Final Technical Report

Deformation transients in major fault zones and relation to earthquake generation

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Investigations undertaken

Determining conditions under which rate and state friction with lab-based temperature-dependent -- and hence depth-dependent -- properties, when incorporated into a continuum mechanical model of a subduction zone, lead to prediction of spontaneous aseismic transient sequences, or show responses to step-like stress perturbations as transient sequences.

Exploring how modeled events may better resemble geodetically inferred transients, or otherwise change, when two-state-variable friction laws (which better describe the high temperature lab data) are employed.

Studying how geodetic constraints on the time-dependence of post-seismic transients in subduction zones may help us to better constrain the depth-varying friction properties which are adopted in our modeling.

Results

Our modeling of subduction earthquake sequences applies rate and state friction to the interface between the subducting oceanic crust and the overlying plate. We have used a Dieterich-Ruina type friction law with a single evolving state variable, and with temperature dependent a and b parameters based on the data of Blanpied et al. (1995, 1998) on granite gouge under hydrothermal conditions. Because we suspect that the one-state-variable fit overestimates the stability of response in the $T > \sim 350$ºC regime, where much transient slip seems to be hosted, according to geodetic and thermal modeling, we have also begun investigating two-state-variable fits to the high-T data. Further, we are exploring the fits of the various models we concoct to geodetic constraints on postseismic deformation after subduction earthquakes.

Transients are a natural outcome of the rate- and state-dependent friction processes revealed in laboratory fault-sliding experiments (Liu & Rice, 2005, 2006). They arise spontaneously when that constitutive formulation is applied to model subduction earthquake sequences, in models with temperature-dependent (hence depth-dependent) frictional constitutive parameters.

We showed 3D results for subduction in our May 2005 proposal (and published some in Liu & Rice, *JGR,* 2005). All results shown here are for 2D versions of the subduction model, in which slip is made to be independent of coordinate x along strike (2D allows much higher grid resolution and shortened enough computer time for exploration of wide parameter ranges). The results show that continuing sequences of transients can be triggered by a modest, one-time, step-like stress perturbation at some time during an interseismic period, and can also arise spontaneously.

Such perturbations may result (Fig. 1) from stress steps along the thrust interface due to extensional normal-faulting earthquakes in the descending slab (Dmowska et al., 2005), and we

have also moedeled perturbations due to steps in pore pressure, which may represent an episode of metamorphic fluid release. E.g., see Fig. 2, in which the immediate transient response to normal faulting at $t \approx 430$ yr is followed by two long-delayed transients; here the maximum slip rate at any place on the fault is plotted in (a) as a function of t, and the highest spikes represent large subduction earthquakes. Fig. 3 shows effects of introducing perturbations in the form of

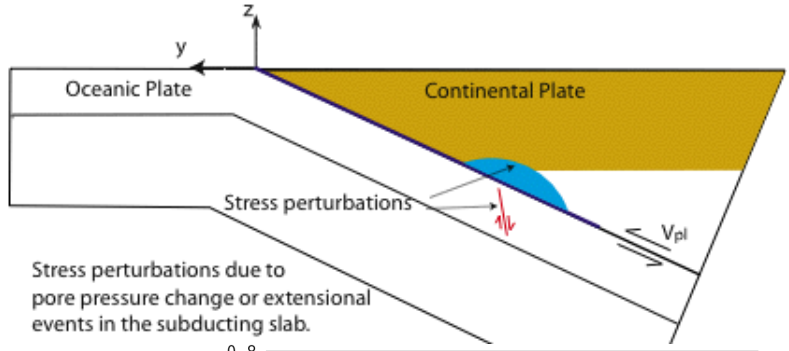

Fig. 1: 2D subduction model, for studying effect of step-like stress/pressure perturbations on subsequent response

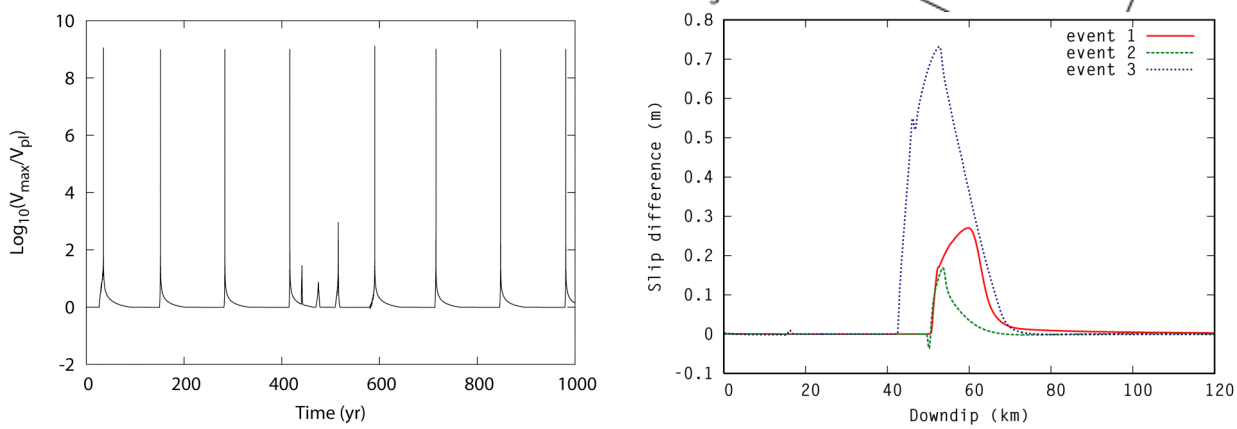

Fig. 2: (a) Perturbed earthquake sequence due to normal-fault static stress perturbation. (b) Differential slip due to the stress perturbation for the three transients episodes which result. (Dmowska et al., 2005).

modest step-increases (on left) or step-decreases (on right) in pore pressure p. Both increases and decreases of p triggered transient sequences. Perturbations as small as $\Delta p = 0.1$ MPa in a region with $\bar{\sigma} = 50$ MPa induced a long-delayed transient; see Fig. 4, where slip rate at a particular

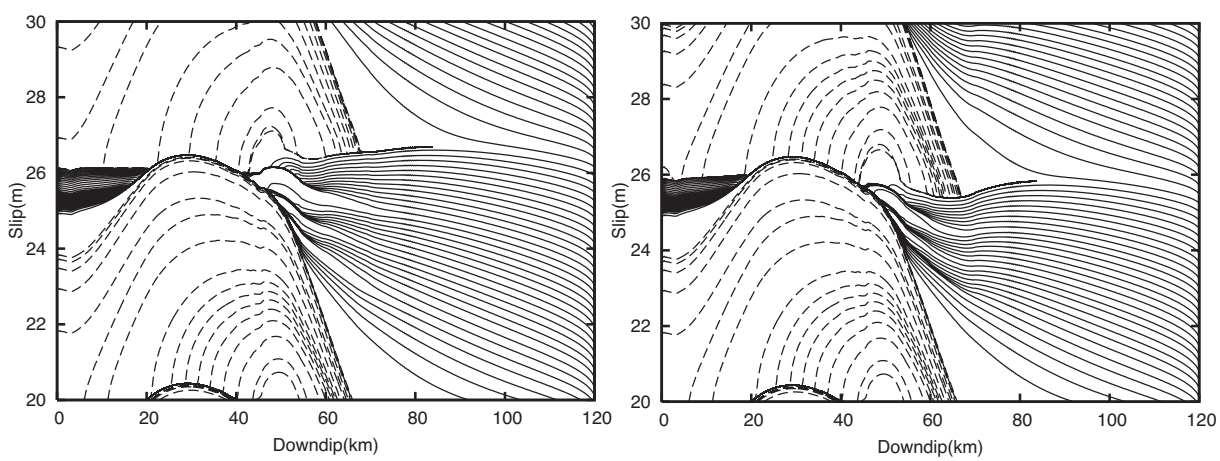

Fig. 3: One-time step perturbation $\Delta p = +1$ MPa at left, -1 MPa at right, on fault with $\bar{\sigma} = 50$ MPa. Both

induce transients. Solid lines drawn every 5 yrs. Dashed lines show seismic slip (Liu & Rice, 2005).

point on the fault, near the stability transition, is shown; the case Δp = 0.1 MPa (solid line, right panel) induces hardly any immediate transient response but it has a distinct longer-term effect. Note in all cases that transients interact with the earthquake recurrence time.

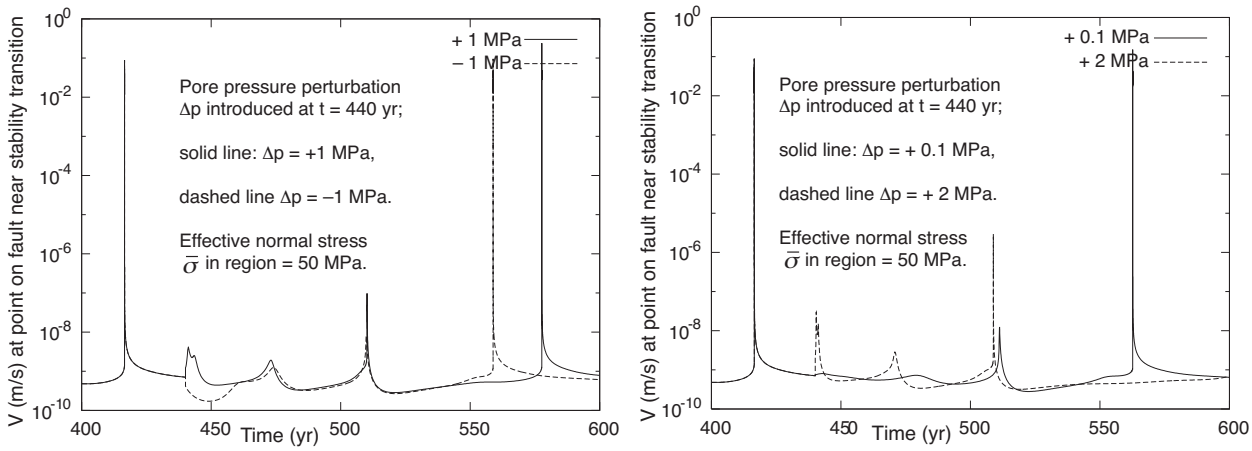

Fig. 4: Slip rate V at a point vs. t due to Δp perturbation. Left, the two cases in Fig. 4. Right, even an very small perturbation, Δp = 0.1 MPa, with $\bar{\sigma}$ = 50 MPa, induces a long-delayed transient episode.

The time intervals between transients in these examples is large, ~20-40 yr. However those are for $\bar{\sigma}$ = 50 MPa in the region near and downdip of the transition (at ~350ºC) from rate-weakening to rate-strengthening, whereas our recent work (Liu & Rice, 2006; Rice & Liu, 2006) shows that the time scale of transient phenomena decreases as $\bar{\sigma}$ there is decreased. In 3D modeling, the speed with which transient slip zones propagated along strike increased with reduction of $\bar{\sigma}$; e.g., that speed increased by a factor of ~3 when the assumed $\bar{\sigma}$ was reduced by a factor of 2, from 200 to 100 MPa.

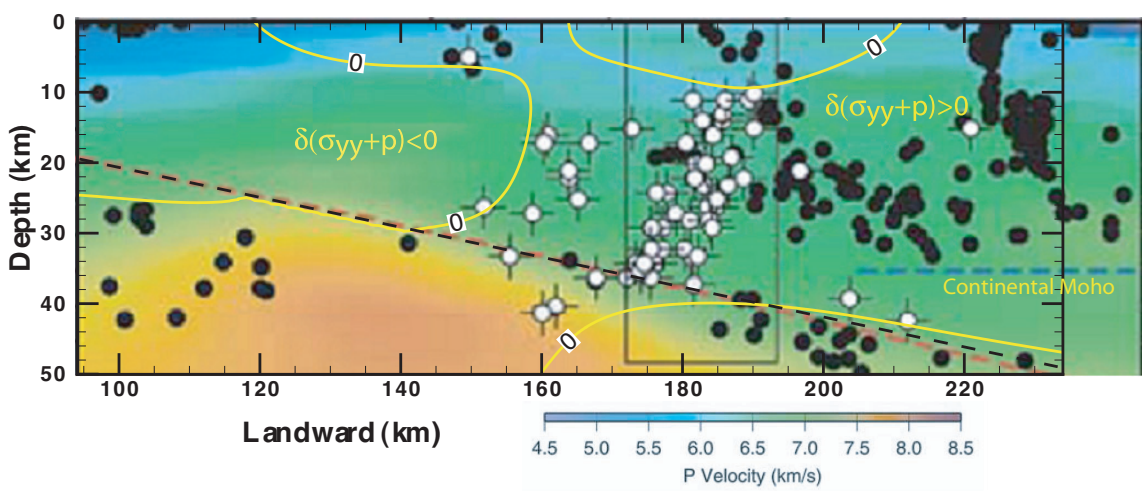

Fig. 5: Open symbols are Kao et al. (2005) inferred hypocenters for nonvolcanic tremors in a Cascadia section. Contours delineate the region where Liu & Rice (2005b, 2006) calculated positive unclamping effective stress changes on vertical fissure orientations, using the Dragert et al. (2001) slip model for a representative transient (calculation based on Poisson ratio 0.25 and Skempton B = 0.6; results are barely

different for $B = 0.4$). Stress change at hypocenters is extensional but small, of order 0.001-0.01 MPa.

We are examining the hypothesis that short-term transients reflect low $\bar{\sigma}$, i.e., high, near-lithostatic, p near the downdip end of the seismogenic zone, and further downdip into the stably slipping zone. Two lines of evidence support the liklihood that in some of the regions which have shown pronounced transients (e.g., Cascadia in the Pacific NW, Nankai in SW Japan, Guerrero in Mexico) the pore pressure is indeed high: We have shown that Cascadia tremors (Rogers & Draggert, 2003), clearly occurring during the time period of the aseismic transient deformations, have hypocentral locations (Kao et al. 2005, 2006) which mostly correspond to "unclamping" effective stress changes on any hypothesized vertical fissures, but where the unclamping amounts usually to well less than 0.01 MPa (calculating stress changes from the slip model of Dragert et al. (2001) for representative Cascadia transients). Fig. 5 is our nicest case, but few hypocenters in any section locate in the predicted region of stress decrease, and those tend to be near the border contours between regions of increase and decrease. Kao et al. (2006) similarly associate small but positive dilation during transient slip with the region of the tremors. This sensitivity to such small stress changes is consistent with a picture of near-lithostatic fluid pressure in the region, although other mechanism might be at play.

Also, Peacock (1999) and Peacock et al. (2002) pointed out that dehydration conditions would be met, around ~350ºC and above, which means around and downdip of the frictional stability transition, for shallow-dipping subduction zones such as those exhibiting transients, but not for deep-dipping zones like NE Japan which do not. All the regions mentioned above as showing short-period transients are similarly shallow-dipping, and may be expected to show a sequence of relatively low pressure dehydration reactions in the vicinity of the stability transition and downdip. In deep dipping zones, dehydration at those relatively low temperatures is suppressed by the greater overburden pressure and occurs much deeper, under the volcanic front.

These considerations have led us to examine elevated pore pressure models, in a specifically Cascadian geometry, Fig. 6. The actual situation envisioned is shown in the upper panel of that figure, but a simplification that we considered worth getting an understanding of along the way is shown in the lower panel (Rice & Liu, 2006; Liu & Rice, 2006; Liu & Rice, submitted 2007). In that lower panel, it is assumed that the $\bar{\sigma}$ is so high updip in the sieismogenic zone that most of that region is effectively locked on the timescale of transients that we are interested in, but that a width W of interface extending up-dip of the stability transition, and the whole interface that we consider downdip, is at much lower $\bar{\sigma}$ due to dehydration. Such model simplifications have the merit of creating a simple enough problem that we could learn a little about the solution by dimensional analysis,

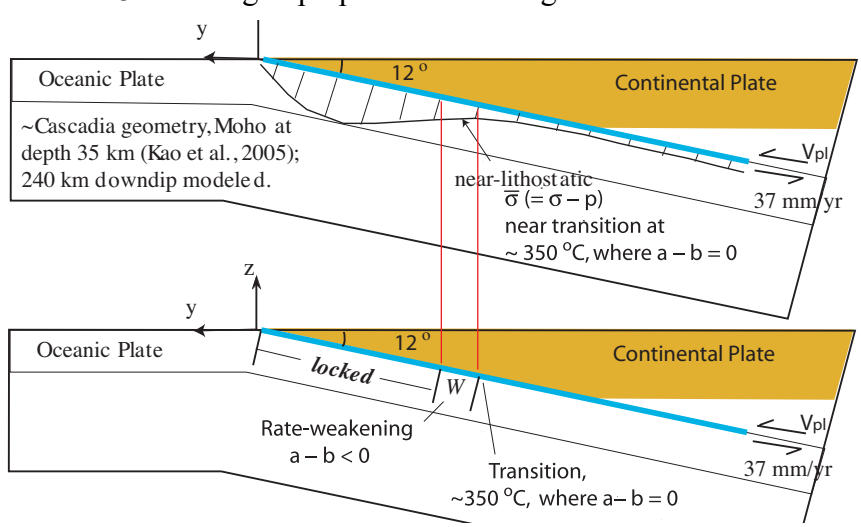

Fig. 6: Cascadia-like model with very low $\bar{\sigma}$, i.e., near-lithostatic p, around and downdip of stability transition.

and then use numerical simulations to fill in the rest. We assume that the stability transition is at depth H (we take $H = 14$ km), and H' is the depth at a fixed factor of H (with $H'/H > 1$; we take $H'/H = 3.6$), such that below H' the subduction interface has slip imposed at the plate convergence rate V_{pl}. Analysis of the governing equations shows that time t can enter only in the combination of $V_{pl}\,t$, which can be made dimensionless by the frictional contact-evolution length scale L_f, and that $\bar{\sigma}$ and L_f enter in the combination of $\bar{\sigma}/L_f$. By dimensional analysis and the structure of the equations, we showed that the quasistatic fault response (non-dimensional slip rate V/V_{pl} at any specified distance, scaled by H, from the stability transition) must be given by a function having the form

$$V/V_{pl} = F(V_{pl}\,t/L_f,\ \mu L_f/\bar{\sigma} H,\ \mu L_f/\bar{\sigma} W,\ a,\ b)$$

This is for a fxed H'/H, dip angle, and Poisson ratio ν. Also, μ is the shear modulus and "a, b" is a shorthand for the a and b distribution, which we here understand to be given functions of distance from the stability transition divided by H. We expected that one important thing about all above variables is how they combine to form h^*, the stable slip patch size for steady sliding with rate-weakening friction (Rice, 1993), and how that compares to W; here

$$h^* = 2\mu L_f/\pi(1-\nu)\langle b-a\rangle\bar{\sigma}$$

where $\langle b-a\rangle$ is the average of $b-a$ over the width W (and thus is a function of W/H). This expectation was remarkably well supported by our simulations. The model is also simple enough

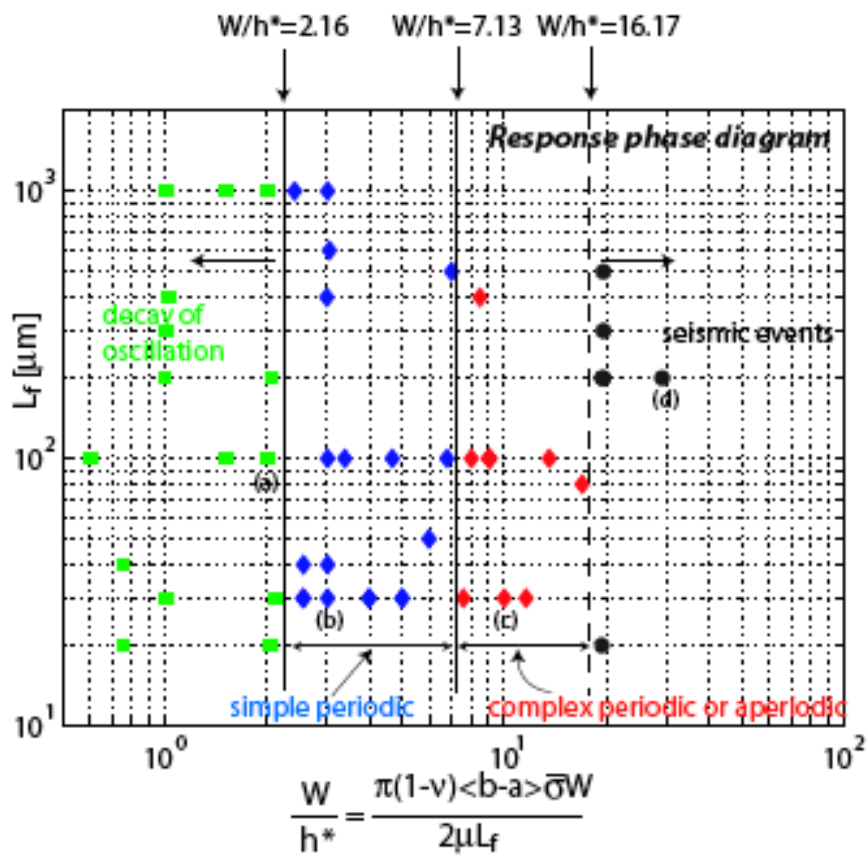

Fig. 7: Response phase diagram for the model in the lower panel of Fig. 8. For each L_f, calculations were done for a fixed W in the range 1.5 to 30 km, letting $\bar{\sigma}$ vary, and sometimes letting W vary too. Clearly, W/h^* is the controlling variable, and for any given W, periodic solutions exist for broad range of $\bar{\sigma}$, i.e., over a range of ~7.5.

for us to do calculations with actual, lab-sized values of L_f (note that Fig. 9 goes down to 15 μm, something not normally achievable in rate-state earthquake simulations (and not achieved in the models discussed earlier here).

The period of the predicted transients, in the range of W/h^* corresponding to periodic spontaneous slip oscillations, is shown in Figure 8. That shows that for a lab-like $L_f = 30$ μm, an effective stress of 2-3 MPa would be required to produce a 14 month recurrence period. While the time scale thus can be made consistent with the recurrence intervals of 9 to 15 months

suggested in different regions of Cascadia, the amplitudes of the transient slips (or, more precisely, the horizontal ground motions at earth's surface resulting form those slips) are too small by an order of magnitude in the best case, and yet smaller in others. Further, most of the aseismic moment in our modeling is contributed over a zone extending up-dip and moderately downdip from the stability transition, whereas a much broader down-dip zone is thought to contribute in the natural events.

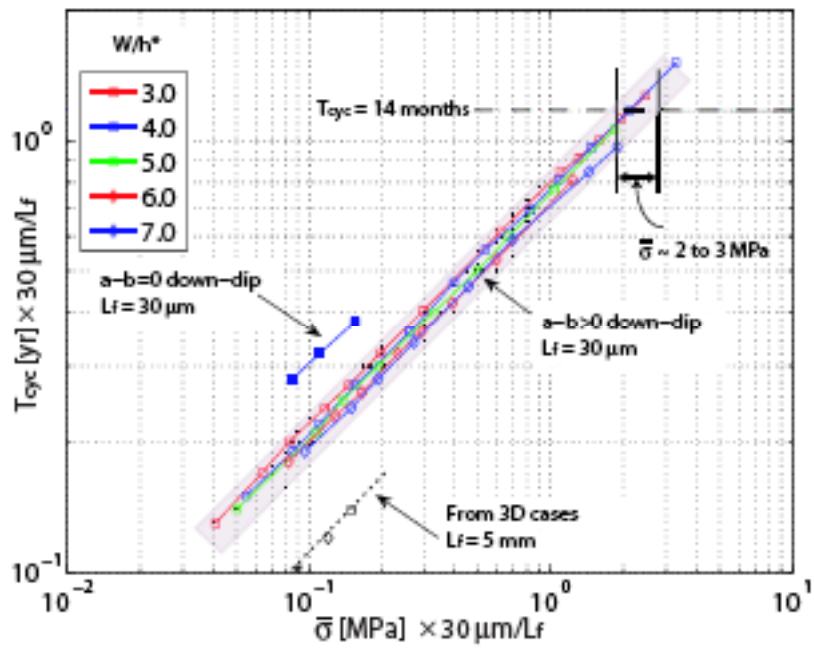

Fig 8: Period of self-sustained periodic slip oscillation vs. $\bar{\sigma}$. Here V_{pl} is taken as 37 mm/yr and L_f is taken as 30 μm, although because we know how the solution scales with L_f, it is possible to label the axes so that the solution can be interpreted for $L_f \neq 30$ μm.

We are therefore studying different aspects of the modeling to see if those are insurmountable objections or not. We are focused on two aspects:

(*i*) Relaxations of the complete locking in the simple model discussed in the lower panel of Figure 6, and in Figures 7 and 8, in which we model that zone as simply being at higher $\bar{\sigma}$, so that slip can penetrate naturally into it by a small amount, show that the amplitude of the slip oscillations increases substantially. An illustration is given in Figure 9.

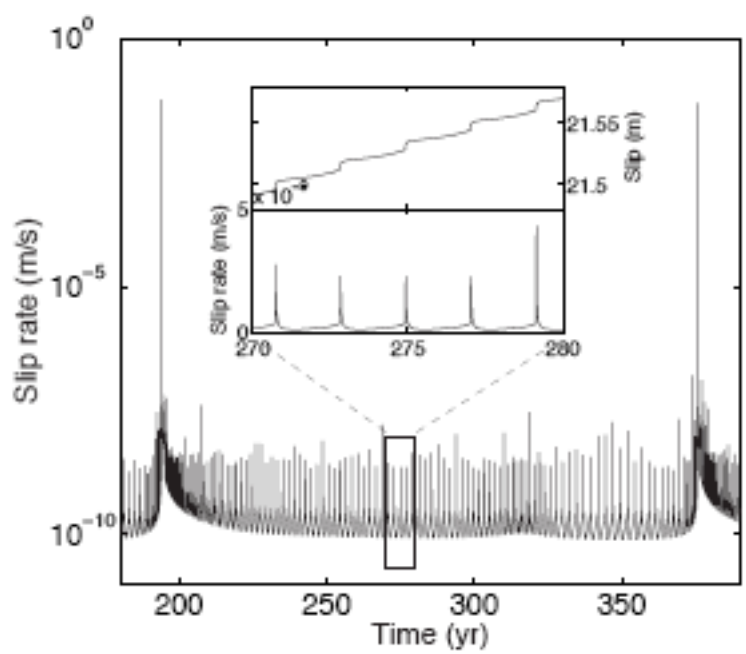

Fig 9: Slip rate at the stability transition in an unlocked seismogenic zone model, with $\bar{\sigma}$ = 50 MPa, L_f = 7.85 mm in the up-dip seismogenic zone and $\bar{\sigma}$ = 2 MPa, L_f = 0.246 mm in the transition zone and further down-dip. Interseismic time is filled with quasi-periodic aseismic transients. Periods vary through time, ranging from 0.8-4 yrs, and averaging 2 yrs. Inset shows the detailed slip (top) and slip rate (bottom) of the transients over a 10-yr period. Note that the slip rate of order 10^{-8} m/s is much higher than that in the periodic oscillations with a nearly completely locked seismogenic zone. Accumulated slip during the transients is 1-2 cm.

(ii) Also, the fitting of the Blanpied et al. (1995, 1998) high temperature data to a one-state-variable friction law overestimates the degree of stability in that stable regime, for reasons made clear in Figure 10. Our preliminary results in abstracts for the Fall 2006 AGU (Liu and Rice, 2006; DeDontney et al., 2006) suggest that with plausible -- but non-unique -- fits to the high temperature friction data, we can produce models for which the amount of slip during transients, and region slipped, are consistent with the Cascadia observations.

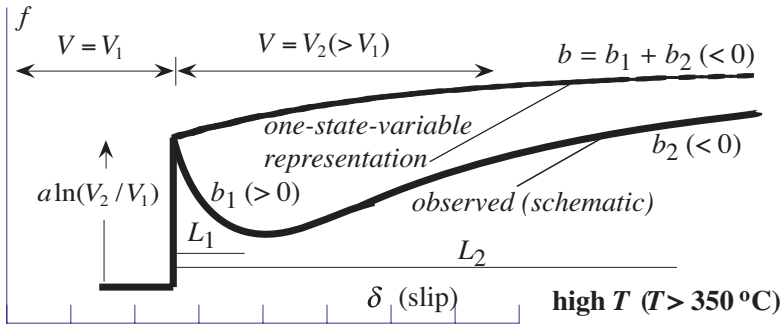

Fig. 10: Schematic, high temperature test (like in Blanpied et al., 1998) with idealized abrupt jump in slip rate V. Friction coefficient f vs. slip; the post-jump response is described poorly, and made overly stable, by fitting data to a one-state-variable description.

Non-technical Summary

The goal is to establish the physical basis of aseismic deformation transients and related nonvolcanic tremors in the Pacific Northwest and other shallow subduction zones, and along the San Andreas Fault (SAF). Our modeling suggests that transients with features like those observed may be a natural outcome of the rate and state friction processes revealed in laboratory experiments. Transients can arise spontaneously in that description or be triggered by a modest step-like stress perturbations during an interseismic period. Their time scale decreases as the effective normal stress is decreased in the region near and downdip from the stability transition.

Abstracts published or submitted during the 1 Jan '06 to 31 Dec '06 grant period:

DeDontney, N., Y. Liu, and J. R. Rice (2006), Frictional stability conditions and aseismic deformation transients based on two-state- variable friction laws, *Eos Trans. AGU*, *87*(52), Fall Meet. Suppl., Abstract T41A-1539.

King, G. C., A. Mignan, D. D. Bowman, R. Dmowska and R. Lacassin (2006), Earthquake risk following the 17 July Java earthquake, *Eos Trans. AGU*, *87*(52), Fall Meet. Suppl., Abstract S21A-0133

Liu, Y., and J. R. Rice (2006), Physical processes underlying aseismic deformation transients and relation to non-volcanic tremors: what can we learn from the rate and state friction?, *Western Pacific Geophysics Meeting*, July 2006, Bejing, China.

Liu, Y., and J. R. Rice (2006), Recurrence interval and magnitude of aseismic deformation transients: An investigation using rate- and state-dependent friction, *Eos Trans. AGU*, *87*(52), Fall Meet. Suppl., Abstract T41A-1543

Lectures related to these studies during the 1 Jan '06 to 31 Dec '06 grant period:

Rice, J. R., The dynamics of subduction earthquakes, including past and future Sumatran events, Public Lecture, Jan 2006, National University of Singapore.

Rice, J. R., and Y. Liu, What physical processes underlie aseismic deformation transients?,

Keynote Lecture, *UNAVCO Science Workshop*, Mar 2006, Denver.

Dmowska, R., Dynamics of earthquake rupture through branched and offset fault systems, Seminar, Mar 2006, Rhode Island College, Providence.

Rice, J. R., Aseismic transients in subduction zones: attempts at mechanical modeling, Seminar, July 2006, Departement Terre Atmosphere Ocean, Ecole Normale Superieure, Paris.

Dmowska, R., Dynamics of earthquake rupture through branched and offset fault systems, Seminar, Oct 2006, UNAM, D.F., Mexico.

Dmowska, R., Accelerated Moment Release as an Intermediate Term Earthquake Precursor, Lecture, Oct 2006, Homenaje al Profesor Takeshi Mikumo, Geofisica, UNAM, D.F., Mexico.

Rice, J. R., and Y. Liu, Aseismic transients in subduction zones: What physical basis?, Lecture, Oct 2006, Earth Materials - Deformation and Transport Properties, A Symposium in Honor of Brian Evans, MIT, Cambridge.

Paper submitted for publication after the close of the 1 Jan '06 to 31 Dec '06 grant period, but based in large part on work during that period:

Liu, Y., and J. R. Rice, Spontaneous and triggered aseismic deformation transients in a subduction fault model, submitted to *J. Geophys. Res.*, June 2007. (Paper was subsequently accepted for publication and is "in press" at time of submission of this report.)