $t^* = 2c_p t/\Delta s$
- 3) Slip, $\Delta u^* = \mu \Delta u / [(-\sigma_{yy}^0) R_0]$
- 4) Slip Velocity, $V^* = \mu V / [(-\sigma_{yy}^0) c_p]$
- 5) Stress, $\sigma_{ij}^* = \sigma_{ij} / (-\sigma_{yy}^0)$

Here $-\sigma_{yy}^0$ is the initial compressive stress on the primary (Denali) fault, where R_0 $[= (3\pi/8)(\mu D_c / (\tau_p - \tau_r))]$ is the approximate slip-weakening zone length at low rupture velocity as derived in Palmer and Rice [1973] and Rice [1980] and used in Poliakov et al. [2002] and Kame et al. [2003], c_p is the P-wave speed of the medium and μ is the shear modulus of the medium. To fully resolve the slip-weakening process, Δs should be much less than R_0 . We use $R_0/\Delta s = 5$ or 10 in our simulations, the larger number being needed when rupture propagation speed is close to the Rayleigh speed ($\approx 0.92 c_s$).

The numerical simulation of dynamic rupture propagation is carried out in the following two steps.

Static slip distribution along the minimum nucleation length

To obtain the required rupture velocity on the primary fault at the branching location, we nucleate the rupture at various distances from the branching location without referring to the actual nucleation point on the Denali fault. Our goal here is to understand the dynamics of the rupture front, at various speeds, as the branch is approached, and not to simulate the entire event (impossible within our 2D formulation).

The minimum nucleation length (L_c), as described in Andrews [1976] and Kame et al. [2003], obtained from the fracture mechanics energy balance (for Poisson ratio $\nu = 0.25$) is determined using,

$$L_c = \frac{16}{3\pi} \frac{\mu G}{(\sigma_{yx}^0 - \tau_r)^2} = \frac{64}{9\pi^2} \left(\frac{\tau_p - \tau_r}{\sigma_{yx}^0 - \tau_r} \right)^2 R_0 \quad (4)$$

Here L_c is the total length of the slipping zone (twice the length in Andrews [1976]). We choose a certain length of the fault, L , such that L/R_0 is slightly greater than L_c/R_0 . In this region we prescribe a slip distribution, and prevent any slip outside the region, such that fault is in static equilibrium. This causes an initial stress concentration which is slightly

larger than the peak strength at both ends of the static nucleation zone, and finitely accelerates rupture in the first dynamic time steps [Kame et al., 2003].

Dynamic rupture propagation

After prescribing the slip distribution as explained in the previous step, the rupture is allowed to propagate dynamically along the main fault and the rupture velocity history is calculated to position a branch to the primary fault so that the rupture velocity on the primary fault, when approaching the branch, is the one desired.

The branch is placed in position and dynamic rupture is then allowed to continue both along the main and the branched faults. We monitor stress in each time step, to see if rupture begins ($\tau \geq -\mu_s \sigma_n$), at the first element of the branch and at the front of any rupture along it and the main fault.

SUMMARY OF RESULTS

Numerical studies were conducted using the boundary integral equation method elaborated earlier. Figure 6 shows the fault geometry adopted for our simulations, of which preliminary results were reported in Bhat et al. [2002].

Since the S ratio governs the nature of rupture (super-shear or sub-shear), a desired value is first chosen. This would then give the initial shear stress acting on the fault (as a fraction of $-\sigma_{yy}^0$) if values of μ_s and μ_d are assumed. If the pre-stress field is normalized by the fault normal pre-stress then the normalized fault parallel pre-stress can be obtained by using the desired value of Ψ , the orientation of the principal maximum compressive stress with the primary fault. The pre-stress parameters thus obtained must be checked so that the Mohr-Coulomb failure criterion based on μ_s is not violated either on the primary or the branched fault.

Dreger et al. [2004] noted, in their dynamic source modeling of the Denali event using a 3-D finite element method, that the rupture actually jumps ahead, by 14 km, of the primary rupture front triggering slip on Totschunda. We do not observe such phenomenon in our simulations.

Our calculations were done for various values of v_r , and Ψ at the Denali-Totschunda branching location.

Case 1: $v_r = 0.60c_s$; $\Psi = 70^\circ$; $\mu_s = 0.60$; $\mu_d = 0.12$; $S_{Den} = 3$; $S_{Tot} = 0.6$

When the velocity of the rupture approaching the branching location at Totschunda was $0.6c_s$, it was observed that the rupture branches completely onto the Totschunda fault. Figure 7 shows the combined plots of slip velocity along both the Denali and Totschunda faults. It is clearly observed that once the rupture on Denali crosses the branching location

the slip velocity dies off rapidly with time. This is a clear indication of the fact that the main fault can no longer accommodate slip beyond the branching location.

At time step 365 the rupture has reached the branching point. We observe in our simulations that the slip velocity at the right end of the rupture front, at this time step, picks up a bit for a while before slowing down. This could be because of numerical oscillations in our calculations.

Case 2: $v_r = 0.80c_s$; $\Psi = 70^\circ$; $\mu_s = 0.60$; $\mu_d = 0.12$; $S_{Den} = 3$; $S_{Tot} = 0.6$

For this case, the rupture again branches along the Totschunda fault with no further continuation on the Denali fault. Figure 8 shows the plot of slip velocity along both the Denali and Totschunda faults. It is clear, as in the previous case, that beyond the branch, the slip velocity dies off rapidly on the Denali fault.

Case 3: $v_r = 0.90c_s$; $\Psi = 70^\circ$; $\mu_s = 0.60$; $\mu_d = 0.12$; $S_{Den} = 3$; $S_{Tot} = 0.6$

Earlier studies by Kame et al., [2003] showed that for this value of rupture velocity and for $\Psi = 56^\circ$, the rupture would tend to propagate both along the main and the branched fault in the extensional side with a small branching angle of 15° . The same happens in this case with $\Psi = 70^\circ$ but not, as we shall see next, when $\Psi = 80^\circ$. Figure 9 shows the variation of slip velocity along the Denali and Totschunda faults. As can be seen in this figure, the slip velocity on the Denali fault beyond the Totschunda fault is significant resulting in simultaneous propagation of rupture along the Denali and Totschunda faults beyond the branching location albeit at a slower rate and with less slip on the Denali fault compared to the same on the Totschunda fault.

Case 4: $v_r = 0.87c_s$; $\Psi = 80^\circ$; $\mu_s = 0.40$; $\mu_d = 0.05$; $S_{Den} = 4$; $S_{Tot} = 0.4$

As mentioned earlier, the possibility of the rupture choosing the extensional branch exclusively increases with increasing inclination of Ψ . In this case we increase Ψ to 80° and maintain the rupture velocity at $0.87c_s$ while approaching the Totschunda fault. We also had to change the friction coefficients, to make the rock weaker, because with the earlier values of friction coefficients the pre-stress field violated the Mohr-Coulomb failure criterion outside the fault zones.

Our results show that, for the above case, the rupture proceeds rapidly along the Totschunda fault with almost no continuation on the Denali fault. Figure 10 shows the plot of slip velocity along both the Denali and Totschunda faults. It is clear that beyond the Totschunda fault, the slip velocity dies off quickly on the Denali fault. There is some continuation of rupture on the Denali fault beyond the Totschunda fault, although this length is of the order of R_0 , the size of the slip-weakening zone, which is negligible in

comparison with the progress of rupture on the Totschunda fault. Hence, we can conclude here that the rupture takes the Totschunda fault exclusively.

Case 5: $v_r = 1.40c_s$; $\Psi = 70^\circ$; $\mu_s = 0.50$; $\mu_d = 0.10$; $S_{Den} = 1$; $S_{Tot} = 0.09$

While we have no reason at present to think that the rupture velocity was super-shear near the branch junction, we also ran a simulation where the rupture velocity when approaching the Denali-Totschunda branching location was $1.40c_s$. In order to make an appropriate choice of the S ratio so that the rupture went super-shear, and the Mohr-Coulomb failure criterion was not violated by the pre-stress field, required us to choose the above values for dynamic and static coefficients of friction.

The plot of slip velocity, Figure 11, on the Denali and Totschunda faults shows that on the part of the Denali fault beyond the junction, the slip velocity is decaying rapidly, suggesting that part of the Denali fault beyond Totschunda will ultimately stop slipping. On the Totschunda fault the speed briefly reduced to sub-Rayleigh then went supershear again leaving a pattern that is somewhat like what has been seen in other cases of sub-Rayleigh to supershear transitions, leaving pulses that move as Rayleigh waves on what was the crack surface before the intersonic transition, and giving a multi-pulse character to the slip-rate distribution.

SUMMARY AND CONCLUSIONS

The theory of fault branching developed by Poliakov et al. [2002] and Kame et al. [2003] was tested on the recent Denali fault earthquake using the numerical method developed in the latter work. The theoretical stress analysis of a propagating mode II rupture had suggested that the tendency to follow a branch is influenced by rupture velocity v_r approaching the branch, preexisting maximum compressive stress inclination Ψ , and prospective branching angle ϕ . This study shows yet another comparison of the rules of branching with a field case; five other such field cases were discussed by Kame et al. [2003].

We numerically simulated the observed slip transfer from the Denali to Totschunda faults by the methodology of Kame et al. [2003] which uses a 2D elastodynamic boundary integral equation model of mode II rupture with self-chosen path along a branched fault system. The strength of the faults was assumed to follow a Coulomb law with friction coefficient which slip-weakens from its static to dynamic value. Figure 12 shows the rupture velocity variation on the Denali and Totschunda faults for cases $\Psi = 70^\circ$; $v_r = 0.6c_s$ and $\Psi = 70^\circ$; $v_r = 0.9c_s$ respectively. It is interesting to note that the rupture velocity on the Totschunda fault beyond the branching location for the case $\Psi = 70^\circ$; $v_r = 0.9c_s$ remains steady at a value of $1.1c_s$, a value which falls within the range for unstable dynamic rupture propagation on a single fault [Freund, 1979]; possibly the speed is stabilized by the existence of the neighboring rupture propagating along the

Denali fault. All our simulations for sub-Rayleigh incoming rupture velocities, except one, predict that the rupture path branches off along the Totschunda fault without continuation along the Denali fault. That exception is the case when the prestress inclination is 70° , a lower limit to the plausible range, and incoming rupture speed at branching is $0.9c_s$. In that case rupture follows the branch but there is also a continuation of rupture along the Denali fault beyond the branching location, at a speed slower than that along the Totschunda fault. However when the prestress inclination is steeper, at 80° , the rupture chooses Totschunda exclusively when its velocity near the branching location is around $0.9c_s$. We also see exclusive continuation of rupture on the Totschunda fault when the rupture is super-shear, $1.4c_s$.

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REFERENCES

- Andrews, D. J. (1976). Rupture velocity of plane strain shear cracks, *J. Geophys. Res.* **81**, 5679-5687.
- Aochi, H., and E. Fukuyama (2002). Three-dimensional non-planar simulation of the 1992 Landers earthquake, *J. Geophys. Res.* **107** (B2), *cn*: 2035, *doi*:10.1029/2000JB000061, pp. ESE 4-1 to 4-12.
- Aochi, H., E. Fukuyama, and M. Matsu'ura (2000a). Spontaneous rupture propagation on a non-planar fault in 3D elastic medium, *Pure Appl. Geophys.* **157**, 2003–2027.
- Aochi, H., E. Fukuyama, and M. Matsu'ura (2000b). Selectivity of spontaneous rupture propagation on a branched fault, *Geophys. Res. Lett.* **27**, 3635–3638.
- Bhat, H., R. Dmowska, J. R. Rice and N. Kame (2002). Testing theory for fault branching: Denali to Totschunda, Alaska, November 3, 2002, *Trans. Amer. Geophys. Un., EOS* **83**, abstr. S72F-1364.
- Cochard, A., and R. Madariaga (1994). Dynamic faulting under rate dependent friction, *Pure Appl. Geophys.* **142**, 419–445.
- Dreger, D. S., D. D. Oglesby, R. Harris, N. Ratchkovski and R. Hansen (2004). Kinematic and Dynamic rupture models of the November 3, 2002, M_w 7.9 Denali, Alaska, earthquake, *Geophys. Res. Lett.* **31**, L04605, *doi*: 10.1029/2003GL018333.
- Eberhart-Phillips, D., P. J. Haeussler, J. T. Freymueller, A. D. Frankel, C. M. Rubin, P. Craw, N. A. Ratchkovski, G. Anderson, G. A. Carver, A. J. Crone, T. E. Dawson, H. Fletcher, R. Hansen, E. L. Harp, R. A. Harris, D. P. Hill, S. Hreinsdóttir, R. W. Jibson, L. M. Jones, R. Kayen, D. K. Keefer, C. F. Larsen, S. C. Moran, S. F.

- Personius, G. Plafker, B. Sherrod, K. Sieh, N. Sitar and W. K. Wallace (2003). The 2002 Denali fault earthquake, Alaska: A large magnitude, slip-partitioned event, *Science* **300**, 1113-1118.
- Ellsworth, W. L., M. Çelebi, J. R. Evans, E. G. Jensen, D. J. Nyman and P. Spudich, Processing and modeling of the pump station 10 record from the November 3, 2002, Denali fault, Alaska earthquake (2004). *Preprint For 11th International Conference On Soil Dynamics & Earthquake Engineering, Berkeley, CA, Jan. 7-9.*
- Estabrook, C. H., D. B. Stone and J. N. Davies (1988). Seismotectonics of northern Alaska, *J. Geophys. Res.* **93**, 12026-12040.
- Estabrook, C. H., and K. H. Jacob (1991). Stress indicators in Alaska, in *Neotectonics of North America*, D. B. Slemmons, E. R. Engdahl, M. D. Zoback, and D. D. Blackwell (Editors), Geological Society of America, Boulder, Colorado, Decade Map vol. **1**, 387-399.
- Freund, L. B., The mechanics of dynamic shear crack propagation (1979). *J. Geophys. Res.* **84**, 2199-2209.
- Fossum, A. F., and L. B. Freund (1975). Nonuniformly moving shear crack model of a shallow focus earthquake mechanism, *J. Geophys. Res.* **80**, 3343-3347.
- Harris, R. A., and S. M. Day (1993). Dynamics of fault interaction: Parallel strike-slip faults, *J. Geophys. Res.* **98**, 4461-4472.
- Ida, Y. (1972). Cohesive force across the tip of a longitudinal-shear crack and Griffith's specific surface energy, *J. Geophys. Res.* **77**, 3796-3805.
- Kame, N., J. R. Rice and R. Dmowska (2003). Effects of pre-stress state and rupture velocity on dynamic fault branching, *J. Geophys. Res.* **108** (B5), *cn*: 2265, *doi*:10.1029/2002JB002189, pp. ESE 13-1 to 13-21.
- Kame, N. and T. Yamashita (1999a). A new light on arresting mechanism of dynamic earthquake faulting, *Geophys. Res. Lett.* **26**, 1997-2000.
- Kame, N. and T. Yamashita (1999b). Simulation of spontaneous growth of dynamic crack without constraints on the crack tip path, *Geophys. J. Int.* **139**, 345-358.
- Kame, N. and T. Yamashita (2003). Dynamic branching, arresting of rupture and the seismic wave radiation in self-chosen crack path modeling, *Geophys. J. Int.* **155**, 1042-1050.
- Kikuchi, M. and Y. Yamanaka (2002). Source rupture processes of the central Alaska earthquake of Nov. 3, 2002, inferred from teleseismic body waves (the 10/23 M6.7 event), *EIC Seismological Note* No. 129, revised 5 November 2002. Available from the Earthquake Information Center, University of Tokyo, at http://www.eic.eri.u-tokyo.ac.jp/EIC/EIC_News/021103AL-e.html.
- Nakamura, K., G. Plafker, K. H. Jacob, and J. N. Davies (1980). A tectonic stress trajectory map of Alaska using information from volcanoes and faults, *Bull. Earthq. Res. Inst.* **55**, 89-100.
- Oglesby, D. D., R. J. Archuleta, and S. B. Nielsen (2000). The three-dimensional dynamics of dipping faults, *Bull. Seism. Soc. Am.* **90**, 616-628.
- Oglesby, D. D., R. J. Archuleta, and S. B. Nielsen (2000). Dynamics of dip-slip faulting: Explorations in two dimensions, *J. Geophys. Res.* **105**, 13,643-13,653.
- Oglesby, D. D., and S. M. Day (2001). The effect of fault geometry on the 1999 Chi-Chi (Taiwan) earthquake, *Geophys. Res. Lett.* **28**, 1831-1834.

- Palmer, A. C., and J. R. Rice (1973). The growth of slip surfaces in the progressive failure of over-consolidated clay, *Proc. Roy. Soc. London, A* **332**, 527-548.
- Poliakov, A. N. B., R. Dmowska and J. R. Rice (2002). Dynamic shear rupture interactions with fault bends and off-axis secondary faulting, *J. Geophys. Res.* **107** (B11), (cn): 2295, doi: 10.1029/2001JB000572, pp. ESE 6-1 to 6-18.
- Ratchkovski, N. A., and R. A. Hansen (2002). New constraints on tectonics of interior Alaska: Earthquake locations, source mechanisms, and stress regime, *Bull. Seism. Soc. Am.* **92**, 998- 1014.
- Ratchkovski, N. A. (2003). Change in stress directions along the central Denali fault, Alaska after the 2002 earthquake sequence, *Geophys. Res. Lett.* **30** (19), 2017,doi:10.1029/2003GL017905.
- Rice, J. R. (1980). The mechanics of earthquake rupture, in *Physics of the Earth's Interior* (Proc. Int'l. School of Physics 'Enrico Fermi', Course 78, pp. 555-649, 1979; ed. A. M. Dziewonski and E. Boschi), Italian Physical Society and North-Holland Publ. Co., Amsterdam.
- Rice, J. R. (1993). Spatio-temporal complexity of slip on a fault, *J. Geophys. Res.* **98**, 9885-9907.
- Rousseau, C.-E., and A. J. Rosakis (2003). On the influence of fault bends on the growth of sub-Rayleigh and intersonic dynamic shear ruptures, *J. Geophys. Res.* **108** (B9), 2411, doi:10.1029/2002JB002310.
- Savage, J. C., and M. Lisowski (1991). Strain accumulation along the Denali fault at the Nenena river and Delta river crossings, Alaska, *J. Geophys. Res.* **96**, 14481-14492.
- Wallace, W. K., B. L. Sherrod, and T. E. Dawson (2002). Character and significance of surface rupture near the intersection of the Denali and Totschunda faults, M7.9 Denali fault earthquake, Alaska, November 3, 2002, *EOS* **83**, abstr. S72F-1335.

FIGURE CAPTIONS:

Figure 1.

(a) Rupture path, solid line, of the M_w 7.9 Denali earthquake. A star towards the left of center of the figure marks the epicenter of the 3 November 2002 event. [Figure courtesy: Alaska Division of Geological and Geophysical Surveys.]

(b) Aftershocks of the M_w 7.9 event, from Eberhart-Phillips et al. [2003], also showing three sub events during the rupture.

Figure 2.

Results of 2D numerical simulations from Kame et al. [2003] showing the influence of branching angle (ϕ) on a right-laterally propagating rupture at a velocity (v_r) of $0.8c_s$ near branching location. The orientation angle Ψ of the principal maximum stress with respect to the main fault is 56° . The solid black line shows the path of the rupture; unruptured fault regions shown in gray. c_s is the shear wave speed of the medium.

Figure 3.

Results of 2D numerical simulations from Kame et al. [2003] showing the influence of the orientation of the principal maximum stress with respect to the main fault (Ψ) on a right-laterally propagating rupture at a velocity (v_r) of $0.8c_s$ near branching location. The fault geometry is fixed with the branching angle $\phi = -15^\circ$.

Figure 4.

Results of 2D numerical simulations from Kame et al. [2003] showing the influence of rupture velocity at branching location (v_r) on a right-laterally propagating rupture approaching a branched fault segment at $\phi = -15^\circ$. The orientation of the principal maximum stress with respect to the main fault (Ψ) is 56° . The solid line shows the path of the rupture. c_s is the shear wave speed of the medium.

Figure 5.

Maximum principal stress orientations prior to the 2002 Denali earthquake sequence (black bars) and for the 2002 Denali earthquake sequence aftershocks (white bars), from Ratchkovski [2003]. Dashed polygons outline inversion blocks for events prior to October 2002. Solid polygons are the inversion regions using the aftershocks. Solid lines are the mapped fault traces. Subevent locations [Eberhart-Phillips et al., 2003] of the magnitude 7.9 earthquake are shown as hexagons.

Figure 6.

Fault geometry used in the model along with the associated parameters.

Figure 7.

Plot of slip velocity along the Denali and Totschunda fault segments for $\Psi = 70^\circ$; $v_r = 0.6c_s$ case. Slip velocity variation along the Totschunda fault is projected on the Denali fault. Totschunda fault begins at $5X/R_0 = 58$. v_r , c_s , R_0 , μ , v , $-\sigma_{yy}^0$ and c_p represent rupture velocity near the branching point, S-wave speed of the medium, size of the slip-weakening zone, shear modulus of the medium, slip velocity, initial normal compressive stress and P-wave velocity of the medium respectively.

Figure 8.

Plot of slip velocity along the Denali and Totschunda fault segments for $\Psi = 70^\circ$; $v_r = 0.8c_s$ case. Slip velocity variation along the Totschunda fault is projected on the Denali fault. Totschunda fault begins at $5X/R_0 = 108$.

Figure 9.

Plot of slip velocity along the Denali and Totschunda fault segments for $\Psi = 70^\circ$; $v_r = 0.9c_s$ case. Slip velocity variation along the Totschunda fault is projected on the Denali fault. Totschunda fault begins at $10X/R_0 = 380$.

Figure 10.

Plot of slip velocity along the Denali and Totschunda fault segments for $\Psi = 80^\circ$; $v_r = 0.87c_s$ case. Slip velocity variation along the Totschunda fault is projected on the Denali fault. Totschunda fault begins at $10X/R_0 = 414$.

Figure 11.

Plot of slip velocity along the Denali and Totschunda fault segments for $\Psi = 70^\circ$; $v_r = 1.4c_s$. Slip velocity variation along the Totschunda fault is projected on the Denali fault. Totschunda fault begins at $10X/R_0 = 104$.

Figure 12.

Variation of rupture velocity along the Denali and the Totschunda fault segments for $\Psi = 70^\circ$; $v_r = 0.6c_s$ and $\Psi = 70^\circ$; $v_r = 0.9c_s$ cases. v_r , c_s , R_0 , and c_p represent rupture velocity near the branching point, S-wave speed of the medium, size of the slip-weakening zone, and P-wave velocity of the medium respectively. Rupture velocity is determined as the time taken to advance three spatial cells and thus the possible values of rupture velocity are quantized.

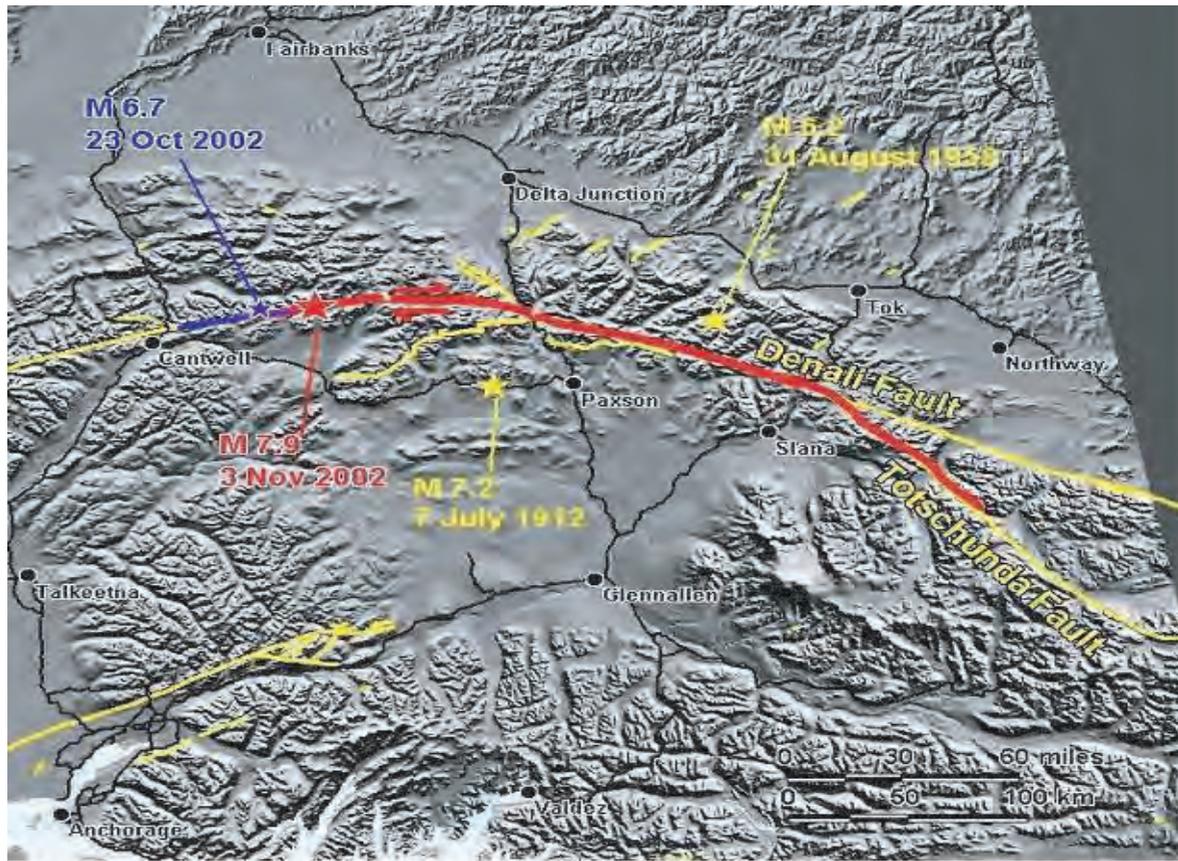


Figure 1a

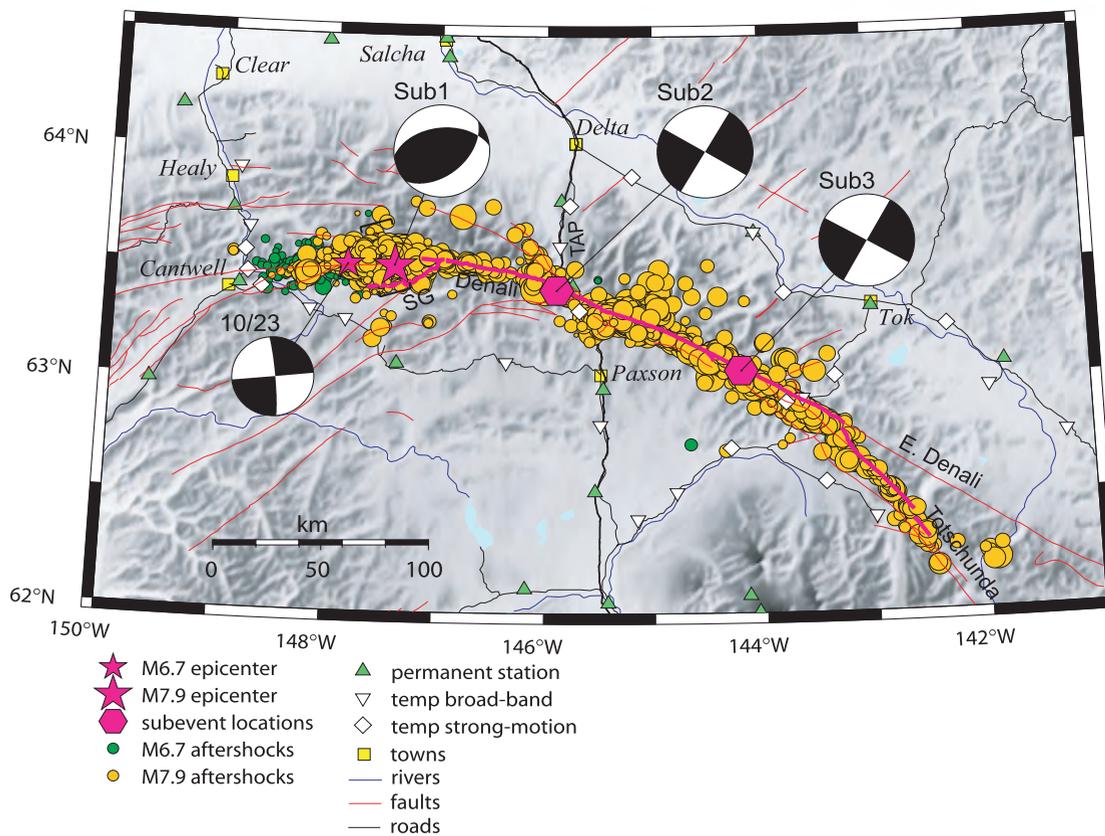


Figure 1b

$$\Psi = 56^\circ ; v_r = 0.8c_s$$

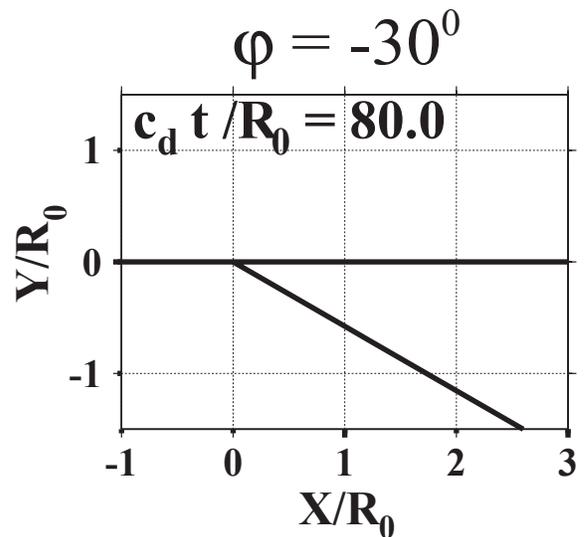
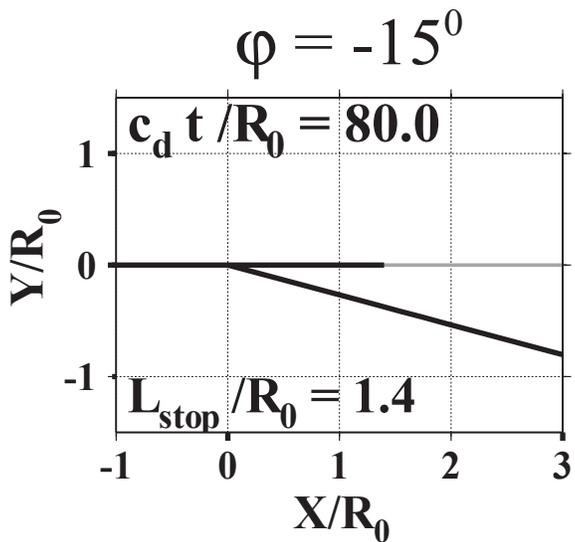
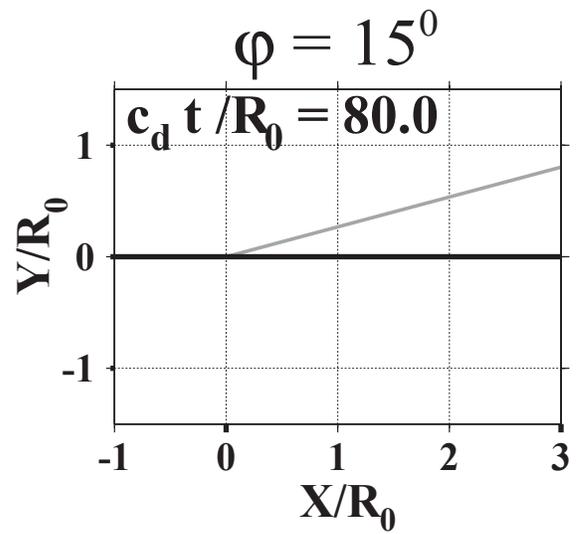
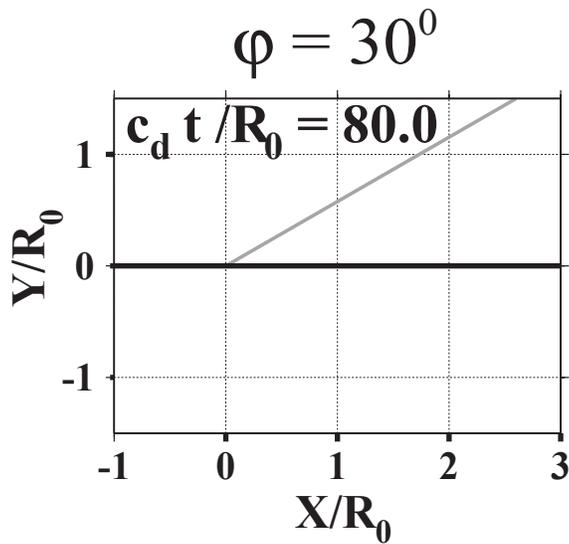
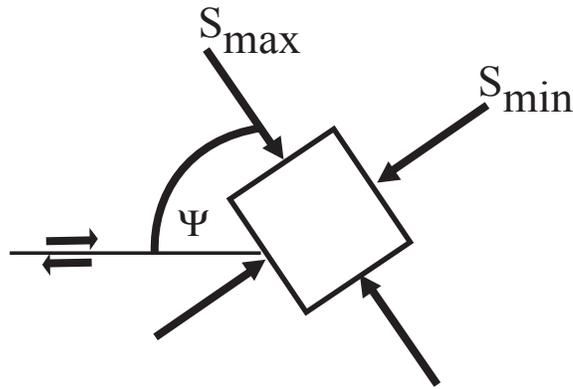


Figure 2

$$v_r = 0.8c_s; \varphi = -15^\circ$$

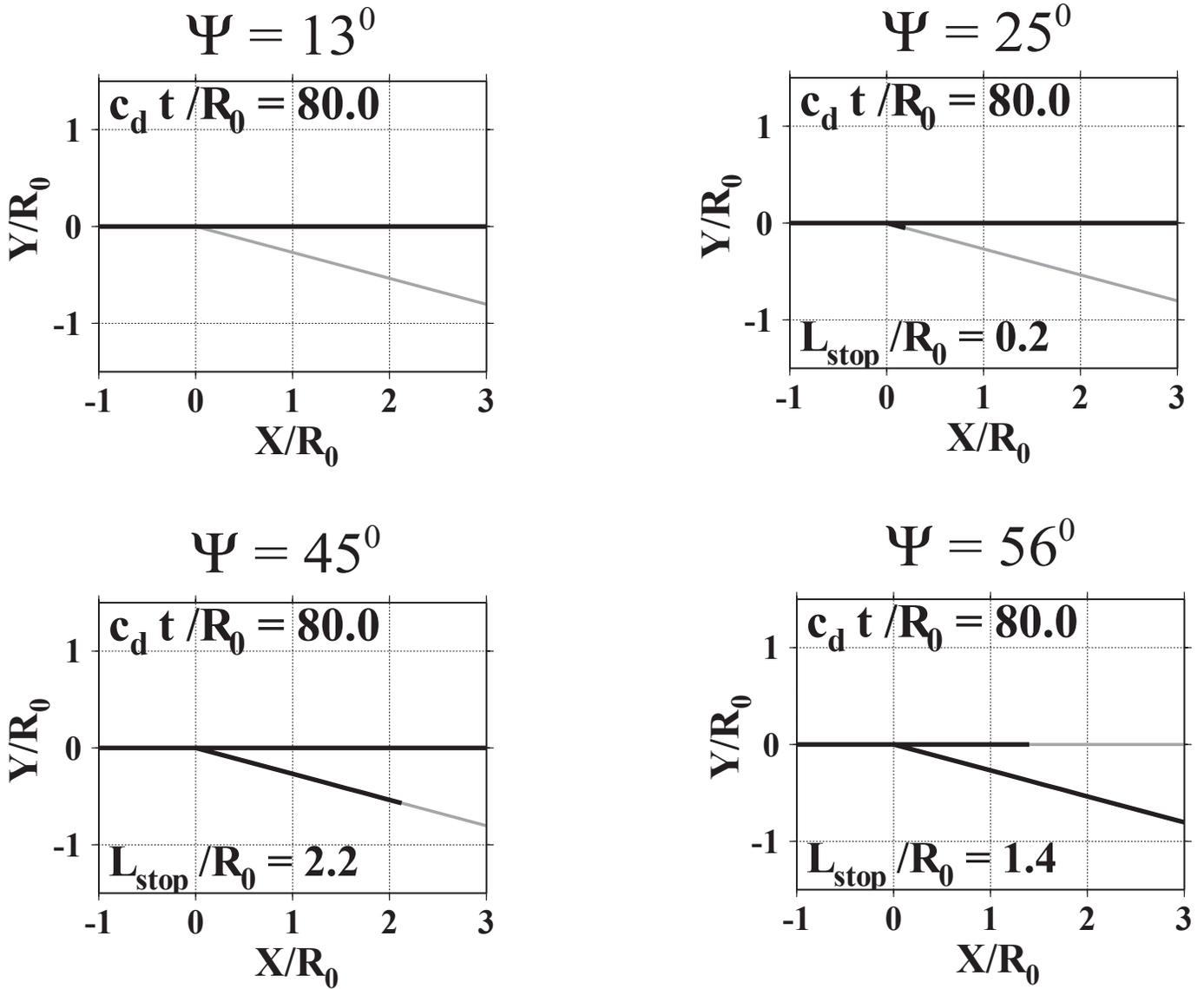


Figure 3

$$\Psi = 56^\circ ; \varphi = -15^\circ$$

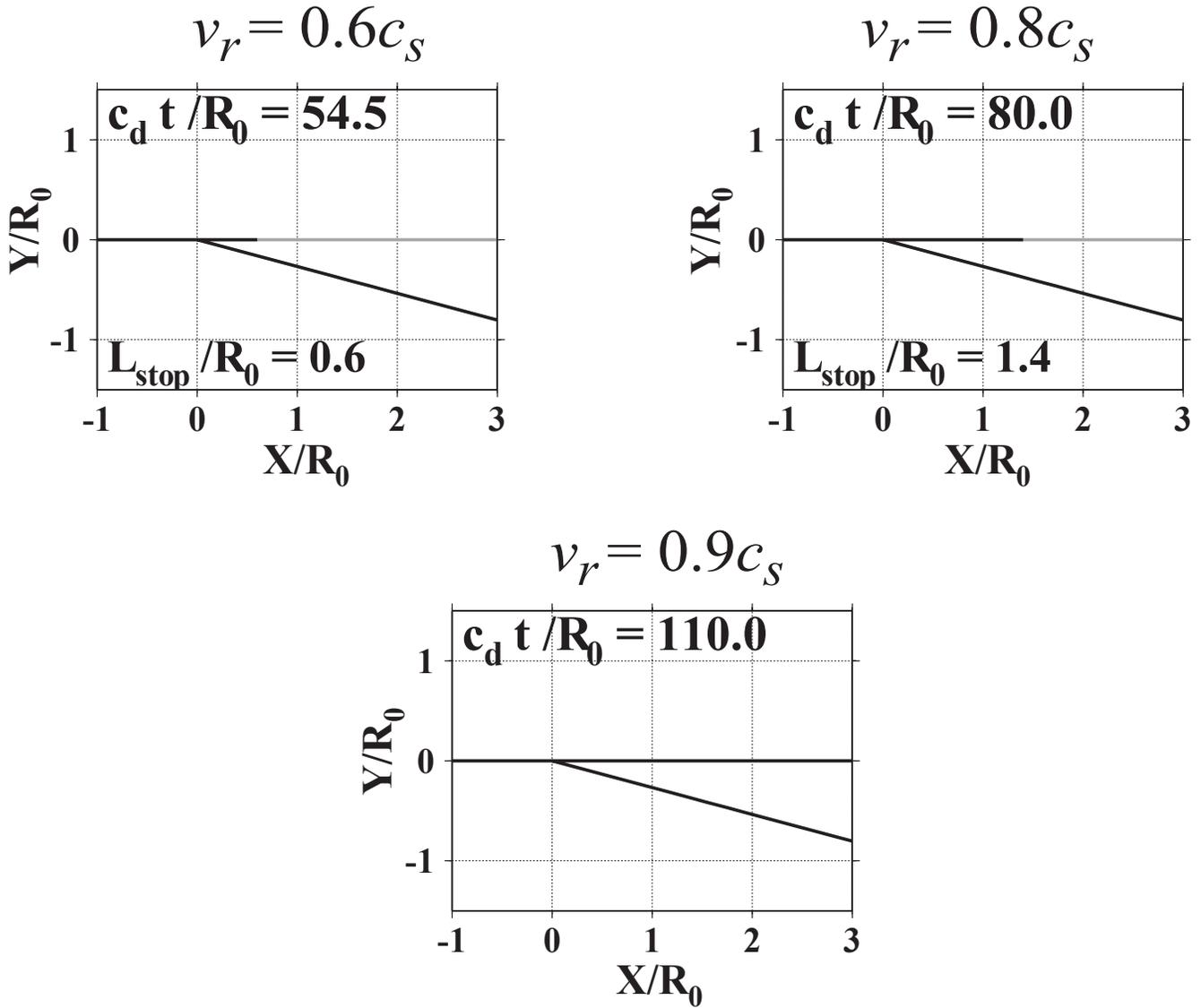


Figure 4

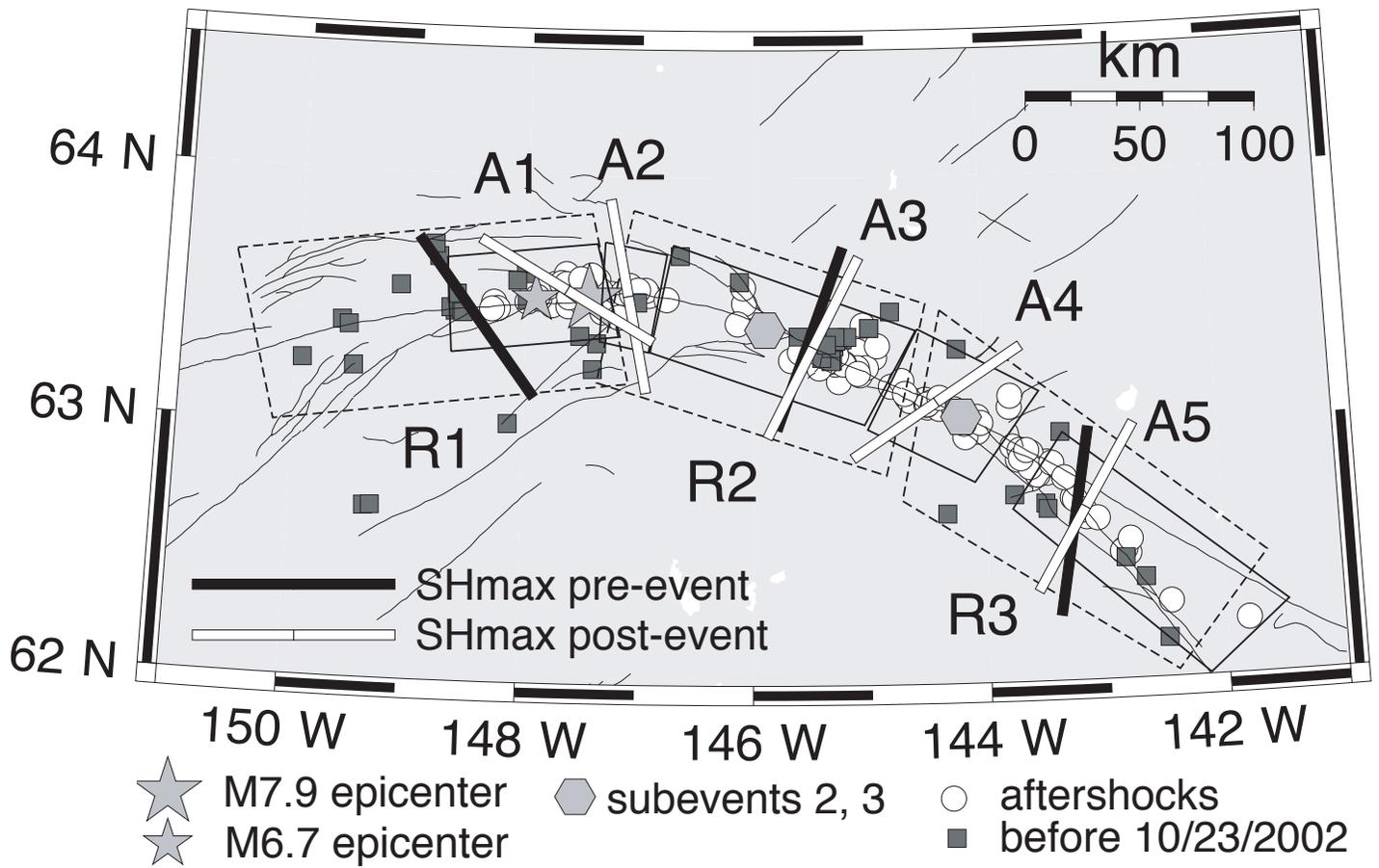


Figure 5

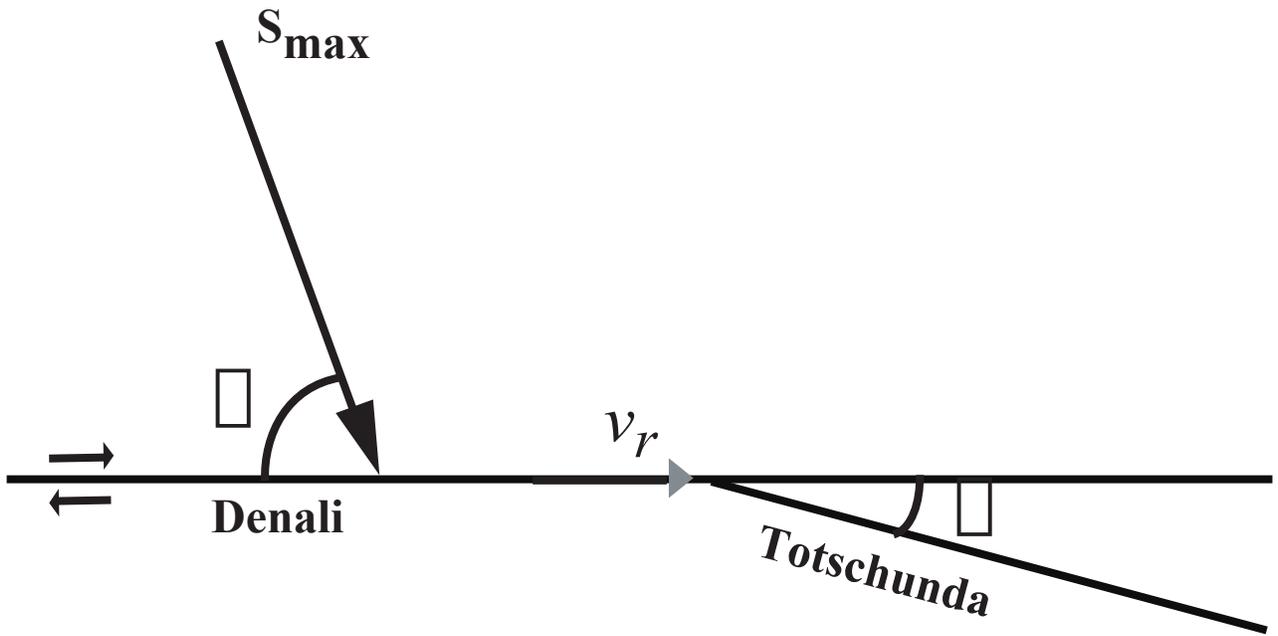


Figure 6

$$\Psi=70^{\circ}, \nu_r = 0.6c_s, \varphi = -15^{\circ}$$

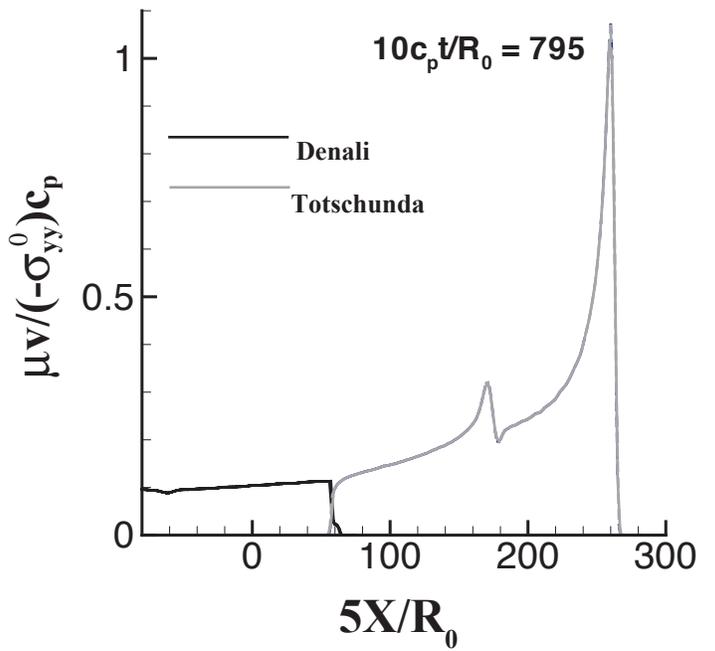
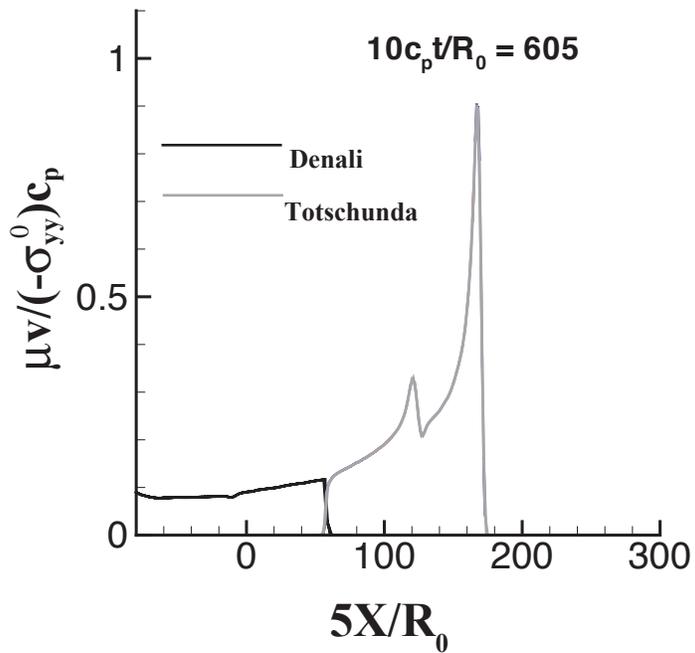
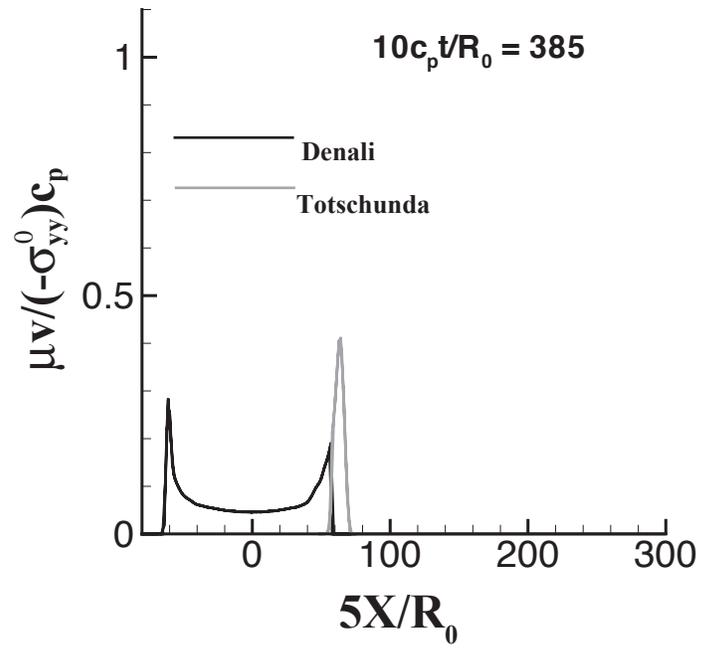
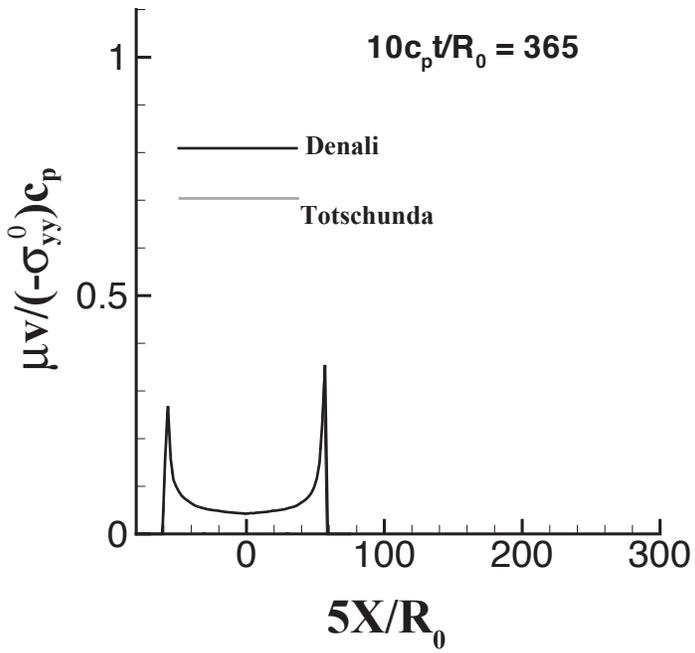


Figure 7

$$\Psi=70^{\circ}, v_r = 0.8c_s, \varphi = -15^{\circ}$$

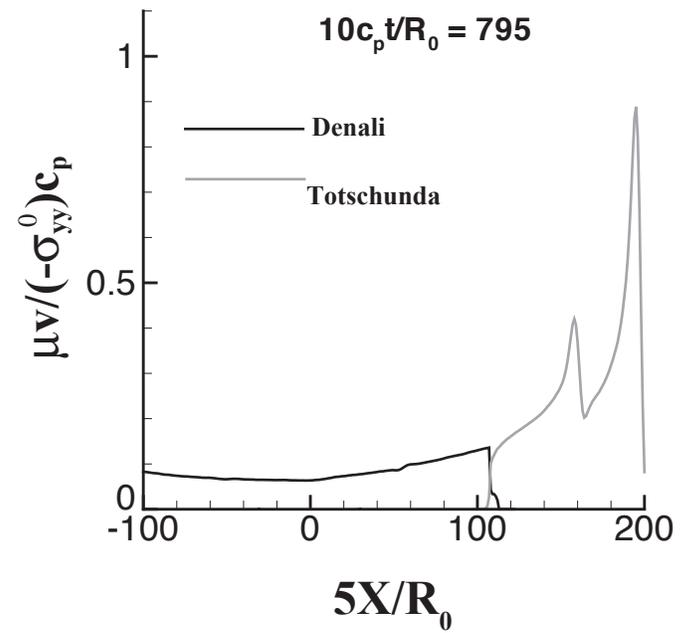
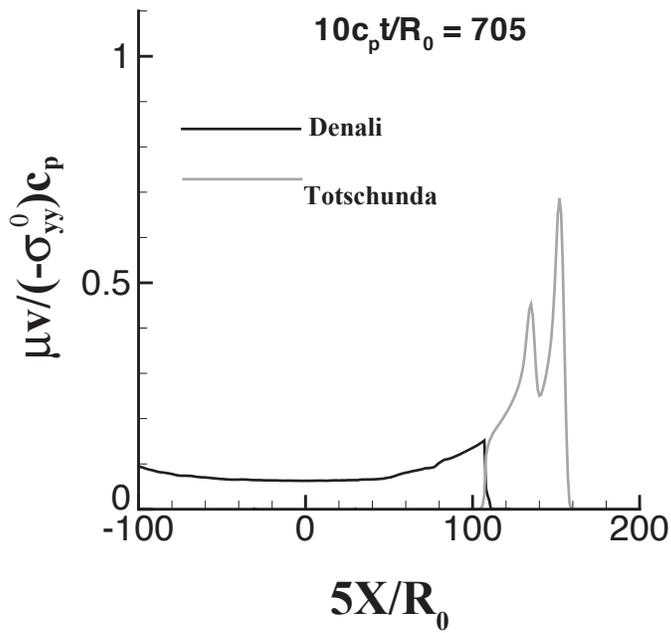
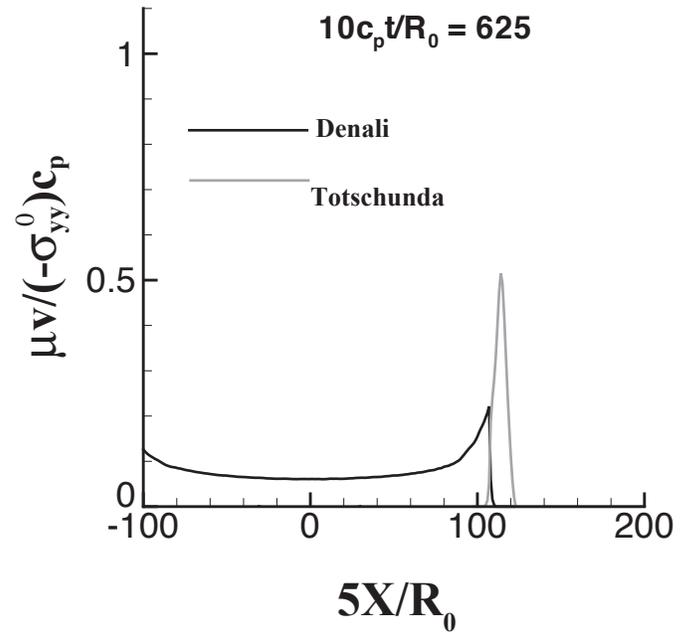
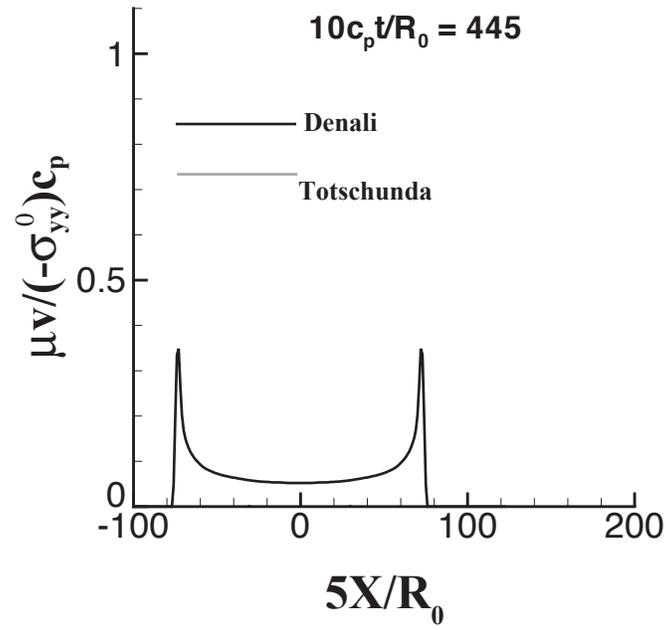


Figure 8

$$\Psi=70^{\circ}, \nu_r = 0.9c_s, \varphi = -15^{\circ}$$

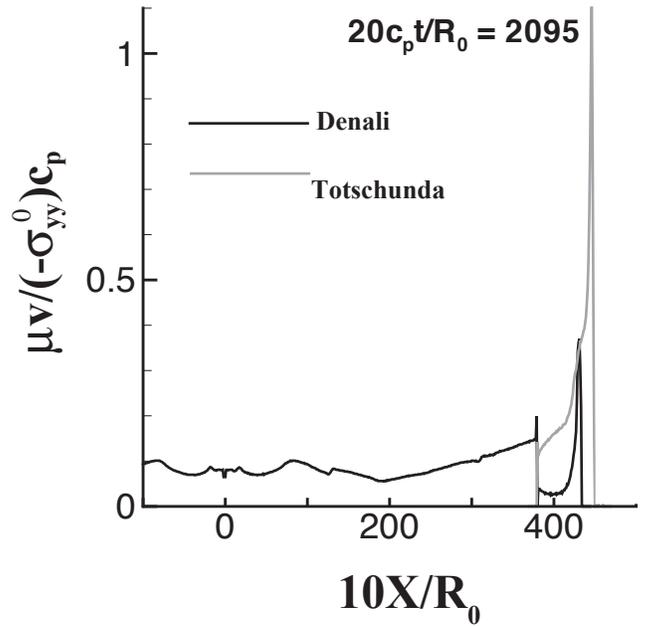
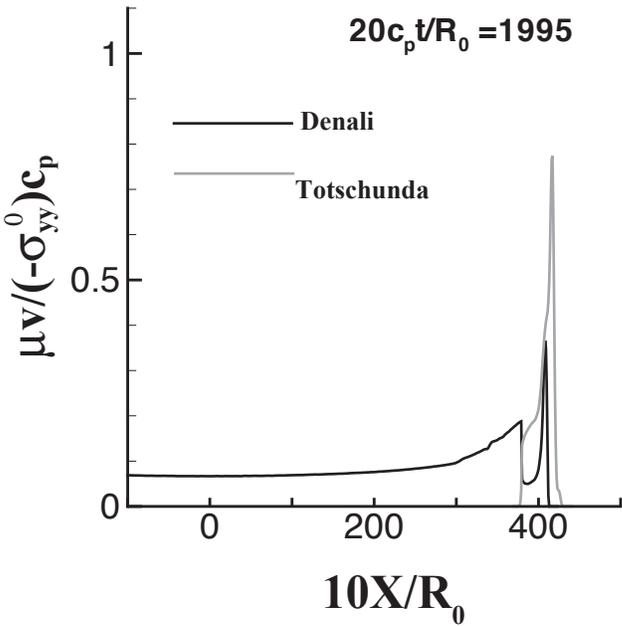
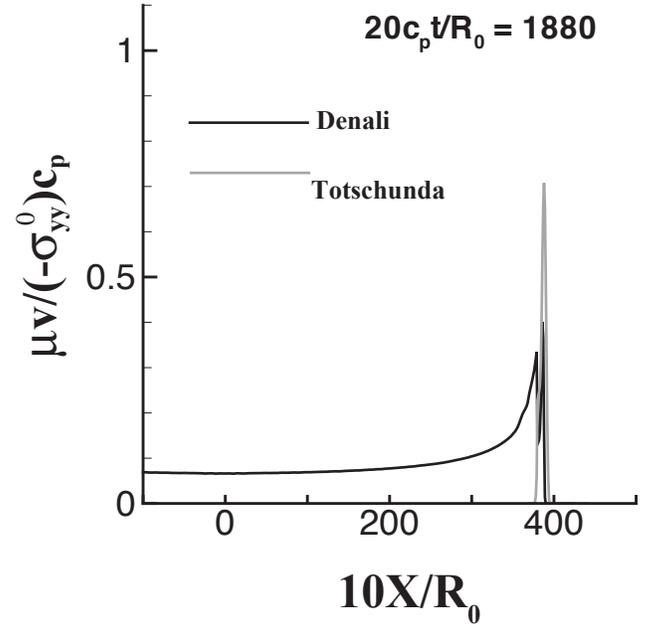
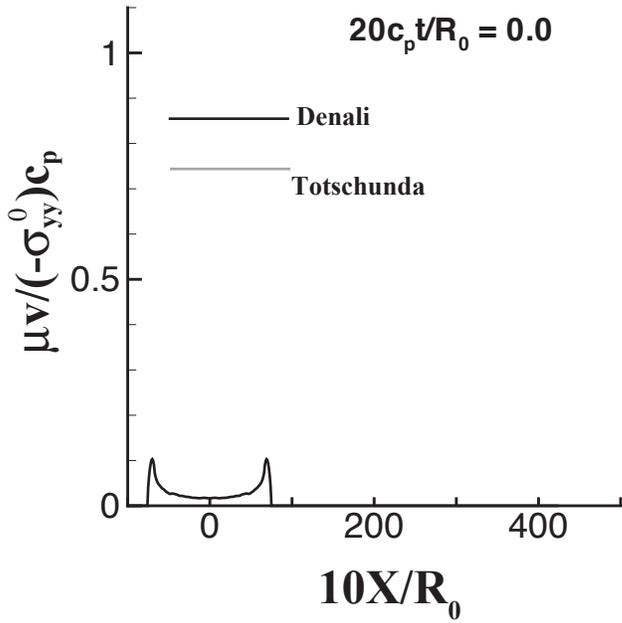


Figure 9

$$\Psi=80^{\circ}, v_r = 0.87c_s, \phi = -15^{\circ}$$

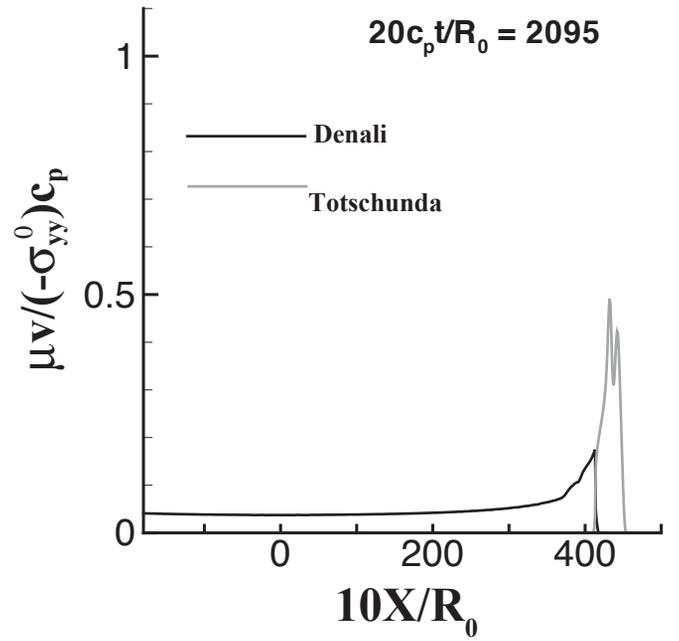
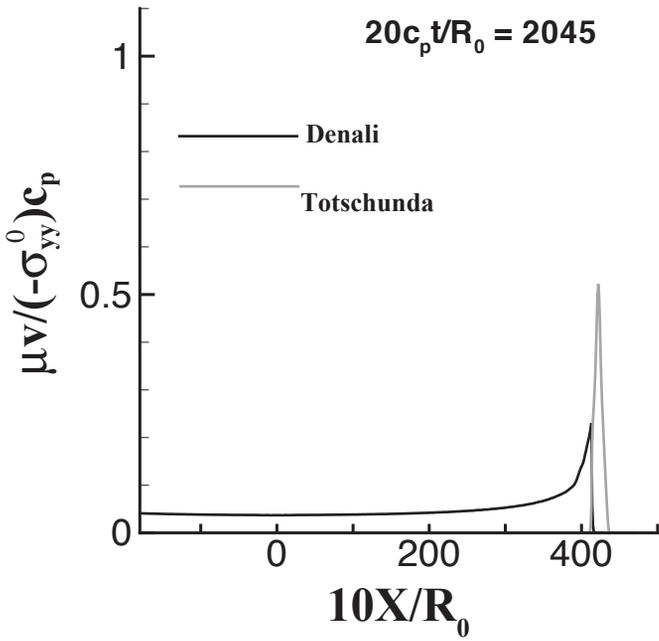
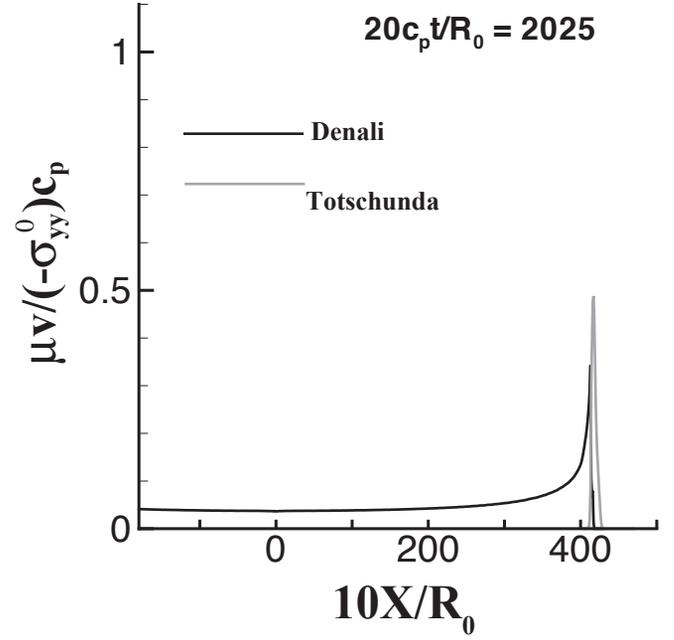
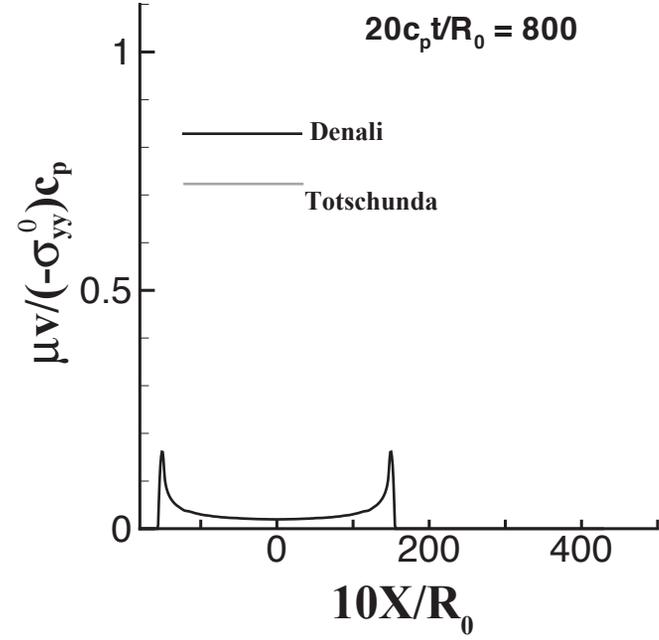


Figure 10

$$\Psi=70^\circ, v_r = 1.4c_s, \varphi = -15^\circ$$

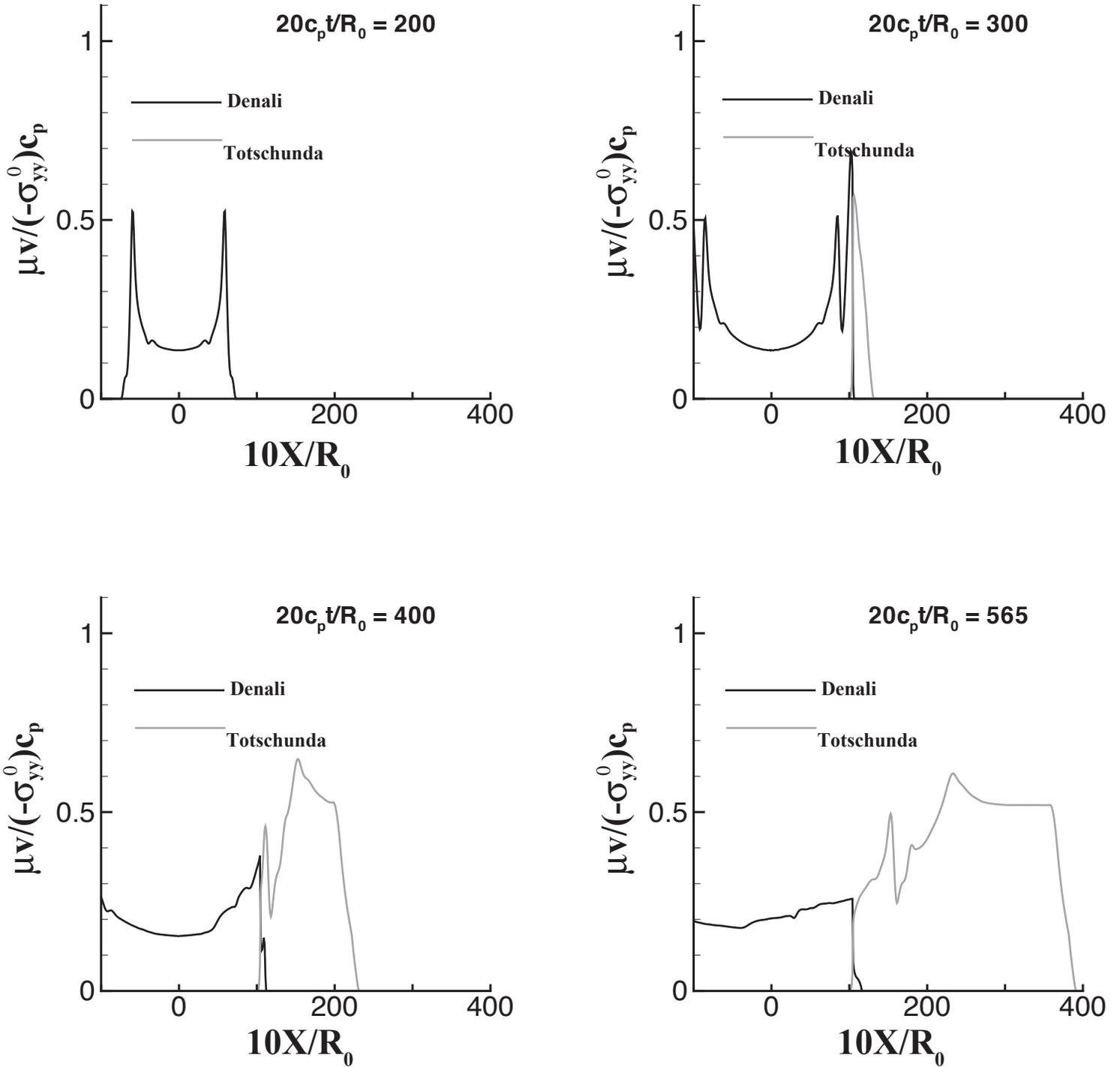
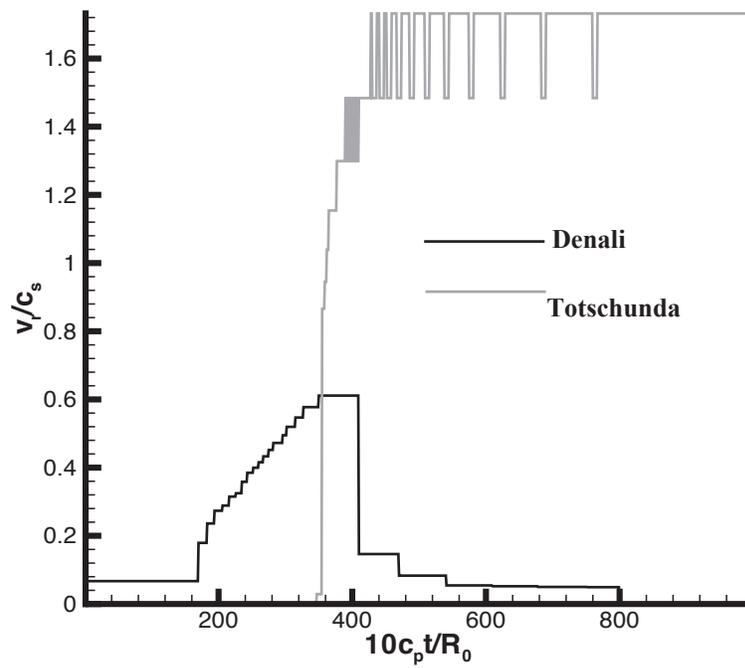


Figure 11

$$\Psi=70^{\circ}, v_r = 0.6c_s, \phi = -15^{\circ}$$



$$\Psi=70^{\circ}, v_r = 0.9c_s, \phi = -15^{\circ}$$

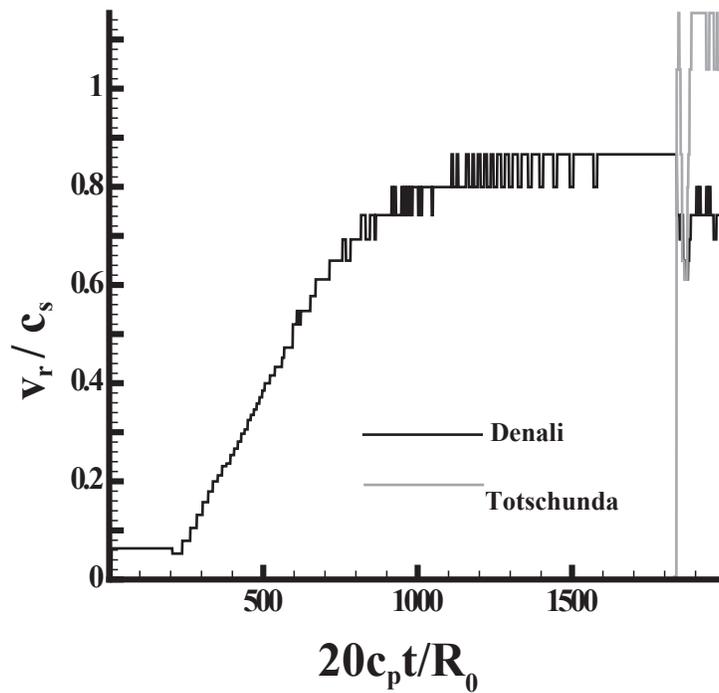


Figure 12

Dynamic Slip Transfer from the Denali to Totschunda Faults, Alaska: Testing Theory for Fault Branching

by Harsha S. Bhat, Renata Dmowska, James R. Rice, and Nobuki Kame

We analyze the observed dynamic slip transfer from the Denali to Totschunda faults during the M_w 7.9 3 November 2002 Denali fault earthquake, Alaska. This study adopts the theory and methodology of Poliakov *et al.* (2002) and Kame *et al.* (2003), in which it was shown that the propensity of the rupture path to follow a fault branch is determined by the preexisting stress state, branch angle, and incoming rupture velocity at the branch location. Here we check that theory on the Denali-Totschunda rupture process using 2D numerical simulations of processes in the vicinity of the branch junction. The maximum compression direction with respect to the strike of the Denali fault near the junction has been estimated to range from approximately 73° to 80° . We use the values of 70° and 80° in our numerical simulations. The rupture velocity at branching is not well constrained but has been estimated to average about $0.8 c_s$ throughout the event. We use $0.6 c_s$, $0.8 c_s$, $0.9 c_s$, and even $1.4 c_s$ as parameters in our simulations. We simulate slip transfer by a 2D elastodynamic boundary integral equation model of mode II slip-weakening rupture with self-chosen path along the branched fault system. All our simulations except for 70° and $0.9 c_s$ predict that the rupture path branches off along the Totschunda fault without continuation along the Denali fault. In that exceptional case there is also continuation of rupture along the Denali fault at a speed slower than that along the Totschunda fault and with smaller slip.

Introduction

A M_w 7.9 earthquake struck central Alaska on 3 November 2002. The Denali fault earthquake (DFE) occurred along the Denali fault system and ruptured a total length of approximately 350 km. The last segment of rupture was along the Totschunda fault, which branches off from the Denali fault, with 68 km of observed surface rupture (Peter Haeussler, U.S. Geological Survey [USGS], Anchorage; personal comm., 2002) (see Figure 1a [epicenter: star in center left of the figure]). Beyond the branching location no surface rupture was visible on the Denali fault for at least 25 km (P. Haeussler, USGS; personal comm., 2002).

Beyond the Denali-Totschunda branching location the aftershocks of the M_w 7.9 event occurred predominantly along the Totschunda fault segment (Fig. 1b) (Eberhart-Phillips *et al.*, 2003). Together with the lack of surface rupture along the continuation of the Denali fault, this indicates that after branching the rupture progressed exclusively along the Totschunda fault.

Summary of Theory for Fault Branching

Following the concepts introduced by Poliakov *et al.* (2002) on factors governing fault branching, Kame *et al.*

(2003) performed an extensive set of numerical simulations of branching. Those were done in the context of a 2D, mode II, rupture model with a slip-weakening friction coefficient, with strength during slip-weakening proportional to the instantaneous local normal stress. They involved a range of branching fault angles (ϕ) with the primary fault, rupture velocities (v_r) approaching the branching location, and maximum horizontal prestress inclinations (Ψ) with the main fault. See Figures 2–4 for their results which are most relevant for the present discussion; all results are shown for right-lateral rupture.

The results can be summarized as follows. For a given rupture velocity the most vulnerable branch orientations change from those on the compressional side ($\phi > 0$) to those on the extensional side ($\phi < 0$) with increasing orientation of the maximum horizontal stress with the main fault (as partly illustrated in Figs. 2 and 3). The tendency of the rupture path to proceed exclusively on the branch also increases (and becomes increasingly independent of rupture velocity) as one approaches the limits of maximum stress inclinations with respect to the main fault (0° or 90° for exclusive propagation on compressional or extensional branches, respectively). With increasing rupture velocity

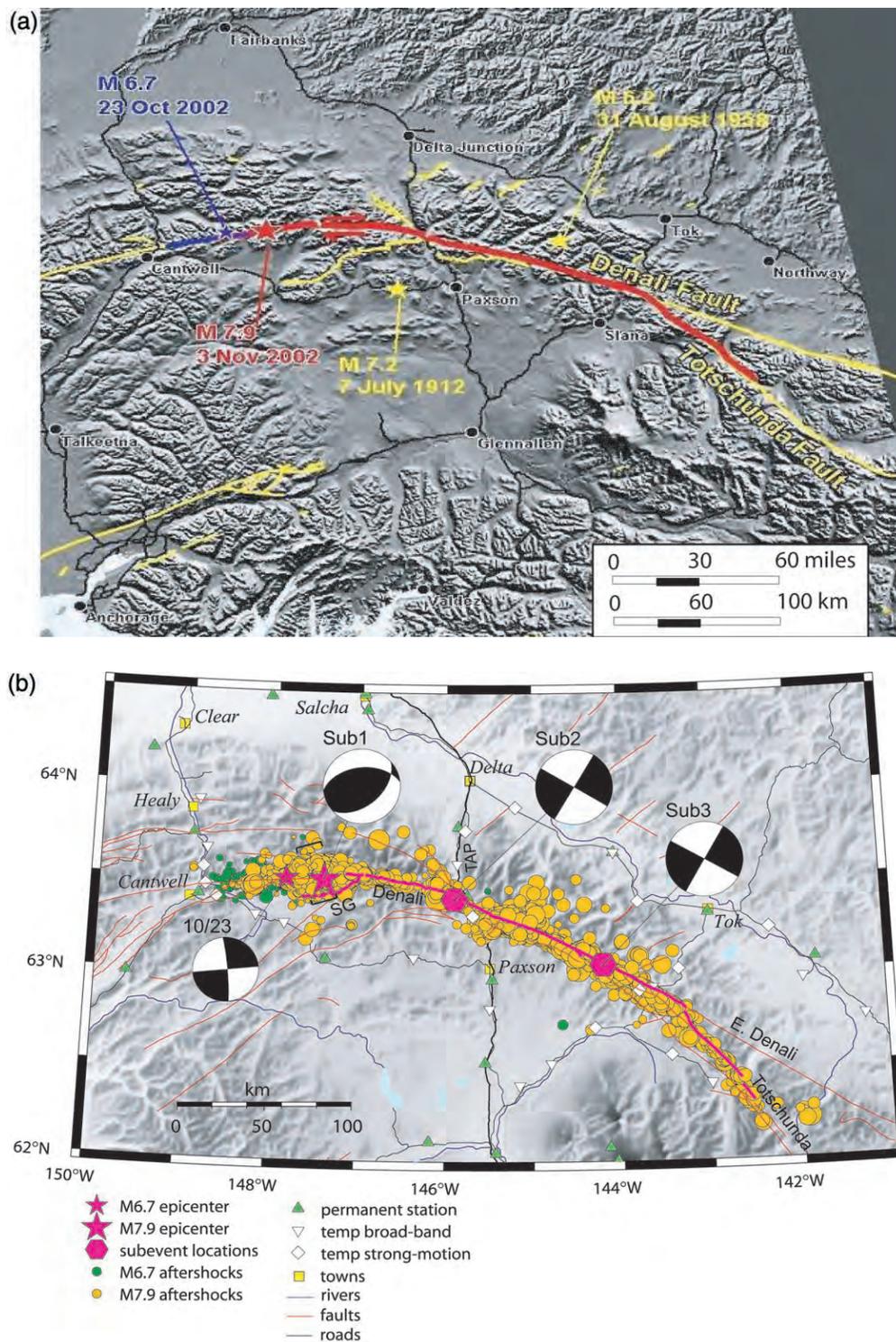


Figure 1. (a) Rupture path, solid line, of the M_w 7.9 Denali fault earthquake. A star toward the left of center of the figure marks the epicenter of the 3 November 2002 event (figure courtesy of Alaska Division of Geological and Geophysical Surveys). (b) Aftershocks of the M_w 7.9 event, from Eberhart-Phillips *et al.* (2003), also showing three subevents during the rupture.

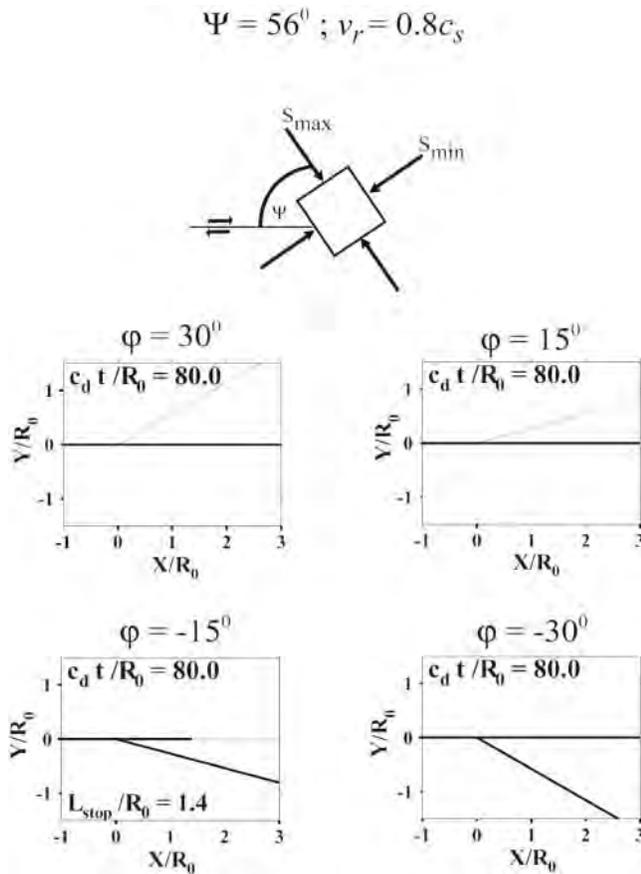


Figure 2. Results of 2D numerical simulations from Kame *et al.* (2003) showing the influence of branching angle (ϕ) on a right-laterally propagating rupture at a velocity (v_r) of $0.8 c_s$ near the branching location. The orientation angle Ψ of the principal maximum stress with respect to the main fault is 56° . The solid black line shows the path of the rupture; fault regions are shown in gray; c_s is the shear-wave speed of the medium.

(keeping Ψ constant) the stress shadow effect of one fault on another, which is important for small branching angles, decreases; this makes the rupture path lie less exclusively either along the main fault or along the branched one (Fig. 4). The parameter L_{stop}/R_0 in the figures refers to the distance, L_{stop} , beyond the branch junction at which propagation has stopped on either the branch or the main fault. L_{stop} is normalized by R_0 , which is the length that the slip-weakening zone would occupy along the main fault in low speed propagation (Kame *et al.*, 2003).

Determination of Parameters Influencing Branching for the Denali Fault Earthquake

Maximum Principal Stress Direction (Ψ)

Nakamura *et al.* (1980) estimated the late Quaternary tectonic stress trajectories in the Aleutians and Alaska, using geologic indicators along continental Alaska. Their results

show averaged directions of maximum horizontal compression. The principal stress direction near to the Denali-Totschunda branching region is estimated from their results as approximately 75° with respect to the main fault. Estabrook and Jacob (1991) later provided a map of maximum horizontal compression-determined stress trajectories from a variety of sources, including seismic focal mechanisms, volcanic, geologic fault, and borehole breakout data, for Alaska, the Aleutians, and the Bering Sea. This was based on the results of Nakamura *et al.* (1980) and Estabrook *et al.* (1988). The principal stress direction nearest to the Denali-Totschunda branching region was again reported to be at approximately 75° with respect to the strike of the Denali fault just before branching.

Azimuths of maximum and minimum horizontal compression, obtained by using stress-tensor inversion from focal mechanisms, were determined along different fault systems in central Alaska by Ratchkovski and Hansen (2002). All their regions were on the order of 100 to 400 km west of the branching location, and most also to the north. The principal stress direction nearest to the Denali-Totschunda branching region was found to be approximately 73° (by extrapolating results from closest locations) with respect to the strike of the Denali fault just before branching.

Based on the more recent focal mechanism inversions of Ratchkovski (2003) it can be seen that as one traverses along the Denali fault eastward, from the epicenter, the direction of principal maximum stress, before the earthquake, rotates slightly in a clockwise sense from R1 to R2 and counterclockwise from R2 to R3 (Fig. 5). The direction of principal maximum compressive stress close to the Denali-Totschunda branching location was therefore inclined at about 80° with respect to the Denali fault prior to the DFE.

We choose two values of Ψ , 70° and 80° , to cover the range of observations. The latter better represents measurements near the branching junction; the former is an approximate lower bound based on regional stress studies. Based on the results of Kame *et al.* (2003), $\Psi = 70^\circ$ is a conservative estimate for our simulations because, as it was noted earlier, the likelihood of the rupture taking the branch exclusively increases with increasing Ψ and becomes increasingly independent of the rupture velocity when approaching the branching location. We will show that the rupture path is predicted to be captured exclusively by the branch in nearly all cases studied when $\Psi = 70^\circ$ and in all cases when $\Psi = 80^\circ$.

Rupture Velocity (v_r)

The average rupture velocity during the DFE seems to be about 80% of the shear-wave speed (Kikuchi and Yamataka, 2002), although the velocity as the branch was approached is not yet constrained very well. Inversion of strong motion records by Eberhart-Phillips *et al.* (2003) revealed three subevents (Fig. 1b) during the DFE with the second and the third subevent occurring at about 125 km and 50 km

$$v_r = 0.8c_s; \varphi = -15^\circ$$

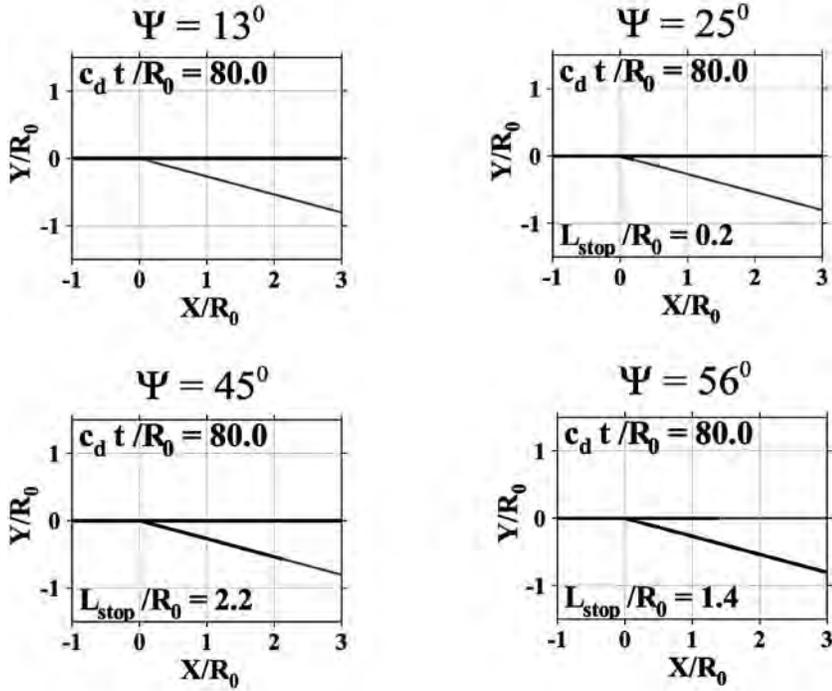


Figure 3. Results of 2D numerical simulations from Kame *et al.* (2003) showing the influence of the orientation of the principal maximum stress with respect to the main fault (Ψ) on a right-laterally propagating rupture at a velocity (v_r) of $0.8 c_s$ near the branching location. The fault geometry is fixed with the branching angle $\varphi = -15^\circ$.

$$\Psi = 56^\circ; \varphi = -15^\circ$$

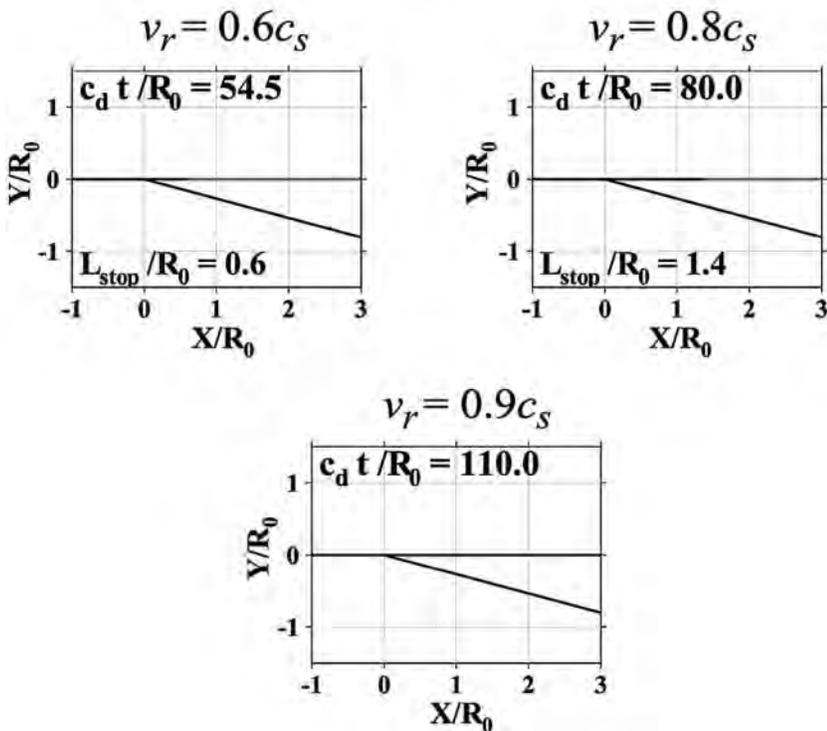


Figure 4. Results of 2D numerical simulations from Kame *et al.* (2003) showing the influence of the rupture velocity at the branching location (v_r) on a right-laterally propagating rupture approaching a branched fault segment at $\varphi = -15^\circ$. The orientation of the principal maximum stress with respect to the main fault (Ψ) is 56° . The solid line shows the path of the rupture; c_s is the shear-wave speed of the medium.

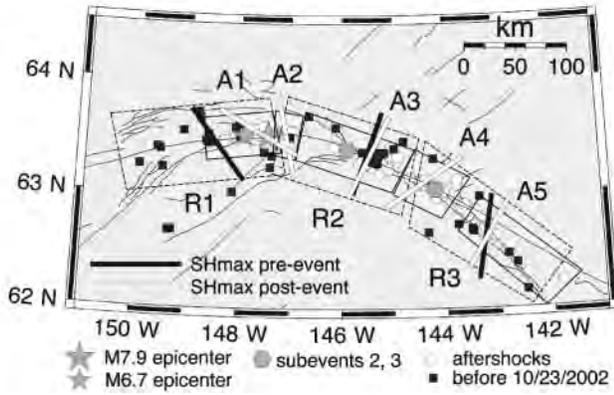


Figure 5. Maximum principal stress orientations prior to the 2002 Denali fault earthquake sequence (black bars) and for the 2002 Denali fault earthquake sequence aftershocks (white bars), from Ratchkovski (2003). Dashed polygons outline inversion blocks for events prior to October 2002. Solid polygons are the inversion regions using the aftershocks. Solid lines are the mapped fault traces. Subevent locations (Eberhart-Phillips *et al.*, 2003) of the M 7.9 earthquake are shown as hexagons.

to the west of the Denali-Totschunda branching location, respectively. Best-fitting inversion required a high rupture velocity of about 3.5 km/sec between subevents 2 and 3. Ellsworth *et al.* (2004) note that the rupture actually went supershear near Trans-Alaska Pipeline Pump Station no. 10 (PS10), whose location is much further to the west of the branching location and is very close to subevent 2. They also mention that the rupture velocity is about $0.8 c_s$ for about 20 km east of PS10. We therefore carry out our numerical simulations for different values of rupture velocity when approaching the branching location, including supershear rupture velocity. (Rousseau and Rosakis [2003] have extended branching concepts like in Poliakov *et al.* (2002) to the supershear regime.)

Branching Angle (φ)

The Totschunda fault branches away from the Denali fault, to the extensional side, at an angle of approximately 15° . The angle was measured from a fault map of central Alaska provided by Savage and Lisowski (1991).

Wallace *et al.* (2002) suggested that the northern part of the Totschunda fault system may consist of multiple discontinuous southeast-striking strands and is locally connected by south-striking step-over faults. This may reflect the immaturity of the northern Totschunda system. The aim of our study is to do a first-order analysis of the branching process by simplifying the geometry. This approach to a simpler model is supported by examination of an aerial photo (P. Haeussler, personal comm.) of the branch location, which suggests a simple branching geometry.

Numerical Implementation Using the Boundary Integral Equation (BIE) Method

Numerical implementation of the dynamic rupture propagation scheme was done using the 2D Boundary Integral Equation (BIE) method as described in Kame *et al.* (2003). An important advantage of this method is that the domain of calculations is confined to the fault geometry. A long-running rupture, which is depth limited, as for the DFE event, cannot be modeled in a 2D framework. However, observing the theoretical concepts outlined in Poliakov *et al.* (2002), Kame *et al.* (2003), and Rousseau and Rosakis (2003), we can argue that the critical factor, other than the geometry and prestress, is the rupture speed as the branch is approached. This can be suitably simulated in 2D, with far greater grid refinement than in 3D simulations, by nucleating a 2D rupture at various distances from the branching location. Given the present computing capabilities, the 2D formulation allows adequate grid refinement to fully resolve the slip-weakening process, a feature which is not generally achieved in 3D simulations. Nevertheless, the rupture phenomenon is clearly a 3D one, and much has been learned about branching from such simulations by Aochi *et al.* (2000a,b), Aochi and Fukuyama (2002), Oglesby *et al.* (2000a,b), and Oglesby and Day (2001).

Following the discretized form of the dynamic representation theorem evaluated by Kame and Yamashita (1999a,b, 2003), we obtain the following algebraic equation for the change in shear traction on spatial cell l , at the end of time step n , due to the slip history up to that time:

$$\Delta\tau^{l,n} = \sum_{k=1}^n \sum_i V^{i,k} K^{l-i,n-k}, \quad (1)$$

where $V^{i,k}$ is the slip velocity of cell i , during time step k , and $K^{l-i,n-k}$ is the response to unit slip velocity in cell i in time step k .

If we now assign the discretization parameters, cell size Δs and time step Δt , such that $c_p \Delta t / \Delta s = 0.5$, then equation (1) decouples (actually for all $c_p \Delta t / \Delta s < 1$) resulting in an explicit formulation as below (c_p is the P -wave speed of the medium):

$$\Delta\tau^{l,n} = V^{l,n} K^{0,0} \sum_{k=1}^{n-1} \sum_i V^{i,k} K^{l-i,n-k}, \quad (2)$$

where $K^{0,0} (= -\mu/2c_s)$ is the radiation damping term (Cochard and Madariaga, 1994) for shear modulus μ and shear-wave velocity c_s . This term represents the instantaneous contribution of the current slip velocity to the shear stress at the same position (μ is the shear modulus of the medium and c_s is the shear wave speed of the medium). A similar expression applies for the change of normal stress on the fault, except that there is zero instantaneous contribution (Kame *et al.*, 2003).

We use a slip-weakening friction law as originally proposed by Ida (1972) and Palmer and Rice (1973). We formulate this in a Coulomb manner so that the fault strength is always proportional to the normal stress acting on the fault. Thus, it is the friction coefficient that slip weakens. According to this law, the strength of the fault, at constant compressive normal stress, decreases linearly from an initial peak strength, τ_p , to a residual strength, τ_r , up to a critical slip, $\Delta u = D_c$, and then remains constant at the residual level for any further slip. Thus,

$$\begin{aligned} \tau &= \tau_r + (\tau_p - \tau_r)(1 - \Delta u/D_c)H(1 - \Delta u/D_c) \\ \tau_p &= \mu_s(-\sigma_n); \quad \tau_r = \mu_d(-\sigma_n), \end{aligned} \quad (3)$$

where $H(\cdot)$ is the Heaviside function, μ_s and μ_d are the static and dynamic coefficients of friction, respectively; $(-\sigma_n)$ is the normal stress acting on the fault (stress defined as positive in tension). We use the same expression during general stress and slip histories, taking τ_p and τ_r to be proportional to the instantaneous effective normal stress as indicated. Andrews (1976) defined a parameter $S = (\tau_p - \sigma_{yx}^0)/(\sigma_{yx}^0 - \tau_r)$ associated with the slip-weakening law where σ_{yx}^0 is the initial shear stress on the fault. This parameter has a critical value (approximately 1.77) below which the rupture propagates with a speed that ultimately transitions to supershear for propagation paths that are sufficiently long compared with the size of the nucleation zone.

All parameters in our calculations are nondimensionalized as follows:

1. Length, $X^* = X/R_0$
2. Time, $t^* = 2c_p t/\Delta s$
3. Slip, $\Delta u^* = \mu \Delta u / [(-\sigma_{yy}^0)R_0]$
4. Slip velocity $V^* = \mu V^* = \mu V / [(-\sigma_{yy}^0)c_p]$
5. Stress, $\sigma_{ij}^* = \sigma_{ij} / (-\sigma_{yy}^0)$

Here, $-\sigma_{yy}^0$ is the initial compressive stress on the primary (Denali) fault, where $R_0 = [(3\pi/8)(\mu D_c)(\tau_p - \tau_r)]$ is the approximate slip-weakening zone length at low rupture velocity as derived in Palmer and Rice (1973) and Rice (1980) and used in Poliakov *et al.* (2002) and Kame *et al.* (2003). The P -wave speed of the medium is c_p and μ is the shear modulus. To fully resolve the slip-weakening process, Δs should be much less than R_0 . We use $R_0/\Delta s = 5$ or 10 in our simulations, the larger number being needed when rupture propagation speed is close to the Rayleigh speed ($\approx 0.92 c_s$).

The numerical simulation of dynamic-rupture propagation is carried out in the following two steps.

Static Slip Distribution along the Minimum Nucleation Length. To obtain the required rupture velocity on the primary fault at the branching location, we nucleate the rupture at various distances from the branching location without referring to the actual nucleation point on the Denali fault. Our goal here is to understand the dynamics of the rupture front

at various speeds as the branch is approached and not to simulate the entire event (impossible within our 2D formulation).

The minimum nucleation length (L_c), as described in Andrews (1976) and Kame *et al.* (2003), obtained from the fracture mechanics energy balance (for Poisson ratio $\nu = 0.25$) is determined using

$$L_c = \frac{16}{3\pi} \frac{\mu G}{(\sigma_{yx}^0 - \tau_r)^2} = \frac{64}{9\pi^2} \left(\frac{\tau_p - \tau_r}{\sigma_{yx}^0 - \tau_r} \right)^2 R_0, \quad (4)$$

where L_c is the total length of the slipping zone (twice the length in Andrews [1976]). We choose a certain length of the fault, L , such that L/R_0 is slightly greater than L_c/R_0 . In this region we prescribe a slip distribution and prevent any slip outside the region, such that the fault is in static equilibrium. This causes an initial stress concentration that is slightly larger than the peak strength at both ends of the static nucleation zone and finitely accelerates rupture in the first dynamic time steps (Kame *et al.*, 2003).

Dynamic Rupture Propagation. After prescribing the slip distribution as explained in the previous step, the rupture is allowed to propagate dynamically along the main fault and the rupture-velocity history is calculated to position a branch to the primary fault so that the rupture velocity on the primary fault, when approaching the branch, is the one desired.

The branch is placed in position and dynamic rupture is then allowed to continue both along the main and the branched faults. We monitor stress in each time step to see whether rupture begins ($\tau \geq -\mu_s \sigma_n$) at the first element of the branch and at the front of any rupture along it and the main fault.

Summary of Results

Numerical studies were conducted by using the boundary integral equation method elaborated earlier. Figure 6 shows the fault geometry adopted for our simulations, of which preliminary results were reported in Bhat *et al.* (2002).

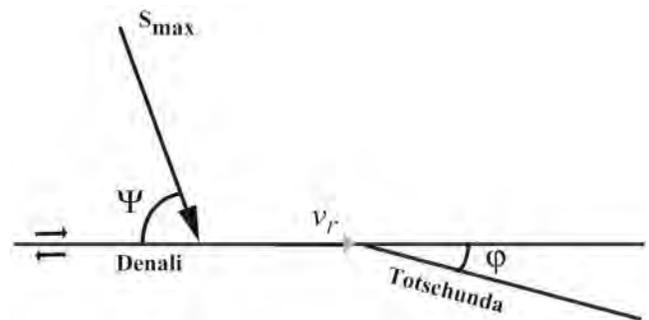


Figure 6. Fault geometry used in the model along with the associated parameters.

Because the S ratio governs the nature of rupture (super-shear or subshear), a desired value is first chosen. This would then give the initial shear stress acting on the fault (as a fraction of $-\sigma_{yy}^0$) if values of μ_s and μ_d are assumed. If the prestress field is normalized by the fault normal prestress, then the normalized fault parallel prestress can be obtained by using the desired value of Ψ , the orientation of the principal maximum compressive stress with the primary fault. The prestress parameters thus obtained must be checked so that the Mohr-Coulomb failure criterion based on μ_s is not violated either on the primary or the branched fault.

Dreger *et al.* (2004) noted, in their dynamic source modeling of the DFE using a 3D finite element method, that the rupture actually jumps ahead of the primary rupture front by 14 km, triggering slip on the Totschunda fault. We do not observe such a phenomenon in our simulations.

Our calculations were done for various values of v_r and Ψ at the Denali-Totschunda branching location.

Case 1: $v_r = 0.60 c_s$; $\Psi = 70^\circ$; $\mu_s = 0.60$;
 $\mu_d = 0.12$; $S_{\text{Den}} = 3$; $S_{\text{Tot}} = 0.6$

When the velocity of the rupture approaching the branching location at the Totschunda fault is $0.6 c_s$, the rupture branches completely onto the Totschunda fault. Figure 7 shows the combined plots of slip velocity along both the

Denali and Totschunda faults. It is clearly observed that once the rupture on the Denali fault crosses the branching location the slip velocity decreases rapidly with time. This is a clear indication of that the main fault can no longer accommodate slip beyond the branching location.

At time step 365 the rupture has reached the branching point. We observe in our simulations at this time step that the slip velocity at the right end of the rupture front accelerates briefly before slowing down. This may be a result of numerical oscillations in our calculations.

Case 2: $v_r = 0.80 c_s$; $\Psi = 70^\circ$; $\mu_s = 0.60$;
 $\mu_d = 0.12$; $S_{\text{Den}} = 3$; $S_{\text{Tot}} = 0.6$

For this case, the rupture again branches along the Totschunda fault with no further continuation on the Denali fault. Figure 8 shows slip velocity along both the Denali and Totschunda faults. It is clear, as in the previous case, that beyond the branch, the slip velocity diminishes rapidly on the Denali fault.

Case 3: $v_r = 0.90 c_s$; $\Psi = 70^\circ$; $\mu_s = 0.60$;
 $\mu_d = 0.12$; $S_{\text{Den}} = 3$; $S_{\text{Tot}} = 0.6$

Earlier studies by Kame *et al.*, (2003) showed that, for this value of rupture velocity and for $\Psi = 56^\circ$, the rupture

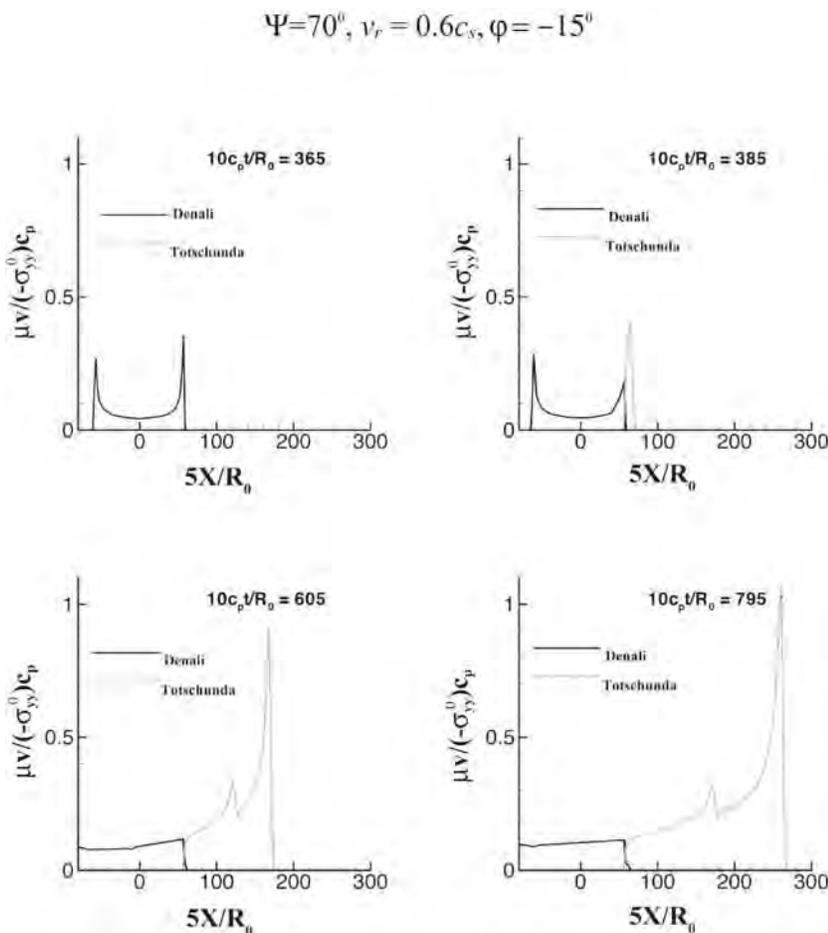


Figure 7. Plot of slip velocity along the Denali and Totschunda fault segments for $\Psi = 70^\circ$; $v_r = 0.6 c_s$. Slip velocity variation along the Totschunda fault is projected onto the Denali fault. The Totschunda fault begins at $5X/R_0 = 58$. v_r , c_s , R_0 , μ , v , $-\sigma_{yy}^0$, and c_p represent the rupture velocity near the branching point, the S -wave speed of the medium, the size of the slip-weakening zone, the shear modulus of the medium, the slip velocity, the initial normal compressive stress, and the P -wave velocity of the medium, respectively.

$$\Psi = 70^\circ, v_r = 0.8 c_s, \varphi = -15^\circ$$

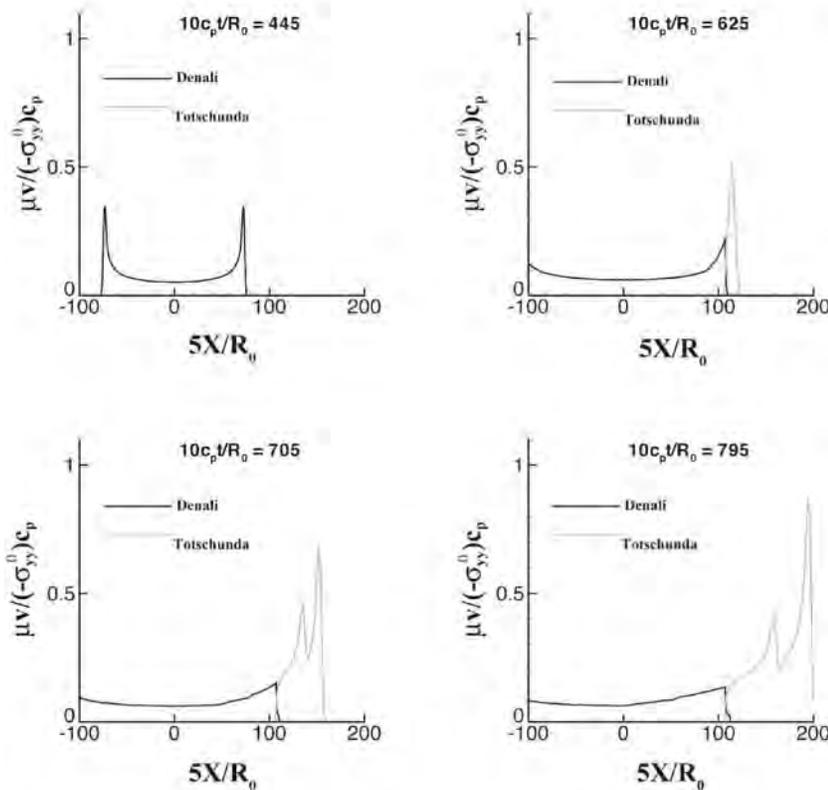


Figure 8. Slip velocity along the Denali and Totschunda fault segments for $\Psi = 70^\circ$; $v_r = 0.8 c_s$. Slip-velocity variation along the Totschunda fault is projected on the Denali fault. Totschunda fault begins at $5X/R_0 = 108$.

tends to propagate both along the main and the branched fault in the extensional side with a small branching angle of 15° . The same happens in this case with $\Psi = 70^\circ$ but not, as we shall see next, when $\Psi = 80^\circ$. Figure 9 shows the variation of slip velocity along the Denali and Totschunda faults. As can be seen in this figure, the slip velocity on the Denali fault beyond the Totschunda fault is significant, resulting in simultaneous propagation of rupture along both faults beyond the branching location, albeit at a slower rate and with less slip on the Denali fault than on the Totschunda fault.

$$\text{Case 4: } v_r = 0.87 c_s; \Psi = 80^\circ; \mu_s = 0.40; \\ \mu_d = 0.05; S_{\text{Den}} = 4; S_{\text{Tot}} = 0.4$$

As stated earlier, the likelihood of the rupture propagating exclusively along the extensional branch increases with increasing inclination of Ψ . In this case, we increase Ψ to 80° and maintain the rupture velocity at $0.87 c_s$ while approaching the Totschunda fault. In this model, we changed the friction coefficients because with the earlier values of friction coefficients the prestress field violated the Mohr-Coulomb failure criterion outside the fault zones.

Our results show that, for the case 4, the rupture proceeds rapidly along the Totschunda fault with almost no con-

tinuation on the Denali fault. Figure 10 shows slip velocity along both the Denali and Totschunda faults. Again, beyond the Totschunda fault, the slip velocity diminishes quickly on the Denali fault. There is some continuation of rupture on the Denali fault beyond the Totschunda fault, although this length is of the order of R_0 , the size of the slip-weakening zone. This is negligible in comparison with the progress of rupture on the Totschunda fault. Hence, we can conclude here that the rupture takes the Totschunda fault exclusively.

$$\text{Case 5: } v_r = 1.40 c_s; \Psi = 70^\circ; \mu_s = 0.50; \\ \mu_d = 0.10; S_{\text{Den}} = 1; S_{\text{Tot}} = 0.09$$

Although we have no reason at present to think that the rupture velocity was supershear near the branch junction, we also performed a simulation in which the rupture velocity when approaching the Denali-Totschunda branching location was $1.40 c_s$. To make an appropriate choice for the S ratio so that the rupture velocity was supershear and the Mohr-Coulomb failure criteria were not violated by the prestress field, we were required to choose these values for dynamic and static coefficients of friction.

Slip velocity (Fig. 11) on the Denali and Totschunda faults shows that on the part of the Denali fault beyond the

$$\Psi = 70^\circ, v_r = 0.9 c_s, \phi = -15^\circ$$

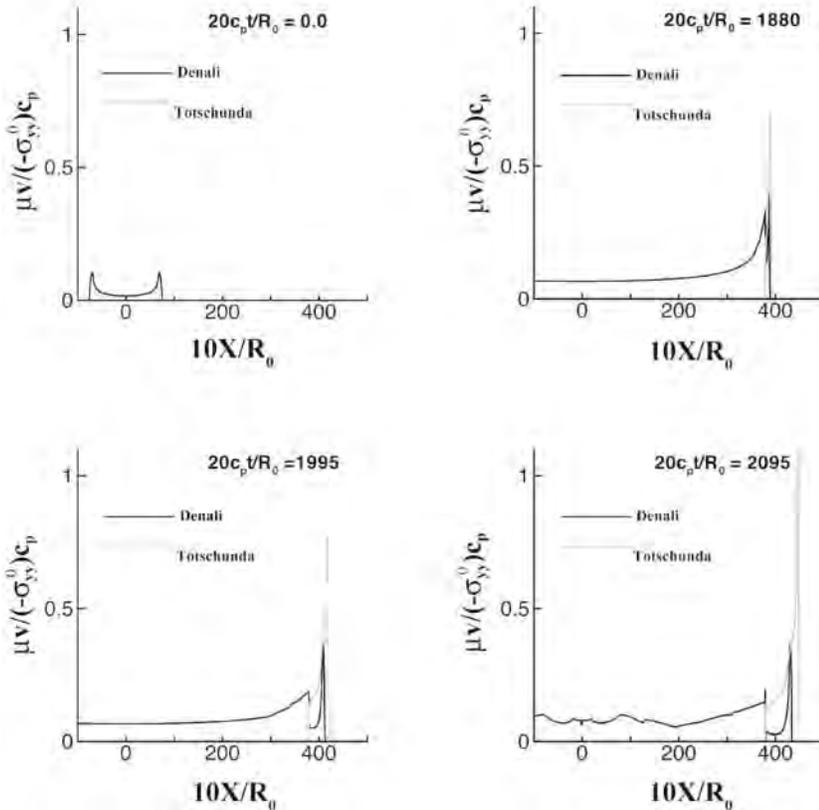


Figure 9. Slip velocity along the Denali and Totschunda fault segments for $\Psi = 70^\circ$; $v_r = 0.9 c_s$. Slip-velocity variation along the Totschunda fault is projected onto the Denali fault. The Totschunda fault begins at $10X/R_0 = 380$.

junction, the slip velocity decays rapidly, suggesting that segment of the Denali fault beyond the Totschunda intersection will ultimately stop slipping. On the Totschunda fault the speed briefly reduced to sub-Rayleigh then went supershear again, exhibiting a pattern similar to those observed in other cases of sub-Rayleigh to supershear transitions, leaving pulses that move as Rayleigh waves on what was the crack surface before the intersonic transition and provide a multipulse character to the slip-rate distribution.

Summary and Conclusions

The theory of fault branching developed by Poliakov *et al.* (2002) and Kame *et al.* (2003) was tested on the recent Denali fault earthquake using the numerical method developed by Kame *et al.* (2003). The theoretical stress analysis of a propagating mode II rupture suggests that the tendency to follow a branch is influenced by rupture velocity v_r , approaching the branch, preexisting maximum compressive stress inclination Ψ , and prospective branching angle ϕ . This study provides another comparison of the rules of branching with a field case; five other such field cases were discussed by Kame *et al.* (2003).

We numerically simulated the observed slip transfer from the Denali to Totschunda faults by the methodology of Kame *et al.* (2003), which uses a 2D elastodynamic boundary integral equation model of mode II rupture with self-chosen path along a branched fault system. The strength of the faults was assumed to follow a Coulomb law with a friction coefficient that slip-weakens from its static to dynamic value. Figure 12 shows the rupture velocity variation on the Denali and Totschunda faults for cases $\Psi = 70^\circ$; $v_r = 0.6 c_s$ and $\Psi = 70^\circ$; $v_r = 0.9 c_s$, respectively. The rupture velocity on the Totschunda fault beyond the branching location for the case $\Psi = 70^\circ$; $v_r = 0.9 c_s$ remains steady at a value of $1.1 c_s$, a value that falls within the range for unstable dynamic rupture propagation on a single fault (Freund, 1979); the speed may be, stabilized by the existence of the neighboring rupture propagating along the Denali fault. All but one of our simulations for incoming sub-Rayleigh rupture velocities predict that the rupture path will branch off along the Totschunda fault without continuation along the Denali fault. The exception is the case when the prestress inclination is 70° , a lower limit to the plausible range, and incoming rupture speed at the branching point is $0.9 c_s$. In this case rupture follows the branch, but rupture

$$\Psi = 80^\circ, v_r = 0.87c_s, \phi = -15^\circ$$

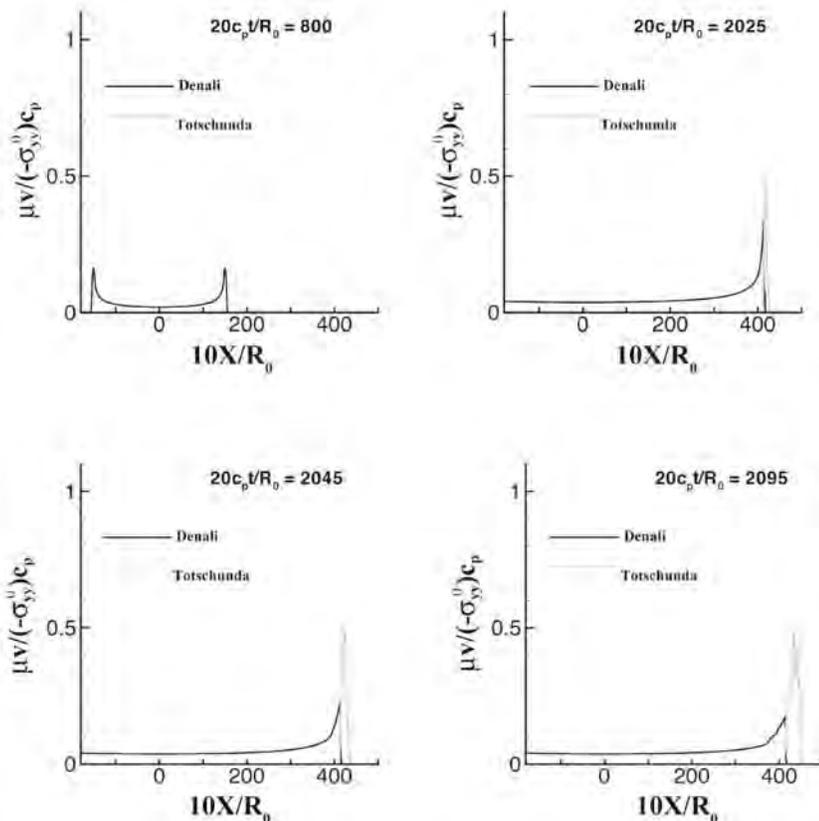


Figure 10. Slip velocity along the Denali and Totschunda fault segments for $\Psi = 80^\circ$; $v_r = 0.87 c_s$ case. Slip velocity variation along the Totschunda fault is projected onto the Denali fault. The Totschunda fault begins at $10X/R_0 = 414$.

also continues along the Denali fault beyond the branching location, at a lower speed than that along the Totschunda fault. However, when the prestress inclination is steeper, at 80° , the rupture chooses Totschunda exclusively when its velocity near the branching location is about $0.9 c_s$. We also see exclusive continuation of rupture on the Totschunda fault when the rupture is supershear, $1.4 c_s$.

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References

- Andrews, D. J. (1976). Rupture velocity of plane strain shear cracks, *J. Geophys. Res.* **81**, 5679–5687.
- Aochi, H., and E. Fukuyama (2002). Three-dimensional non-planar simulation of the 1992 Landers earthquake, *J. Geophys. Res.* **107**, 2035, doi 10.1029/2000JB000061, pp. ESE 4-1 to 4-12.
- Aochi, H., E. Fukuyama, and M. Matsu’ura (2000a). Spontaneous rupture propagation on a non-planar fault in 3D elastic medium, *Pure Appl. Geophys.* **157**, 2003–2027.
- Aochi, H., E. Fukuyama, and M. Matsu’ura (2000b). Selectivity of spontaneous rupture propagation on a branched fault, *Geophys. Res. Lett.* **27**, 3635–3638.
- Bhat, H., R. Dmowska, J. R. Rice, and N. Kame (2002). Testing theory for fault branching: Denali to Totschunda, Alaska, November 3, 2002 (abstract), *Trans. Am. Geophys. U., EOS* **83**, S72F-1364.
- Cochard, A., and R. Madariaga (1994). Dynamic faulting under rate dependent friction, *Pure Appl. Geophys.* **142**, 419–445.
- Dreger, D. S., D. D. Oglesby, R. Harris, N. Ratchkovski, and R. Hansen (2004). Kinematic and Dynamic rupture models of the November 3, 2002, M_w 7.9 Denali, Alaska, earthquake, *Geophys. Res. Lett.* **31**, L04605, doi 10.1029/2003GL018333.
- Eberhart-Phillips, D., P. J. Haeussler, J. T. Freymueller, A. D. Frankel, C. M. Rubin, P. Craw, N. A. Ratchkovski, G. Anderson, G. A. Carver, A. J. Crone, T. E. Dawson, H. Fletcher, R. Hansen, E. L. Harp, R. A. Harris, D. P. Hill, S. Hreinsdóttir, R. W. Jibson, L. M. Jones, R. Kayen, D. K. Keefer, C. F. Larsen, S. C. Moran, S. F. Personius, G. Plafker, B. Sherrod, K. Sieh, N. Sitar, and W. K. Wallace (2003). The 2002 Denali fault earthquake, Alaska: a large magnitude, slip-partitioned event, *Science* **300**, 1113–1118.
- Ellsworth, W. L., M. Çelebi, J. R. Evans, E. G. Jensen, D. J. Nyman, and P. Spudich (2004). Processing and modeling of the pump station 10 record from the November 3, 2002, Denali fault, Alaska earthquake,

$$\Psi = 70^\circ, v_r = 1.4c_s, \varphi = -15^\circ$$

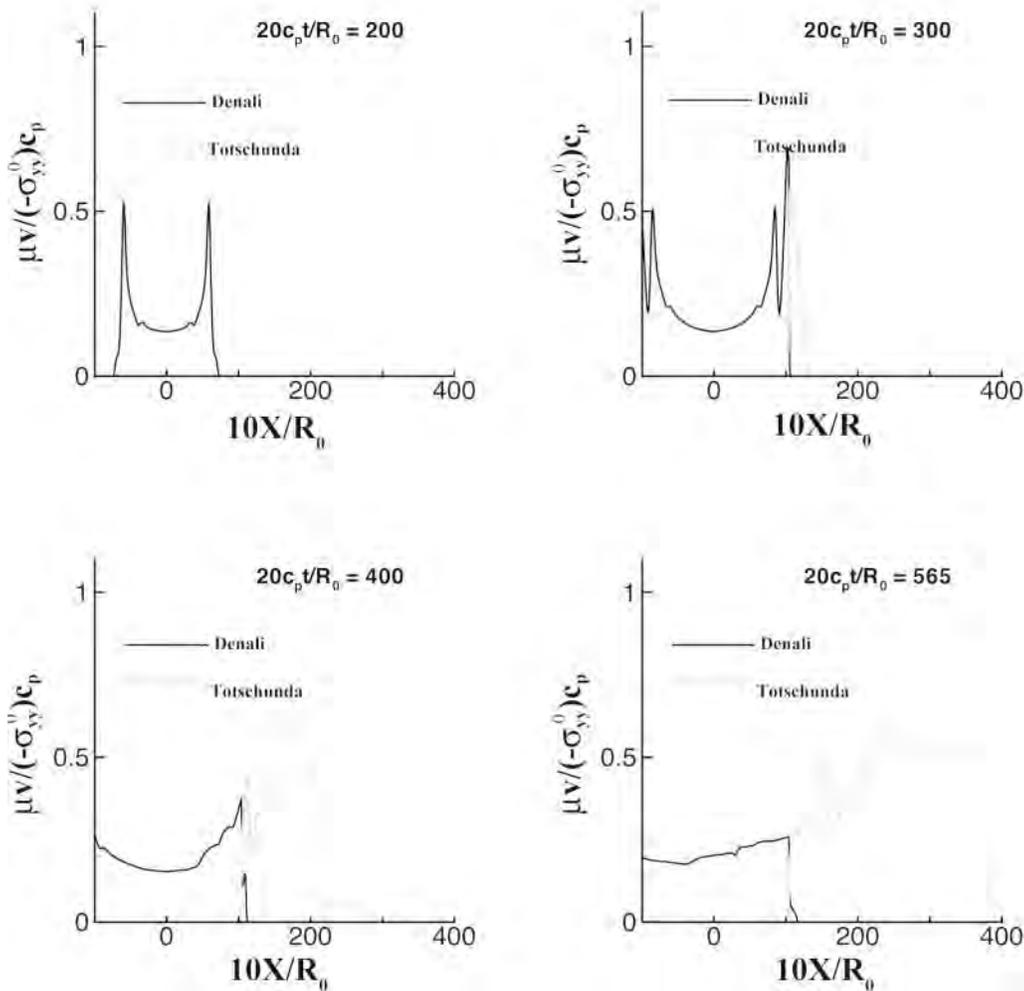


Figure 11. Slip velocity along the Denali and Totschunda fault segments for $\Psi = 70^\circ$; $v_r = 1.4 c_s$. Slip-velocity variation along the Totschunda fault is projected onto the Denali fault. The Totschunda fault begins at $10X/R_0 = 104$.

11th International Conference On Soil Dynamics & Earthquake Engineering, Berkeley, California, 471–477.

- Estabrook, C. H., and K. H. Jacob (1991). Stress indicators in Alaska, in *Neotectonics of North America*, D. B. Slemmons, E. R. Engdahl, M. D. Zoback, and D. D. Blackwell (Editors), Geological Society of America, Boulder, Colorado, Decade Map vol. 1, 387–399.
- Estabrook, C. H., D. B. Stone, and J. N. Davies (1988). Seismotectonics of northern Alaska, *J. Geophys. Res.* **93**, 12,026–12,040.
- Freund, L. B. (1979). The mechanics of dynamic shear crack propagation, *J. Geophys. Res.* **84**, 2199–2209.
- Ida, Y. (1972). Cohesive force across the tip of a longitudinal-shear crack and Griffith's specific surface energy, *J. Geophys. Res.* **77**, 3796–3805.
- Kame, N., and T. Yamashita (1999a). A new light on arresting mechanism of dynamic earthquake faulting, *Geophys. Res. Lett.* **26**, 1997–2000.
- Kame, N., and T. Yamashita (1999b). Simulation of spontaneous growth of dynamic crack without constraints on the crack tip path, *Geophys. J. Int.* **139**, 345–358.

- Kame, N., and T. Yamashita (2003). Dynamic branching, arresting of rupture and the seismic wave radiation in self-chosen crack path modeling, *Geophys. J. Int.* **155**, 1042–1050.
- Kame, N., J. R. Rice, and R. Dmowska (2003). Effects of pre-stress state and rupture velocity on dynamic fault branching, *J. Geophys. Res.* **108**, 2265, doi 10.1029/2002JB002189, pp. ESE 13-1 to 13-21.
- Kikuchi, M., and Y. Yamanaka (2002). Source rupture processes of the central Alaska earthquake of Nov. 3, 2002, inferred from teleseismic body waves (the 10/23 M6.7 event), *EIC Seismological Note No. 129*, revised 5 November 2002. Available from the Earthquake Information Center, University of Tokyo, at www.eic.eri.u-tokyo.ac.jp/EIC/EIC_News/021103AL-e.html.
- Nakamura, K., G. Plafker, K. H. Jacob, and J. N. Davies (1980). A tectonic stress trajectory map of Alaska using information from volcanoes and faults, *Bull. Earthquake Res. Inst.* **55**, 89–100.
- Oglesby, D. D., and S. M. Day (2001). The effect of fault geometry on the

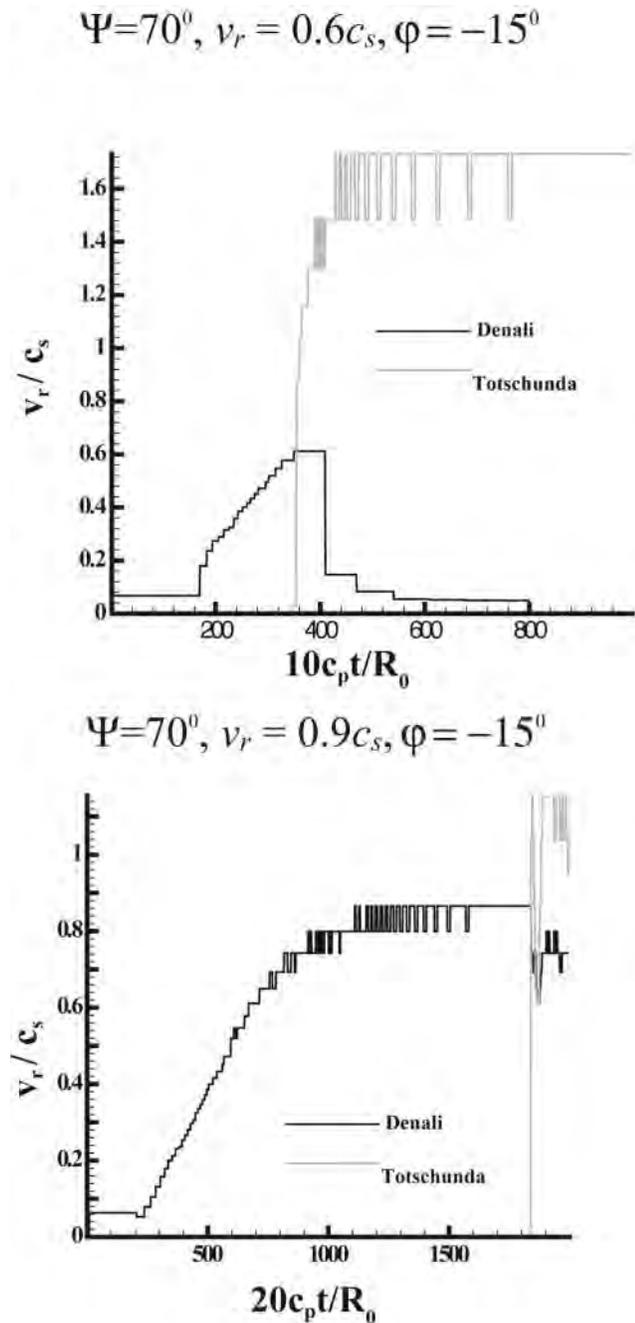


Figure 12. Variation of the rupture velocity along the Denali and the Totschunda fault segments for $\Psi = 70^\circ; v_r = 0.6 c_s$ and $\Psi = 70^\circ; v_r = 0.9 c_s$ cases. v_r, c_s, R_0 , and c_p represent the rupture velocity near the branching point, the S -wave speed of the medium, the size of the slip-weakening zone, and the P -wave velocity of the medium, respectively. The rupture velocity is determined using the time required to advance three spatial cells, hence possible values of the rupture velocity are quantized.

- 1999 Chi-Chi (Taiwan) earthquake, *Geophys. Res. Lett.* **28**, 1831–1834.
- Oglesby, D. D., R. J. Archuleta, and S. B. Nielsen (2000a). The three-dimensional dynamics of dipping faults, *Bull. Seism. Soc. Am.* **90**, 616–628.
- Oglesby, D. D., R. J. Archuleta, and S. B. Nielsen (2000b). Dynamics of dip-slip faulting: Explorations in two dimensions, *J. Geophys. Res.* **105**, 13,643–13,653.
- Palmer, A. C., and J. R. Rice (1973). The growth of slip surfaces in the progressive failure of over-consolidated clay, *Proc. R. Soc. London A* **332**, 527–548.
- Poliakov, A. N. B., R. Dmowska, and J. R. Rice (2002). Dynamic shear rupture interactions with fault bends and off-axis secondary faulting, *J. Geophys. Res.* **107**, 2295, doi 10.1029/2001JB000572, pp. ESE 6-1 to 6-18.
- Ratchkovski, N. A. (2003). Change in stress directions along the central Denali fault, Alaska after the 2002 earthquake sequence, *Geophys. Res. Lett.* **30**, 2017, doi 10.1029/2003GL017905.
- Ratchkovski, N. A., and R. A. Hansen (2002). New constraints on tectonics of interior Alaska: Earthquake locations, source mechanisms, and stress regime, *Bull. Seism. Soc. Am.* **92**, 998–1014.
- Rice, J. R. (1980). The mechanics of earthquake rupture, in *Physics of the Earth's Interior* (Proc. Int'l. School of Physics 'Enrico Fermi', Course **78**, pp. 555–649, 1979), A. M. Dziewonski and E. Boschi (Editors), Italian Physical Society and North-Holland Publishing Co., Amsterdam.
- Rousseau, C.-E., and A. J. Rosakis (2003). On the influence of fault bends on the growth of sub-Rayleigh and intersonic dynamic shear ruptures, *J. Geophys. Res.* **108**, 2411, doi 10.1029/2002JB002310.
- Savage, J. C., and M. Lisowski (1991). Strain accumulation along the Denali fault at the Nenena river and Delta river crossings, Alaska, *J. Geophys. Res.* **96**, 14,481–14,492.
- Wallace, W. K., Sherrod, B. L., and T. E. Dawson (2002). Character and significance of surface rupture near the intersection of the Denali and Totschunda faults, M7.9 Denali fault earthquake, Alaska, November 3, 2002 (abstract). *EOS* **83**, S72F-1335.

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