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Deformation transients in major fault zones and relation to earthquake generation

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PI: James R. Rice, Co-PI: Renata Dmowska
Harvard University
Department of Earth and Planetary Sciences, and School of Engineering and Applied Sciences
224 Pierce Hall, 29 Oxford Street, Cambridge, MA 02138
tel 617-495-3445, fax 617-495-9837, rice@seas.harvard.edu, http://seas.harvard.edu/rice/

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Y. Liu, J. R. Rice, and K. M. Larson, "Seismicity variations associated with aseismic transients in Guerrero, Mexico, 1995-2006", Earth and Planetary Science Letters, 262, pp. 493–504, doi:10.1016/j.epsl.2007.08.018, 2007.

Abstracts during (and slightly after) the 1 Jan '07 to 31 Dec '07 grant period:

DeDontney, N., and J. R. Rice, "Using postseismic observations to constrain rate and state model parameters for aseismic slip events in shallowly dipping subduction zones", *Workshop to Integrate Subduction Factory and Seismogenic Studies in Central America*, Heredia, Costa Rica, 18-22 June 2007.

DeDontney, N., and J. R. Rice, "Role of splay faulting and dispersion in tsunami waveforms", *Eos Trans. AGU* , 88(52), Fall Meet. Suppl., Abstract S53A-1040, 2007.

Liu, Y., "Modeling moment-duration relation of aseismic slip events in subduction zones", EarthScope Workshop on *Aseismic Slip, Non-Volcanic Tremor, and Earthquakes*, Sidney, British Columbia, 25-28 February 2008.

Liu, Y., N. L. DeDontney, and J. R. Rice, "Explaining postseismic and aseismic transient deformation in subduction zones with rate and state friction modeling constrained by lab and geodetic observations", *Eos Trans. AGU* , 88(52), Fall Meet. Suppl., Abstract T21A-0375, 2007.

Liu, Y., K. M. Larson, and J. R. Rice, "Seismicity variations associated with aseismic transients, Guerrero, Mexico, 1995-2006", Eos Trans. AGU, 88(23), Jt. Assem. Suppl., Abstract G33A-06, 2007.

Liu, Y., and J. R. Rice, "Studies on the physical origin of aseismic deformation transients", EarthScope Workshop on *Aseismic Slip, Non-Volcanic Tremor, and Earthquakes*, Sidney, British Columbia, 25-28 February 2008.

Raoul, S., E. L. Templeton, N. DeDontney, R. Dmowska, and J. R. Rice, "Effects of initial stress state on splay fault activation during dynamic rupture propagation," *Eos Trans. AGU* , 88(52), Fall Meet. Suppl., Abstract T53A-1110, 2007.

Segall, P., A. Rubin and J. R. Rice, "Dilatancy stabilization of frictional sliding as a mechanism for slow slip events", EarthScope Workshop on *Aseismic Slip, Non-Volcanic Tremor, and Earthquakes*, Sidney, British Columbia, 25-28 February 2008.

Ph.D. Thesis:

Liu, Y., "Physical basis of aseismic deformation transients in subduction zones", *Dissertation* presented to the Department of Earth and Planetary Sciences, Harvard University, approved April 2007.

Lectures by PI related to these studies during (and slightly after) the 1 Jan '07 to 31 Dec '07 grant period:

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Univ. of British Columbia, Institute of Applied Mathematics, "Distinguished Colloquium", 12 Feb 2007: "Episodic slow slipping of seafloor under Cascadia: What physical processes cause aseismic deformation transients?".

Univ. of California at Berkeley, Dept. of Earth and Planetary Science, seminar, 27 Feb 2007: "Aseismic transients in subduction zones: What physical basis?".

Univ. Josef Fourier, Grenoble, France, Laboratory for Study of Earth's Interior, seminar, 24 May 2007: "Aseismic transients in subduction zones: What physical basis?".

Tsunami Source Forum, San Francisco, 9 Dec 2007: "Dispersion of Tsunami Waveforms and Evidence for Splay Faulting in the Sumatra 2004 Earthquake".

U. S. Geological Survey, Vancouver, WA, Cascades Volcano Observatory, Seminar, 29 Feb 2008: "Aseismic transients in subduction zones: What physical basis?"

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 depend on the friction law, considering two-state-variable friction laws, which better describe the high temperature lab data for granite gouge under hydrothermal conditions, and considering data for dry granite and, as recently available, for gabbro under hydrothermal conditions, and also considering effects of dilatancy stabilization.

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

These studies have received complementary support from USGS under this FY 2007 grant 07HQGR0057 and the FY 2006 grant 06HQGR0047, and from NSF under NSF-EAR Award 0510196.

In theoretical and modeling studies, we have sought to determine conditions under which rate and state friction, with laboratory-based temperature-dependent, hence hence depth-dependent properties, when incorporated into a continuum mechanical model of a subduction zone, leads to prediction of spontaneous aseismic transient sequences, or show responses to step-like stress perturbations as transient sequences. We have a number of new results on that as explained below (Liu and Rice, *JGR*, 2007; Liu, *Ph.D. thesis*, 2007).

In more recent work we have explored 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, and also how the inclusion of dilatancy (associated with increase of shear rate) in the constitutive modeling interacts with transients. Further, while our work up to mid-2007 was based exclusively on lab data for granite gouge under hydrothermal conditions, because that is the most completely characterized case, our recent work has studied how results change when based instead on data for dry granite and granite gouge and, as only very recently available, for gabbro under hydrothermal conditions,

Our studies on 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 had first focus on the region of afterslip in the Colima-Jalisco 1995 earthquake. That has now been extended to studies based on GPS characterization of response during transient slips along Cascadia, especially northern Washington and southern British Columbia.

Other studies focused on how seismicity is associated with transients (Liu et al., *EPSL,* 2007) in Guerrero, Mexico. The work shows shows that the three largest recorded transients in 1998, 2001-2002 and 2006 are all spatio-temporally correlated with high seismic rates. The initiation of the transients seems to coincide with a cluster of extensional earthquakes well inland from the trench, and they may be followed by thrust earthquakes nearer to the trench, or bracketed by both. This suggests transients may act as a mechanism of stress communication between distant seismicity clusters in shallow subduction zones.

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 (ageing) 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 $T > \sim 350^{o}$C 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.

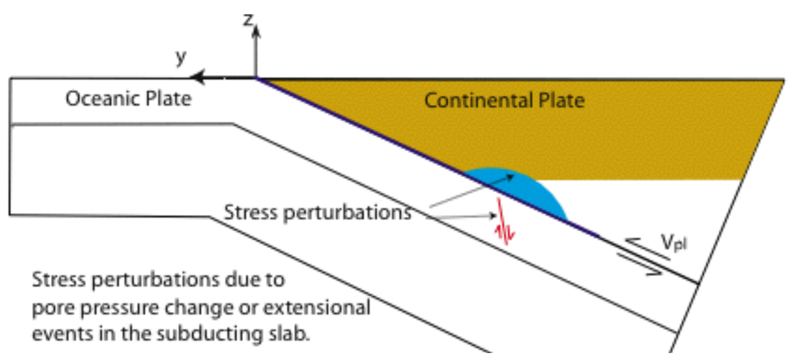
Transients are a natural outcome of the rate- and state-dependent friction processes revealed in laboratory fault-sliding experiments (Liu & Rice, *JGR,* 2005, 2007). They arise spontaneously when that constitutive formulation is applied to model subduction earthquake sequences, in models with temperature-dependent (hence depth-dependent) frictional constitutive parameters.

We showed 3D results for subduction in 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., *EOS,* 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 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 point on the fault, near the stability transition, is shown; the case $\Delta p = 0.1$ 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. 1: 2D subduction model, for studying effect of step-like stress/pressure perturbations on subsequent response



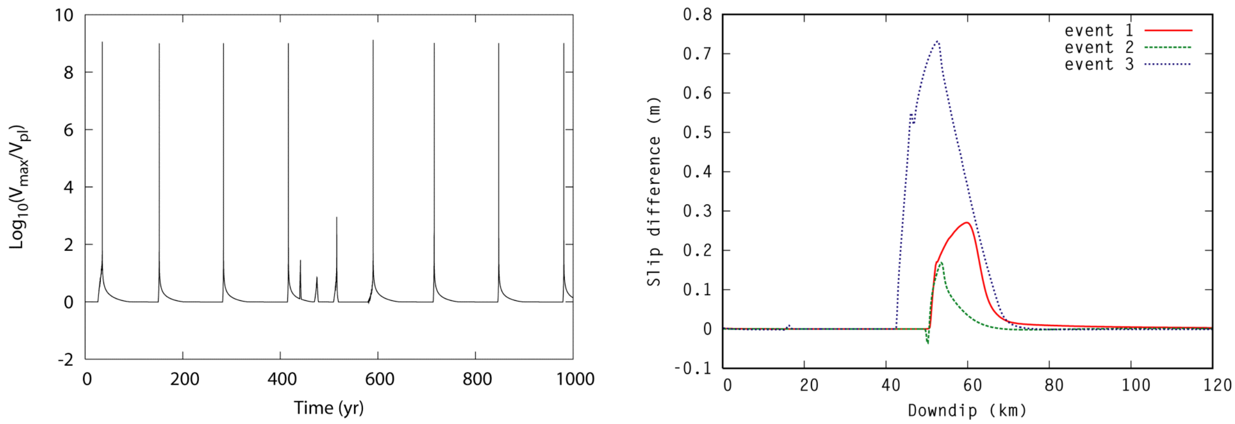


Fig. 2: (a) Perturbed earthquake sequence due to normal-fault static stress perturbation. (b) Differential slip due to the stress perturbation for the three transients episodes which result. (Dmowska et al., 2005).

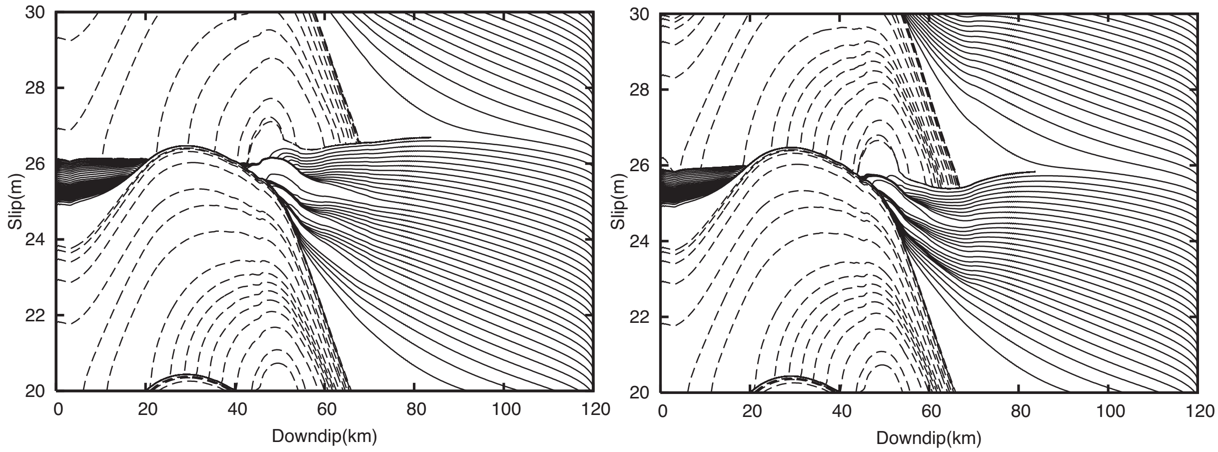


Fig. 3: One-time step perturbation Δp = +1 MPa at left, –1 MPa at right, on fault with $\bar{\sigma}$ = 50 MPa. Both induce transients. Solid lines drawn every 5 yrs. Dashed lines show seismic slip (Liu & Rice, 2005).

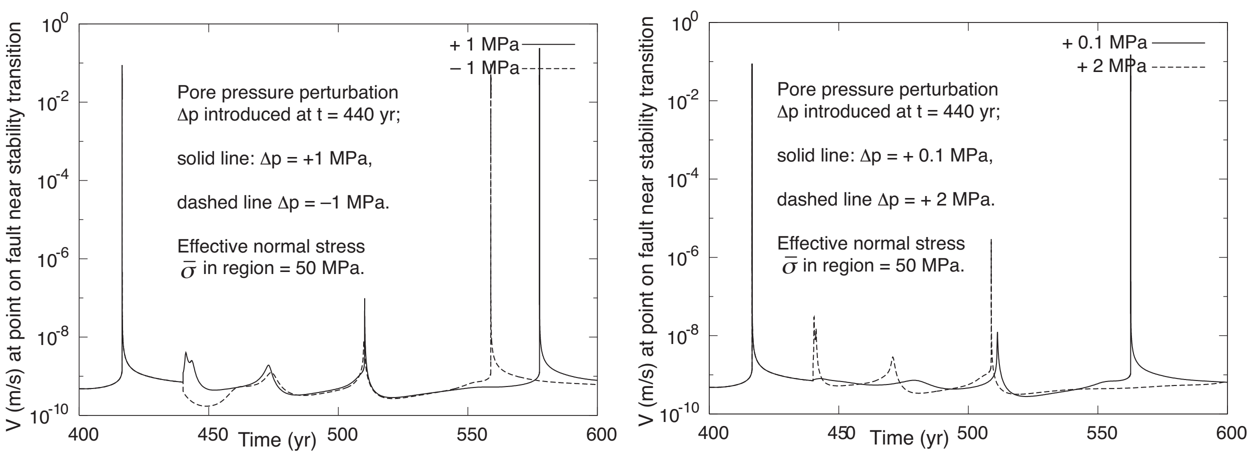


Fig. 4: Slip rate V at a point vs. t due to Δp perturbation. Left, the two cases in Fig. 4. Right, even an very small perturbation, Δp = 0.1 MPa, with $\bar{\sigma}$ = 50 MPa, induces a long-delayed transient episode.

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, *JGR*, 2007) 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 (Liu & Rice, *EOS,* 2005).

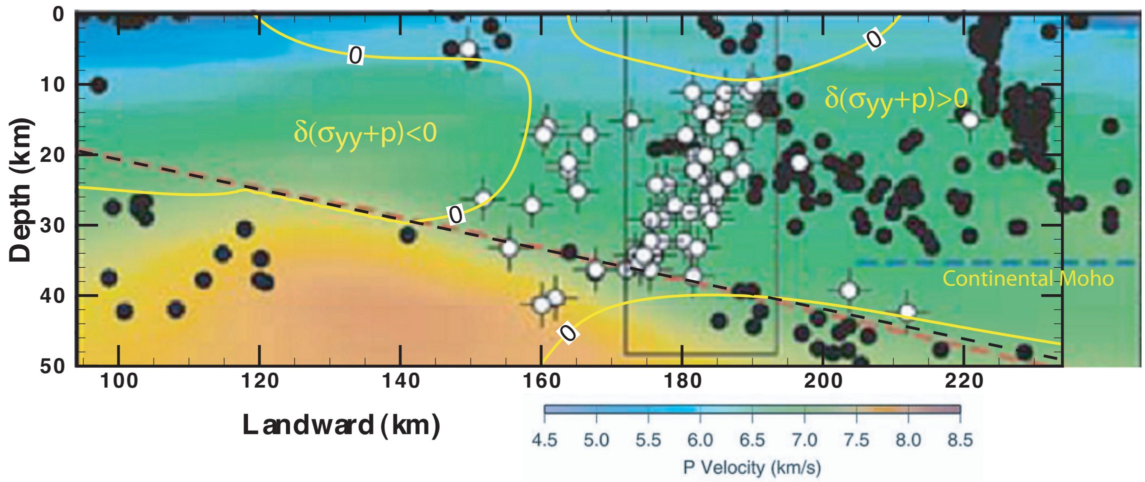


Fig. 5: Open symbols are Kao et al. (2005) inferred hypocenters for nonvolcanic tremors in a Cascadia section. Contours delineate the region where Liu & Rice (2005b, 2006) calculated positive unclamping effective stress changes on vertical fissure orientations, using the Dragert et al. (2001) slip model 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 as estimated by 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 shows that, and 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 there is concern about accuracy of the Kao et al. depths and studies by Shelly et al. (2006, 2007) for Southwest Japan lead those authors to conclude that tremor originates at the plate interface.

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 (Liu & Rice, *JGR,* 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, and then use numerical simulations to fill in the rest.

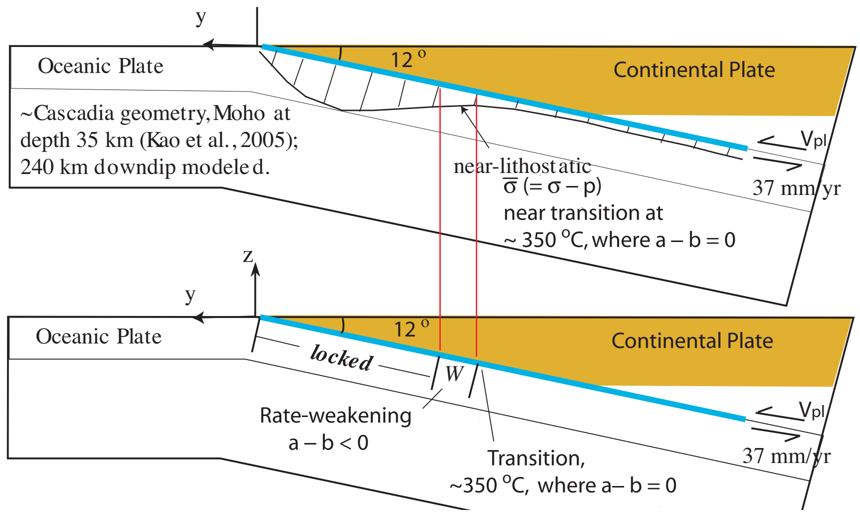


Fig. 6: Cascadia-like model with very low $\bar{\sigma}$, i.e., near-lithostatic p, around and downdip of stability transition.

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

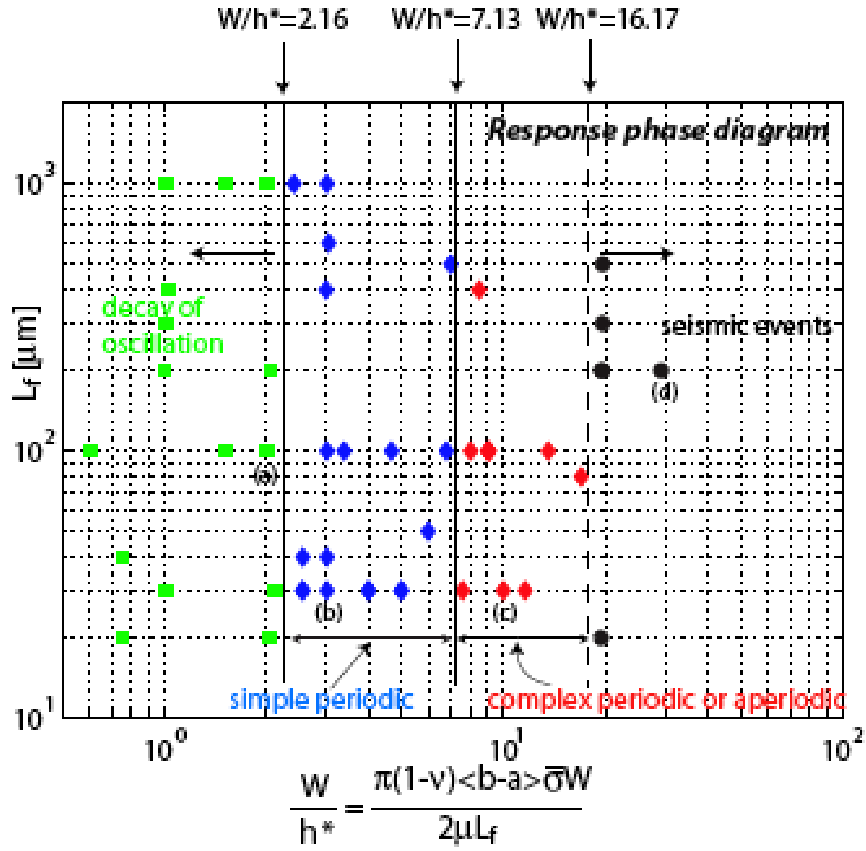
$$V/V_{pl} = F(V_{pl}\, t\, /L_f;\ \mu L_f/\bar{\sigma} H,\ \mu L_f/\bar{\sigma} W,\ a,\ b)$$

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

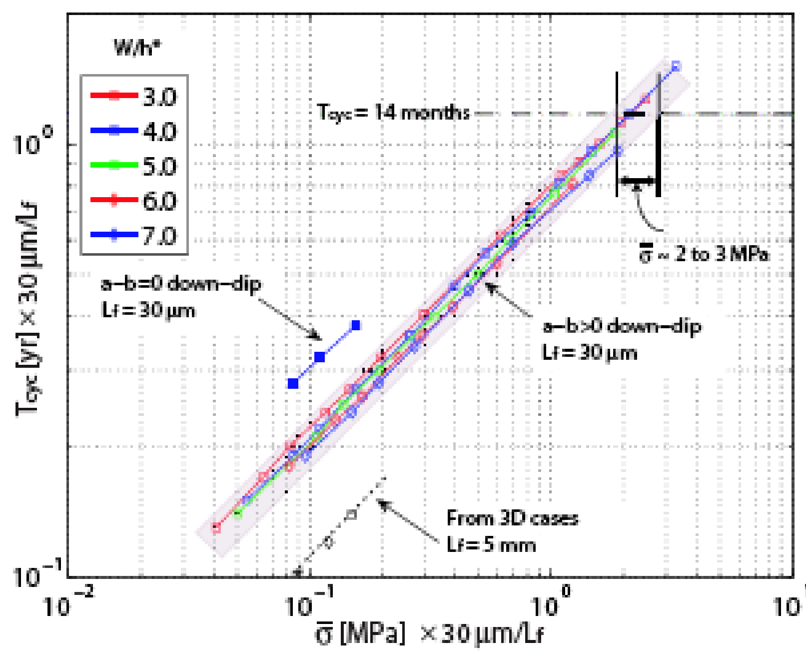
Fig. 7: Response phase diagram for the model in the lower panel of Fig. 8. For each L_f, calculations were done for a fixed W in the range 1.5 to 30 km, letting $\bar{\sigma}$ vary, and sometimes letting W vary too. Clearly, W/h^* is the controlling variable, and for any given W, periodic solutions exist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

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.

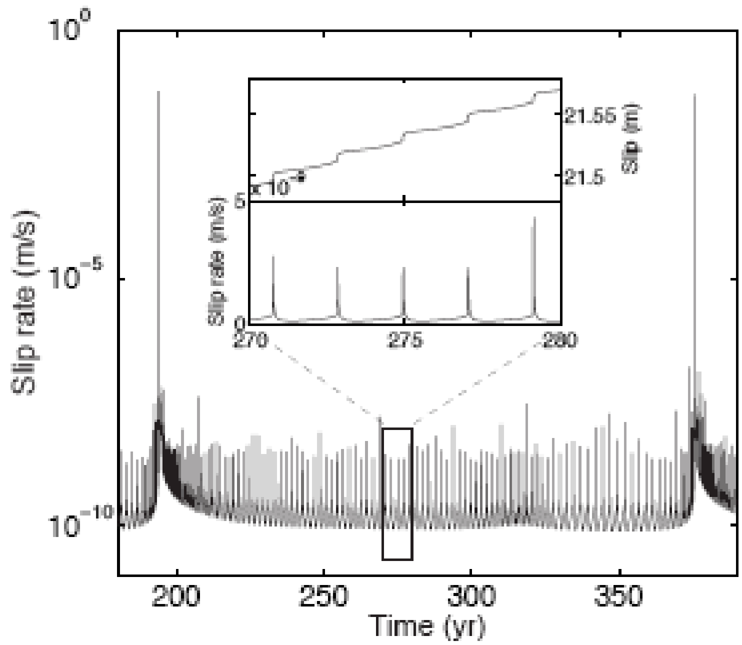


the time scale thus can be made consistent with the recurrence intervals of 9 to 15 months suggested in different regions of Cascadia, the amplitudes of the transient slips (or, more precisely, the horizontal ground motions at earth's surface resulting form those slips) are too small by an order of magnitude 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.

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

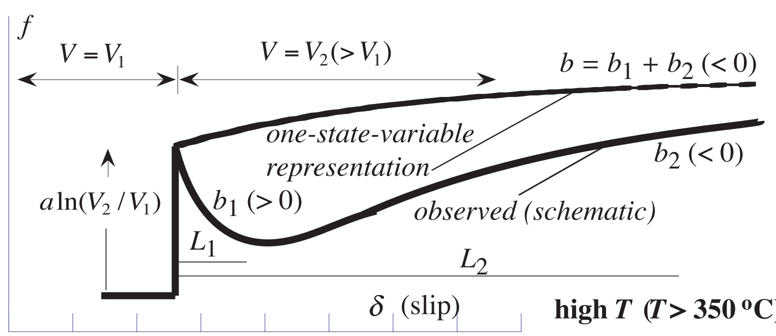
(i) Relaxations of the complete locking in the simple model discussed in the lower panel of Figure 6, and in Figures 7 and 8, in which we model that zone as simply being at higher $\bar{\sigma}$, so that slip can penetrate naturally into it by a small amount, show that the amplitude of the slip oscillations 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, *EOS,* 2006; DeDontney et al., *EOS,* 2006; Liu, *Ph.D. thesis,* 2007) 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 somewhat more like the Cascadia observations, although we now suspect that this cannot be the full explanation.

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.



(iii) As mentioned, dilatancy during shear is also likely to interact with transients. Segall and Rice (1995) showed that the effect could lead in some circumstances to large-amplitude quasi-static oscillations and, further, that dilatancy was most significant when the effective normal stress is low -- the situation which we now suspect to be fundamental to allowing transients. Our studies on this have been primarily in collaboration with Paul Segall of Stanford and Allan Rubin of Princeton, and they have done most of the modeling to date, albeit, for a simplified geometry compared to the configuration in Fig. 6.

(iv) We compared observed and model-simulated surface deformation due to a Cascadia aseismic slip event, for models based, respectively, on "wet granite", "dry granite" and "gabbro" friction data. The standard "wet granite" $a - b$ data underlying most of our earlier modeling is shown in Fig. 11, and "dry granite" results are shown there too.

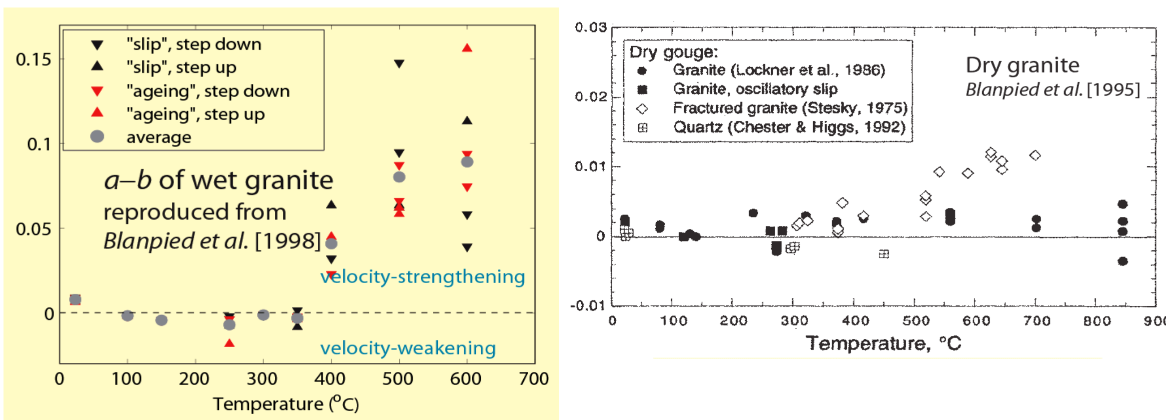


Fig. 11: Blanpied *et al.* [*JGR*, 1995, 1998] wet and dry granite friction data.

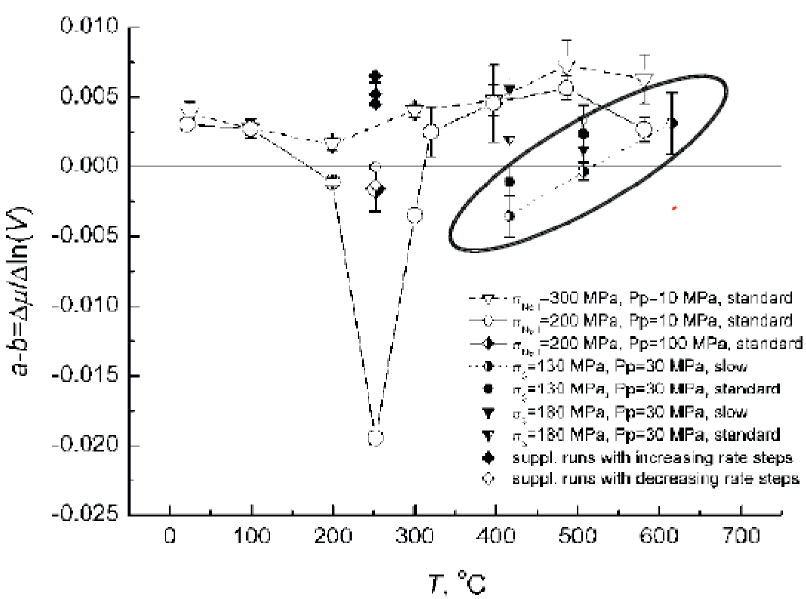


Fig. 12: He *et al.* [*Tectonophys,* 2007] data for gabbro under hydrothermal conditions; oval marks data under supercritical water pressures.

However, gabbro would seem to be a far better proxy for oceanic crust than is granite, although it is the latter which is, by far, the most completely characterized by lab studies in the rate and state friction context. Recent experimental data for gabbro under hydrothermal conditions has been reported by He *et al.* [*Tectonophys,* 2006, 2007]; Fig. 12. The data is very preliminary and conclusions concerning it may change as more experiments are done. We make tentative use of it as the only data available for a reasonable representation of the seafloor. Under supercritical water pressure (p_{H2O} > 22 MPa), He *et al.* find that the velocity-weakening to strengthening stability transition takes place around 500°C, and that at higher temperatures (up to ~600°C), $a - b$ is much smaller than 0.01. Those are extremely different from, and lower than, the wet granite data, for which $a - b$ approaches 0.1 at high T, and significantly lower than for much of the dry granite data.

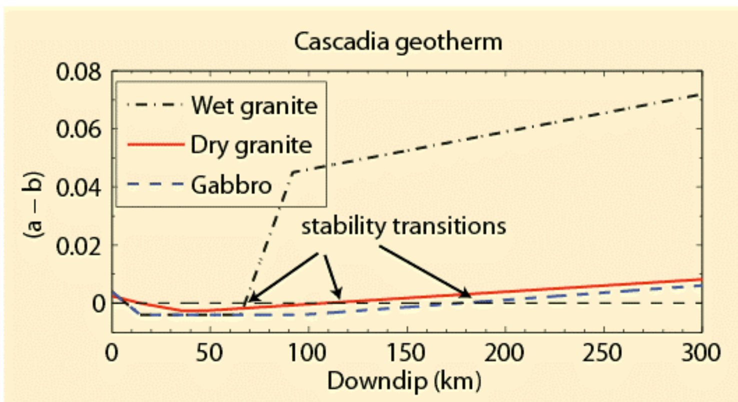


Fig. 13: Assumed $a - b$ versus downdip distance for the wet granite, dry granite and gabbro data, based on the Hyndman and Wang [*JGR*, 1995] thermal model for Cascadia

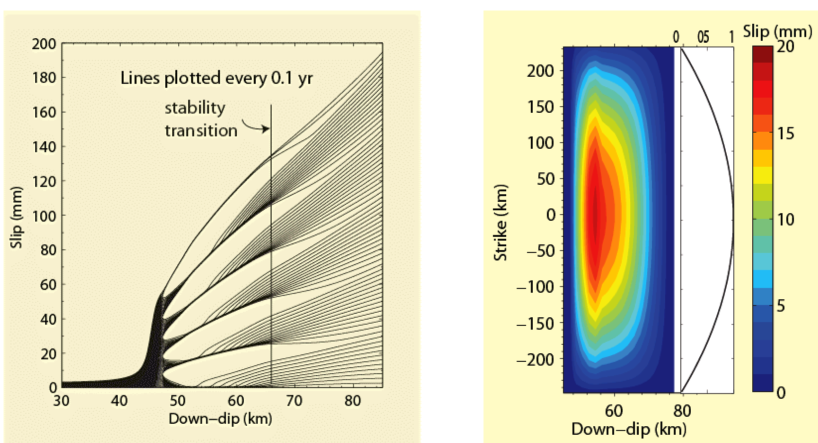


Fig. 14: A "wet granite" case: W = 20 km, s = 0.67 MPa, L ~ 0.4 mm, recurrence interval ~ 14 months, aseismic slip ~ 2 cm. The along-dip slip (interseismic motion removed) is used to generate a pseudo-3d slip on the fault plane, based on the along-strike distribution function shown. Surface deformation is then calculated using Okada's dislocation model in an elastic half-space, and compared with the GPS observations of the 1999 Cascadia transient [Dragert et al., 2001].

Using a Cascadia geotherm [Hyndman and Wang, *JGR*, 1995], the data is used to approximately suggest how $a - b$ should vary with depth (Fig. 13), and those results are used in models like in Figs. 6 and 9, with a uniform high $\bar{\sigma}$ in the up-dip seismogenic zone (after a linear variation from zero $\bar{\sigma}$ at the trench), and with a uniform low $\bar{\sigma}$ in the transition zone and further down-dip. Without following a formal inversion procedure, we tried in that way to find values of model parameters W, $\bar{\sigma}$, and L which gave the best fit to the Cascadia geodetic date, for a suite of forward models examined. The procedure is illustrated in Fig. 14 for modeling based on the wet granite data.

Wet granite (W = 20 km, $\bar{\sigma}$ = 0.67 MPa, L ~ 0.4 mm) Dry granite (W = 40 km, $\bar{\sigma}$ = 6.25 MPa, L ~ 1.67 mm)

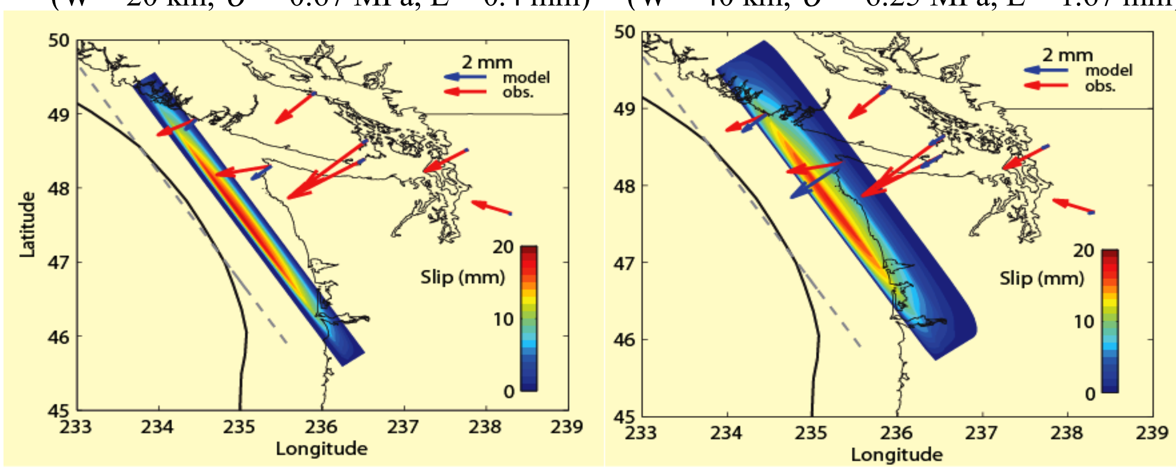


Fig. 15: Comparisons based on modeling with the "granite" data between observed (red) and model simulated (blue) surface deformation due to a Cascadia aseismic slip event. Most slip occurs in the updip velocity-weakening region for "wet granite" case. Application of the "dry granite" data slightly helps to improve the fit (slip occurs at depths which are further downdip), but cannot fully capture the deformation at most inland stations.

Gabbro
(W = 40 km, $\bar{\sigma}$ = 1.15 MPa, L ~ 0.18 mm)

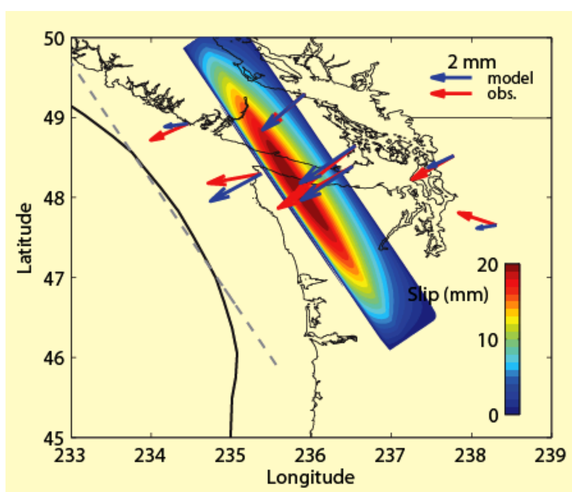


Fig. 16: Comparison based on modeling with the “gabbro” data between observed (red) and model simulated (blue) surface deformation due to a Cascadia aseismic slip event. Application of the “gabbro” data significantly improves the fit at most stations. A much wider velocity-

weakening zone is allowed by a frictional stability transition at higher temperatures, but the seismogenic zone (in the sense of a zone where seismic events may nucleate) could still be limited to a realistically shallower depth by dilatancy stabilization (not included here) at high fluid pressure.

While these results are preliminary, the gabbro profile produces the best fit among the three. All models require values of L that seem large compared to laboratory values, although the L in the best-fitting gabbro model, $L = 180\ \mu\text{m}$, is closest to plausible laboratory values.

Addendum: Abstract of Ph.D. thesis (April 2007) by Yajing Liu:

This work investigates the physical mechanisms underlying aseismic deformation transients in subduction zones, their relation to deep non-volcanic tremors and nearby seismicity, and implications to the slip budget throughout seismic cycles.

We simulate subduction earthquake sequences by applying the single-state-variable "ageing" rate and state friction law to 3D and 2D thrust fault modeling, with temperature and hence depth-dependent frictional properties. Our results show that aseismic deformation transients are a natural outcome of the rate and state processes, observed in laboratory fault-sliding experiments.

Transients can arise spontaneously for certain effective normal stress variations with depth. Velocity-weakening to strengthening stability transitional properties are suggested to be an ingredient allowing transients near the end of the seismogenic zone. When fluid pressure is near-lithostatic around and down-dip from that transition, the system exhibits self-sustained short-period aseismic oscillations, with lab values of friction parameters. A typical northern Cascadia 14-month recurrence interval is predicted at low effective normal stress of 2 to 3 MPa. Evidence of such high fluid pressure conditions is independently provided by the occurrence of non-volcanic tremors as apparent responses to extremely small stress changes, and by petrological constraints on the regions of metamorphic dehydration in shallow-dipping subduction zones. Transients can also be triggered by interseismic stress perturbations, due to extensional earthquakes in the descending slab, fluid pressure changes or other sources. Properties of the triggered transients depend on the time, location and magnitude of the perturbations.

A systematic seismicity catalog study in Guerrero, Mexico, shows that three large transients in 1998, 2001-2002 and 2006 are all spatial-temporally correlated with high seismic rates. The initiation of the transients coincides with a cluster of extensional earthquakes far inland from the trench, and may be followed by thrust earthquakes near the trench, or bracketed by both. This suggests transients may act as a mechanism of stress communication between distant seismicity clusters in shallow subduction zones.

We also investigate the system stability with a two-state-variable interpretation, which better describes the high-temperature friction behaviors revealed by *Blanpied et al.* [1998]. Activation of aseismic oscillations in the down-dip velocity-strengthening region may provide another contributing mechanism to the occurrence of transients.