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# Nonlinear Acoustic/Seismic Waves in Earthquake Processes

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**Abstract.** Nonlinear dynamics induced by seismic sources and seismic waves are common in Earth. Observations range from seismic strong ground motion (the most damaging aspect of earthquakes), intense near-source effects, and distant nonlinear effects from the source that have important consequences. The distant effects include dynamic earthquake triggering—one of the most fascinating topics in seismology today—which may be elastically nonlinearly driven. Dynamic earthquake triggering is the phenomenon whereby seismic waves generated from one earthquake trigger slip events on a nearby or distant fault. Dynamic triggering may take place at distances thousands of kilometers from the triggering earthquake, and includes triggering of the entire spectrum of slip behaviors currently identified. These include triggered earthquakes and triggered slow, silent-slip during which little seismic energy is radiated. It appears that the elasticity of the fault gouge—the granular material located between the fault blocks—is key to the triggering phenomenon.

**Keywords:** Earthquakes, nonlinear dynamics in earthquakes, nonlinear waves in strong ground motion, dynamic earthquake triggering, triggered nonvolcanic tremor and slow-slip
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## INTRODUCTION

Rocks and sediments exhibit highly elastically nonlinear behavior when compared to single crystals, bulk metals and gases, and exhibit hysteresis in stress-strain as well as pronounced memory effects known as *slow dynamics*[1]. As a result, dynamic nonlinear phenomena are common in the Earth, and are key to many phenomena that affect humans in significant manners. For instance, aside from Tsunamis, the most damaging aspect of earthquakes is *strong ground motion* (SGM). SGM takes place when seismic waves encounter low-velocity, soft sediments comprised of granular materials at the Earth's surface. Standing shear waves may be generated that are additionally amplified due to free-surface boundary conditions, leading to potentially damaging displacements and accelerations. These waves can be highly nonlinear and the nonlinearity works in our favor. Strong nonlinear dissipation occurs, damping the waves to potentially less damaging ground accelerations. Importantly, the standing waves contained to the soft sediment layers shift resonant frequency(ies) as they become larger in amplitude, presenting challenges for structural engineers[2] (Fig. 1).

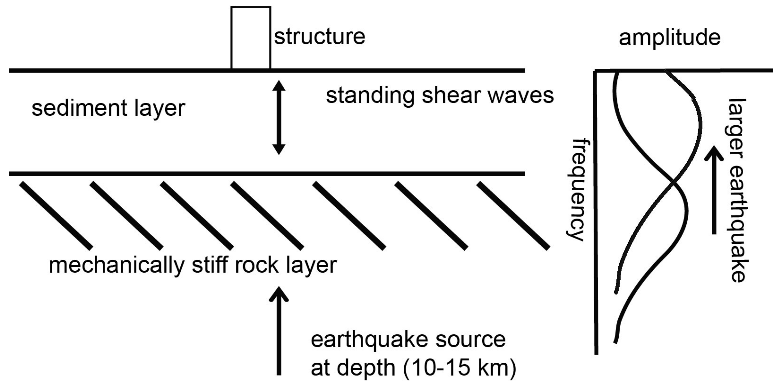


**FIGURE 1.** Simplified view of a Strong Ground Motion scenario during an earthquake. Seismic waves from an earthquake at depth are trapped in the low velocity sediments at the Earth's surface. The waves can resonate as a result (spectrum at right). As wave amplitudes increase from a larger earthquake for instance, the resonance shifts in frequency downward. Simultaneously, nonlinear attenuation becomes stronger aiding in damping large ground accelerations.

In addition to producing SGM, in the last two decades it has been shown that seismic waves from one earthquake can trigger slip on a nearby fault or thousands of km away from the triggering earthquake[3]. The triggered slip may result in an earthquake but also slow and 'silent' slip[4] where little seismic energy is emitted. Changes in quasi-static forces during an earthquake can trigger slip on the same, or adjacent faults. Dynamic triggering is unique in that seismic waves induce triggering. In the following we briefly explore dynamic triggering observed in the laboratory and in the Earth.

## DYNAMIC EARTHQUAKE TRIGGERING AND RECOVERY

The slip spectrum in the Earth ranges from very slow (and more or less silent) to earthquakes that may shake the ground intensely. All of these variations of fault slip may be triggered by seismic waves from other earthquakes. In the past decade, it has been shown that a large percentage, perhaps more than 50% of earthquakes may be triggered[5]. It is an open question regarding how earthquakes are triggered, and it is probable that multiple mechanisms are involved. We have observed an amplitude dependence of the seismic waves that trigger earthquakes[7] suggesting that a nonlinear mechanism may be involved. Our current thinking is that there is a spectrum of earthquake triggering mechanisms that range from Mohr-Coulomb failure to failure induced by nonlinear dynamics. What is clear is that the physical properties of the fault gouge—the granular material at the interface between fault blocks that is created by communition over geologic time— as well as the topology of the gouge surface, are responsible for triggering[5]. Of importance is that the gouge is potentially more elastically nonlinear than the surrounding fault blocks.

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## Dynamic Wave Triggering of Slow-slip

Slow-slip occurs in both the deep and shallow regions of the Earth's crust. Whether triggered or not, slow-slip in the deep crustal region radiates very low-amplitude waves termed *non-volcanic tremor*[7], a long duration noise-like signal. When slow-slip occurs in the upper crust it is all but silent but may have very small radiation associated with it[8].

We find in laboratory studies applying a direct shear apparatus simultaneous to acoustical waves that slow-slip can be triggered, and that this slow-slip is governed by nonlinear dynamics[4]. Figure 2 shows the shear apparatus applied in these experiments. When sheared under certain conditions, the gouge material either stick-slips or slides stably[4]. Figure 3 shows results of triggering while the material is sliding stably. The triggering wave amplitude dependence of the measured quantities shown in Figure 3 strongly suggests a nonlinear dynamical mechanism associated with the granular fault gouge that is responsible for the triggered slow-slip. Coulomb-Mohr-type failure would exhibit no amplitude dependence. At the failure threshold, the material would fail and large wave amplitudes would have not effect above the failure threshold.

Discrete Element Modeling (DEM) by Carmeliet, Griffa and colleagues show very similar behaviors when the model material is subject to acoustic perturbation[9].

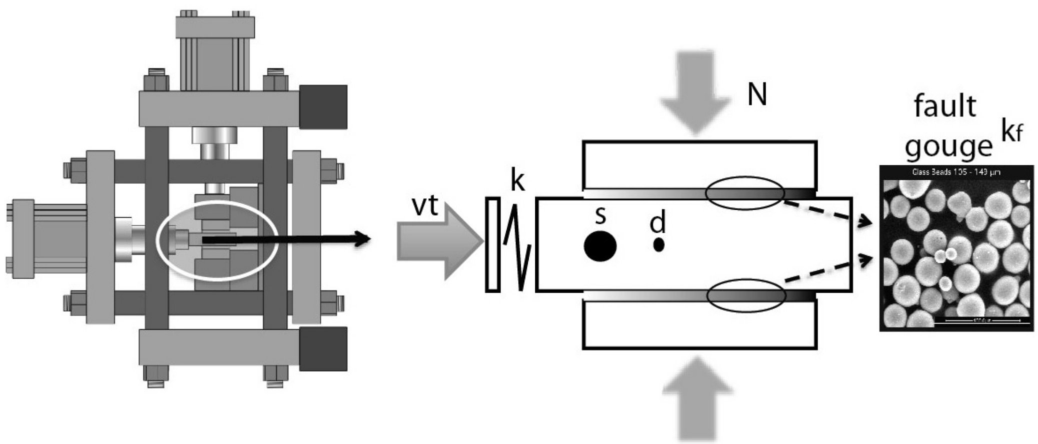


**FIGURE 2.** The 'earthquake machine', a bi-axial shearing device located at the Pennsylvania State University (C. Marone). At left, the device is shown turned on its side. In the center, the steel shearing blocks are shown in expanded view. A constant normal load *N* is applied to the blocks, while it is sheared at constant displacement rate *vt*, via a stiff spring *k*. Two layers of glass beads (representing 'fault gouge') of diameter ~140 micron that act as a second, softer spring $k_f$ and are located between the three blocks. An expanded view of the glass beads is shown at right. Acoustic waves are applied using a piezoceramic source *s*. The waves are detected using an accelerometer *d* located on the backside of the central block. The granular layers are each four mm in thickness, equivalent to about 30-50 bead diameters.

## Dynamic Wave Triggering of Stick-Slip

In experiments that explore triggered stick-slip events we observe a number of interesting phenomena. At applied loads *N* of 4-6 MPa with application of dynamic strains of $\sim 10^{-6}$, we observe complicated nonlinear behavior. When triggering signals are frequently applied the material becomes highly disrupted, as is evidenced by instantaneous and delayed event triggering, and significant changes in laboratory inter-earthquake time. Disruption by acoustic signals progressively changes the response behavior of the gouge material for the duration of the experiment. This indicates some long-lived influence or memory associated with dilation in the material, which is a strong nonlinear dynamical effect[10]. Figure 4 shows laboratory earthquake inter-event times for such an experiment; results of an experiment with no applied acoustical perturbation are shown for comparison.

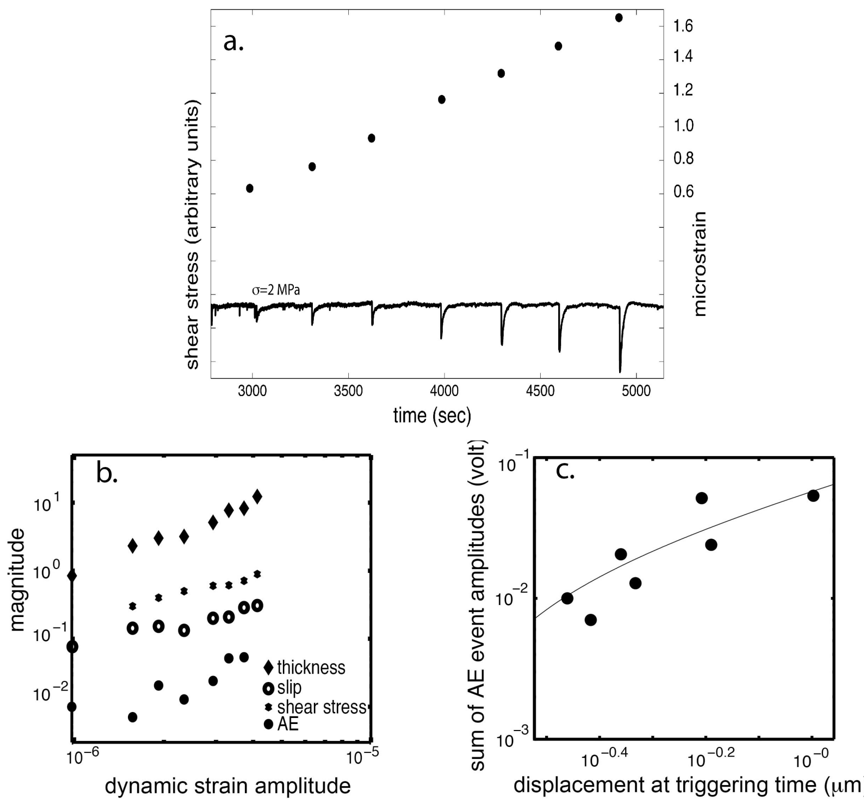


**FIGURE 3.** Observations of the triggering-wave amplitude dependence of slow-slip at 2 MPa applied load (*N* in Figure 2). Shear rate *vt* was 5 microns/sec. (a) Shear stress imposed on the gouge layers versus experiment time (solid curve). Black dots represent triggering acoustic wave strain amplitudes noted on the right-hand y-axis. Progressively large amplitudes were applied. At the time of each triggering wave application there is an associated stress drop corresponding to a triggered slow-slip. (b) With triggered shear stress drop there is also a change in the thickness of the gouge layer, a slip in the direction of shearing and a burst of acoustic emission (AE). These quantities all depend on the triggering wave amplitude as shown in (b). (c) The displacement along the shearing direction correlates with the AE, which means that the AE can be used as a proxy for slip. In the Earth, seismic emission in the form of tremor during slow-slip events is often the only quantity measured from a slip event of any kind[4]. We speculate that the tremor can be used as a proxy for slow-slip in the Earth.

In laboratory studies of triggered stick-slip, we observe no triggering-wave amplitude dependence of the measured parameters that include granular layer thickness change, displacement in the shearing direction, etc. Apparently Mohr-Coulomb-like failure is responsible, followed by significant (elastically nonlinear) memory effects. Figure 5 shows the shear stress, time between laboratory earthquakes, and the change in material thickness during triggering for such an experiment. The memory post-triggering persists through multiple stick-slip events. The memory is very similar to that observed for triggered slow-slip, except the material continues to fail periodically, progressively returning to its pre-triggered behavior. The recovery process termed *slow dynamics*[1,12] resembles that observed in un-sheared granular materials[11]. The memory is associated with a granular material dilation. The stick-slips occurring during the recovery are higher frequency dilation events that take place during a low frequency material dilation. In order to characterize the physics of the triggering and recovery process, we are studying these effects using DEM[9].

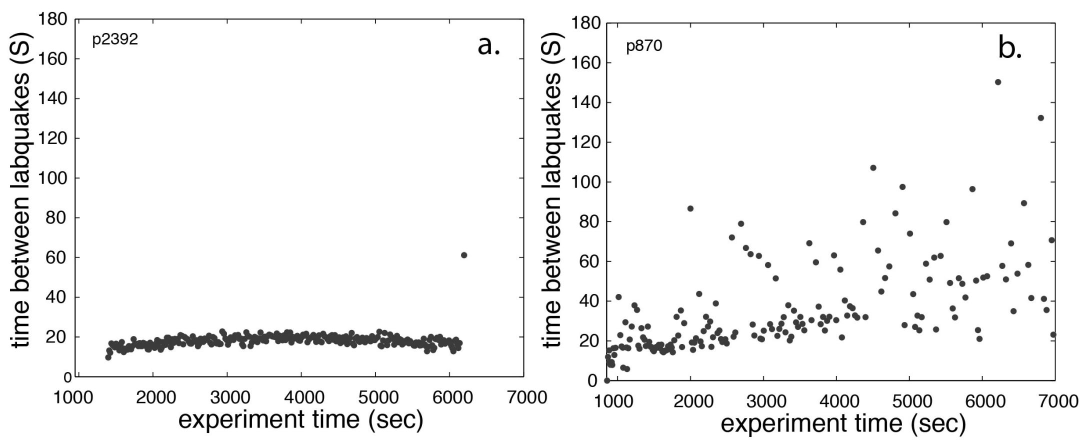


**FIGURE 4.** Observations of time between stick-slip occurrences corresponding to laboratory earthquakes for an experiment with no acoustical triggering (a) and for one with triggering (b). Each dot represents a stick slip event (labquake). The scatter in the time between events becomes pronounced as the experiment progresses, as more and more acoustical triggers are applied.

In Figure 6 we compare the granular material recoveries from three different experiments: one triggered quasi-static, one triggered stick-slip and one triggered slow-slip. The quasi-static experiment (Figure 6a) was conducted in a glass bead pack—a canister that was vibrated in resonance. The resonance waves were of such a strain ($>10^{-6}$) as to decrease the material wavespeed and modulus. Immediately after termination of the large amplitude resonance, a very small amplitude wave was used as a probe to follow the evolution of the wavespeed and modulus back to equilibrium. The recovery, the material slow dynamics, is linear in semi-log space. The recovery post triggered stick-slip is shown in Figure 6b, and that for triggered slow-slip is shown in Figure 6c. All initially have a linear dependence, and subsequently the dependence changes progressively as equilibrium is approached. The equilibrium value post acoustic perturbation is approximately the same as post acoustical perturbation. There are several theoretical approaches one can take to explain the failure and recovery process; for instance an Arrhenius model that employs the well-known Preisach model of elasticity[13,1] or models based on crack shearing[14]. This is an area of intense study at present.

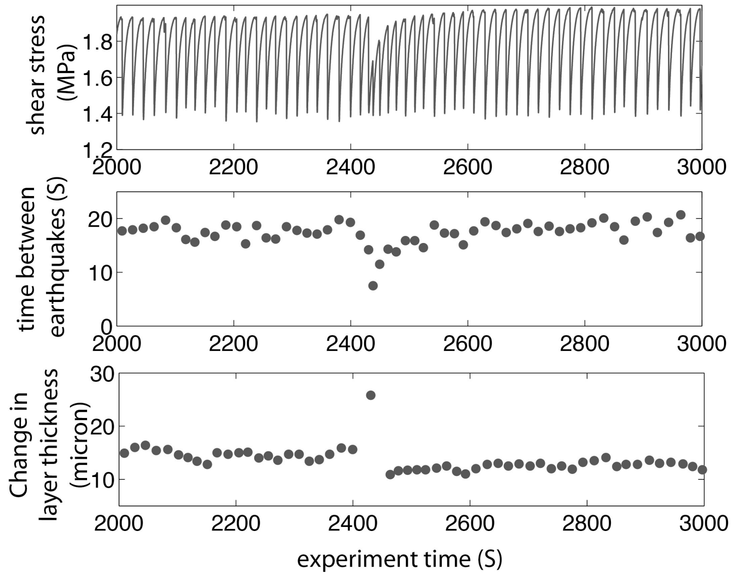


**FIGURE 5.** Experiment exhibiting stick-slip and triggered stick-slip. The top trace shows the shear stress with experiment time. As can be seen, regular stick-slips take place under the conditions of this experiment (5 MPa load applied at 5 microns/S shearing rate). After a typical stick-slip event, the granular material dilates until it becomes unstable and another slip event takes place. At approximately 2420 S, an acoustic pulse is applied of duration ~200 microseconds and >$10^{-6}$ strain. Instantaneous triggering takes place with a significant effect on the gouge layer thickness (it thins by 20-30 microns) [bottom panel] and with a pronounced effect on the succeeding recurrence interval and maximum shear stress [tope and central panels]. There appears to be a long term low frequency dilation occurring along with shorter term dilation between slip events. This long term effect strongly resembles slow dynamics in unsheared granular materials[6] and rock[1]—see figure 6.

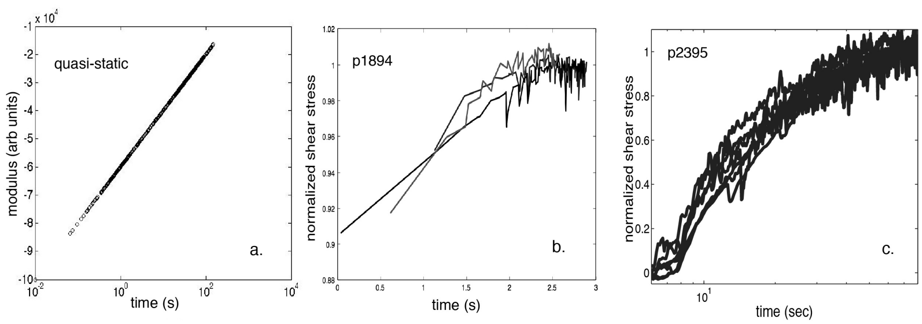


**FIGURE 6.** Recovery (memory) under quasi-static and shearing conditions shown in semi log space. (a) Modulus recovery of a canister of glass beads after applying acoustic vibration, termed slow dynamics[11]. (b) Recovery of the shear stress in a shearing experiment employing the apparatus shown in Figure 2, for three different applications of acoustical pulses. The data are smoothed in contrast to the shear stress data shown in Figure 5 (top). (c) Shear-stress recovery for the triggered slow-slip experiment. All triggering wave data are shown. The traces are normalized to their minimum shear stress values post triggering. The quasi-static data are clearly linear. The slope of the curve progressively changes as the equilibrium value is approached. In the shear data shown in (b) and (c), the approach to equilibrium is shown, after the functionality is first linear. The shear stress recovery strongly resembles the slow dynamics of the quastistatic experiment. Note that the modulus was not recorded in the shearing experiments. The shear stress may or may not exhibit the same type of recovery.

# SIMILAR PROCESSES IN EARTH

In the Earth, many of the same features observed in the laboratory are observed during triggering both under quasistatic and dynamic conditions. Triggering may disrupt the inter-event time—the time between earthquakes—for instance[15] (e.g., Figure 7) and it may affect the velocity of waves in the region of the fault. Long-time recovery of recurrence is commonly observed and velocity recovery has been observed as well over the last decade. These types of correlations are also beyond the scope of this paper expect that we see hints of some of these features in the Earth, as shown in Figure 7.

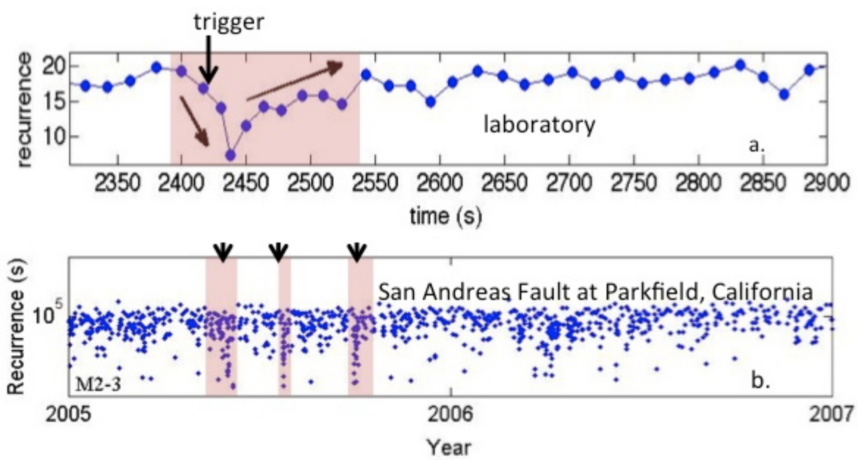


**FIGURE 7.** Similarities in time between labquakes/earthquakes (recurrence) for laboratory data and earthquakes located and along the Parkfield segment of the San Andreas fault in California (USA). (a) In the laboratory data, the solid circles represent stick slip events. At the time denoted by the arrow, an acoustical pulse is applied, disrupting labquake recurrence. (b) The solid circles represent earthquakes of Magnitude 2-3. At the times denoted by the arrows and shading, local and/or regional earthquakes create a disruption in the recurrence interval. Despite the very different timescales, the earthquakes show similar to what takes place in the laboratory. There is also a long recovery time in the earthquake data (not shown due to the compressed scale). We are currently studying such features and determining how widespread they are in the Earth.

# CONCLUSIONS

A brief overview of nonlinear dynamics in Earth process has been presented, with a primary focus on our laboratory investigations of nonlinear dynamics in proxy Earth materials. I briefly described the highly nonlinear processes found in Strong Ground Motion. I detailed our laboratory experiments that defined triggered slip and recovery phenomena. A comparison to quasistatic experiments was also made in order to show similarities in the response fault gouge materials to dynamic excitation. One of our goals is to understand how dynamic triggering affects earthquake hazards. This process is not currently taken into account for earthquake hazard analysis. Another long term goal is to characterize the physics leading to slip and triggered slip. These topics are currently being addressed.

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## REFERENCES

1. R. A. Guyer and P.A. Johnson, *Nonlinear Mesoscopic Elasticity: The Complex Behaviour of Rocks and Soil*, Wiley-VCH Verlag GmbH Berlin (2009).
2. E. H. Field, P. A. Johnson, I. Beresnev, and Y. Zeng, *Nature* **390**, 599-602, (1997).
3. A. M. Freed, *Annual Reviews of Earth and Planetary Sciences* **33**, 335-367 (2005) DOI: 10.1146/annurev.earth.33.092203.122505
4. P. A. Johnson, B. M. Carpenter, M. W. Knuth, B. M. Kaproth, P.-Y. Le Bas, E. G. Daub, and C. Marone , *Jour. Geophys. Res.* **17**, 2012 doi:10.1029/2011JB008594
5. D. Marsan and O. Lengliné, *Science* **319,** 1076-1079 (2008).
6. J. Gomberg and P. A. Johnson, *Nature* **473** 830-834 (2005).
7. K. Obara, Science 296 1679-1680 (2002) DOI: 10.1126/science.1070378.
8. E. F. Glowacka, E., F. Alehandro Nava, G. Diaz de Cossio, V. Wong, and F. Farfan, *Bull. Seismol. Soc. Am.* **92**, 1290–1299 (2002) doi:10.1785/0120000911.
9. M. Griffa, B. Ferdowsia, E.G. Daub,R.A. Guyer, P.A. Johnson, C. Marone and J. Carmeliet, *Philosophical Magazine*, *in press* (2012); M. Griffa., E. Daub, R. Guyer, P. Johnson, C. Marone, and J. Carmeliet, *European Physics Letters* **96**, 14001-14005 (2011).
10. P. A. Johnson, H. Savage, M Knuth, J. Gomberg and C. Marone, *Nature* **451**, 57-60 (2008)| doi:10.1038/nature06440.
11. P. A. Johnson and X. Jia, *Nature* **473** 871-874 (2005).
12. J. A. TenCate, Slow Dynamics of Earth Materials: An Experimental Overview, in *Pure Appl. Geophys. Special issue on Brittle Deformation,* edited by Y. Ben-Zion and C. Sammis, PAGEOPH Topical Volumes, Birkhauser, 2011, pp. 65-74, DOI:10.1007/s00024-011-0268-4.
13 V.E. Gusev and V. Tournat, *Phys. Rev. B* **72**, 054104-1 054104-19 (2005).
14. Vakhnenko, O, V. Vakhnenko, and T. J. Shankland, *Physical Review* B **71**, 174103-174120 (2005).
15 C. Wu, D. Shelly, C. Marone, J. Gomberg and P. A. Johnson, *Geophys. Res. Lett*., *in review* (2012).