Our activity evolved from our work in deriving the microphysical basis of rate and state friction [1-3]. As proposed for last two years, we concentrated on damage processes within shallow (upper ~10s m) off-fault environments. We now recognize that 3 and probably 5 nonlinear effects are related: (1) The attenuation of strong shallow seismic waves increases at high amplitude [5-8]; (2) The low-amplitude seismic velocity decreases after strong shaking and subsequently slowly heals [9-19]; (3) Strong shaking triggers shallow very small earthquakes [20-22]. The largest of these shallow events produce brief extreme ground accelerations [23-24]. (4) Geomorphic studies indicate that damaged easily eroded regolith exists near major seismically active faults [25]. (5) Changes in the permeability of shallow rocks and groundwater pressure in shallow wells in the aftermath of strong shaking are conceivably related to rock damage on fractures [17]. This effect, however, is usually attributed to shaking disrupting debris that clog chock points in groundwater flow paths and to transient groundwater pressure variations due to shaking [e.g., 26]. The time-dependent behavior of renewed clogging and crack closure should differ in principle. Available data do not provide an obvious solution for the extent to which each process operates. We did not attempt to resolve this issue.

During the period of this grant, we have continued to investigate shallow rock damage during strong shaking. Nonlinear attenuation is the process of societal interest. The remaining 4 processes allow its effects to be detected indirectly and facilitate application of rock physics. We gave attention both to nonlinear attenuation of moderately strong seismic waves and to the upper limit on extreme ground motions. We note that there is new evidence for our hypothesis that dynamic stress triggers shallow earthquakes that cause brief extreme dynamic acceleration [23-24]: John Tinsley (USGS) documented patches of flipped cow turds following the 2004 Parkfield mainshock. Overall, such extreme accelerations are an interesting harmless form of nonlinear attenuation, not a harbinger of sustained extreme dynamic accelerations.

We proposed to investigate alternation of seismic activity between nearby parallel strike-slip fault systems by modeling power-law ductile creep beneath the seismogenic zone. However, work presented at SCEC 2009 by David Shelly (USGS) indicates that tremor and hence slow frictional creep occurs beneath the normal seismogenic zone, so we abandoned deep ductile creep as a viable approach but will remain alert for applicable mechanics. The P.I. will maintain his broad interests in seismology and tectonics.

Off-fault damage and nonlinear attenuation near Parkfield. As proposed, we published a paper [27] discussing shallow transient low-amplitude seismic velocity changes associated with the Parkfield mainshock. We obtained an explanation of the local seismic coda with this exercise. The coda for repeating earthquakes in the Parkfield region are progressively delayed with increasing coda-S arrival time [12]. The delay of S- and P-coda relative to their primary phases is mostly from circuitous paths at great depths where the seismic velocity does not change. The coda reverberates briefly in the shallow subsurface where the seismic velocity did change. The change in coda-P and coda-S is comparable to the change in S-P as observed. Conversely modeling the coda a scattered Rayleigh or body where most of the primary to coda delay occurs in the shallow subsurface predicts excessive changes in coda-primary delays. Second, ambient noise seismograms [15] are mostly surface waves (~4 s period, ~1.7 km/s group velocity), which give little depth resolution. We showed that the S-P and Rayleigh data sets are compatible with most of the damage being shallow. However the fractional Rayleigh wave velocity change is sensitive to its group velocity and period.

We examined borehole records before and after the Parkfield mainshock to obtain surface reflected paths that are known to be in the shallow subsurface. Autocorrelated ambient noise in principle gives a virtual zero-offset seismogram. We obtained P-wave (but not S-wave delays) of the free surface reflection of deeper reverberations at one station. We obtained the P-wave surface reflection at another station by stacking on the first peak of P-waves and flipping the polarity if necessary. The P-wave delay changes in both cases are comparable to the S-P delay changes as expected.

The stacking method is generally applicable to the Parkfield borehole stations. David Shelly (USGS) presented tremor data from these stations with a vast number of repeating events. We expect that he will use these arrivals to obtain better P-wave and S-wave surface reflection delays. Continuous records were not retained for the shallow UPSAR Parkfield array. Justin Rubinstein (USGS) is examining transient velocity changes in this triggered data set. We do not plan further borehole studies, as other groups are actively doing excellent work.

Nonlinear attenuation of basin waves. As proposed, we have paper in press on nonlinear attenuation of reverberative waves in basins like Palm Springs and Los Angeles [28]. It is societally important to quantify this effect without having to wait for an Mw = ~7.8 event on the San Andreas Fault. An empirical site-response treatment as typically used for body waves is inadequate as energy passes through the near surface several times. Considerable simplification arises, as these basin waves are essentially fundamental-mode Love waves. We also made computations with Rayleigh waves for completeness. The SCEC Community Modeling Environment model and the synthetic Shake-out event provided the basis for generic calculations [29-30]. To efficiently take derivatives of displacement to obtain dynamic stress, we modified their velocity model so that the layers are homogeneous and oversampled the shallow subsurface. We assumed a maximum ground-surface particle velocity of ~1.5 m s^{-1} and computed that fraction of the elastic energy that resides above given dynamic to lithostatic (~Coulomb) stress ratio. We obtained the perhaps frustrating result that a modest fraction of elastic energy resides at Coulomb stress where failure is expected within a pre-stressed material. Thus nonlinear attenuation is significant, but does not overwhelm the wave.

Nonlinear Coulomb-based (or Drucker-Prager) attenuation can be included in the numerical code used for the Shake-out example [29-30]. We envision a calibration approach. The Los Angeles basin has repeatedly experienced modest (~0.5 m s^{-1} velocity amplitude) basin waves, like from the Landers mainshock [31-32]. Nonlinear behavior is expected in the upper tens of meters. This nonlinear effect does not significant sap 3-4 s period waves, but it should cause rock shallow damage. Marine Denolle (Stanford) is currently studying surface waves from ambient noise in the Los Angeles basin. The study will obtain the low-amplitude seismic behavior and may provide a direct check of whether observable nonlinearity occurred with modest basin waves, like with Landers. She will attempt to obtain results at high enough frequencies to resolve shallow transient velocity changes after strong shaking, but the stations may not be closely enough spaced to do this. In any case, shallow transient damage is resolvable if stations are close enough, so our work is relevant to the effective deployment of instruments.

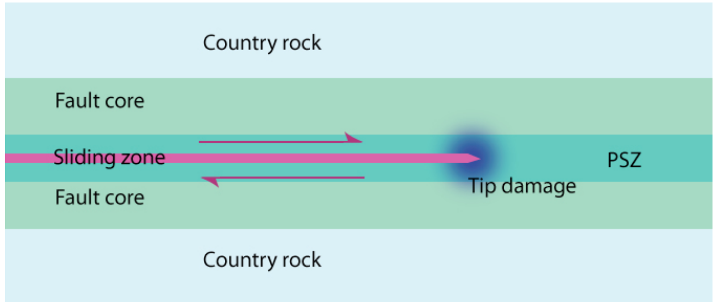
Rock crushing and the upper limit on extreme compressional P-waves. The crushing strength of brittle materials is important to the societal issue of the maximum compressional P-wave that can propagate though porous brittle rock. The SCEC 2009 RFP gave priority to this task as it relates to nuclear waste storage. To theoretically examine this process, we applied microphysics to unify rate and state friction with end-cap behavior [33]. Both processes involve exponential creep at the molecular level. We use a thermodynamic continuum approach that strives to obtain a macroscopic average.

Our conceptual method accrues since rocks have been exposed to lithostatic stress over geological time. For significant seismic failure to occur, the creep rate needs to increase by the ambient geological time to the seismic time, that is, by a factor of $\sim 10^{14}$. For simplicity, we represent the exponential creep rate on stress with an equivalent power-law N. The normal stress needs to increase to a factor of $\sim 10^{14/N}$ of its ambient value for crushing to occur. Frequently jostled regolith near major faults has had the seismic cycle time tens to hundreds of years to compact under lithostatic stress so the ratio of compaction to seismic times is $\sim 10^9$.

We obtained the exponent N by considering the geometry of real contacts where the stress is a few MPa. Both shear and normal traction contribute to the deviatoric stress at the contact. Rate and state friction involves creep within tabular contacts. Shear strain occurs along the contact and normal traction drives extrusion from the contact. The shear tractions from extrusion are much less than the normal traction as typical of a lubricated surface. The value of $N = \sim 30$ is much less than the intrinsic value of $N = \sim 100$ of the material. Near-surface crushing of regolith is expected at sustained dynamic accelerations modestly above 1 g. End-cap crushing occurs by cracking around a grain-grain contact. The predicted value of N is near the intrinsic value ~100. Materials like unwelded tuff with pointy contacts fail at normal tractions modestly above their lithostatic pressure and at sustained dynamic accelerations of a modest fraction of 1 g. Sandstones where pressure solution has broadened contacts have $N = \sim 10$ and do not seismically fail in the Earth by rate and state compaction. They do eventually fail in the end-cap mode at a high normal stress. Overall, the formalism provides a crushing failure criterion that may be calibrated in the laboratory and by petrographic studies real contacts.

Fault-tip behavior. We have submitted a paper on the dynamics of rupture tips [33]. The modern theory of dynamic rupture involves brief dynamic stresses near rupture tips [34-35]. Most of the slip occurs within a principle slip zone which is ~1 mm wide. A ~10 mm wide fault core contains the principle slip zone (PSZ) [36-37]. Initially failure at the rupture tip occurs at stresses expected for Coulomb failure, ~100 MPa for a generic example. Rate and state friction applies initially. Eventually after a small amount of slip, thermal pressurization or flash melting greatly weakens the slip surface. The remainder (meters) of slip occurs at low shear traction.

The amount of slip within the fault core during each event is relevant to observations of exhumed faults. We obtained analytical expressions for this quantity for the aging evolution law of rate and state friction and numerical results for the slip law. In both cases, strain rate localization occurs if the state variable within the PSZ in slightly less than that of the fault core. This result is true even if $a > b$, which implies strain-rate delocalization is the slip velocity changes gradually.



Dynamic stresses near the rupture tip determine the width of the PSZ. Slip occurs on multiple independent surfaces within the PSZ. The rate and state and dynamic weakening slip distances scale linearly to its width. Overall, the PSZ width and slip weakening distance scale self-organize so that dynamic stresses around the rupture tip are those for Coulomb failure. For example, an excessively thin sliding zone (as drawn above) results in rapid slip weakening and huge dynamic velocities at the rupture tip. This situation implies dynamic stresses well above those for failure on the fault. Failure from these stresses at the rupture tip widens the PSZ. Extensive failure by dynamic stresses would also add to macroscopic friction and strengthen the fault. Conversely, strain rate localization weakens the sliding zone if it is initially too thick. This process continues until the weakening distance of the PSZ implies some off-tip failure and the minimum possible macroscopic friction. Note that this width criterion applies only near the rupture tip. The sliding zone within the PSZ can localize as observed in exhumed faults [36] where meters of slip occurs after dynamic weakening.

We have also examined the microphysics of flash melting. The standard theory gives an applicable answer, but both shear and normal traction need to be taken into account. That is, the material within a fully weakened contact will extrude and not support normal traction. The net effect is that if the contact did not exist. Therefore, unmelted contacts would support both shear and normal traction and the macroscopic coefficient of friction does not change. Rather, weakened contacts become more tabular and the unweakened material within contacts retards both shear strain and extrusion strain. A testable prediction is that seismic dilatancy decreases once flash melting commences.

Regolith damage and nonlinear attenuation. We have returned to our work [38] to obtain an improved treatment of nonlinear attenuation in regolith that is repeated jostled in strong seismic events. We retain a fractal distribution of stresses within the material [39]. These stresses are residual stresses immediately after shaking and pre-stresses in the next strong earthquake. The highest stresses relax between earthquakes. A finite dynamic stress is thus needed to bring the sum of dynamic and pre-stress to failure and cause nonlinear attenuation. Regolith that is frequently shaken will have high peak pre-stress and high pre-stress elastic energy and thus tend to fail in subsequent shaking.

We are applying this formalism to obtain microscopic strain energy and explain pulverized rock [40-41]. We agree that extreme dynamic stress do produce pulverized rock in the laboratory [42], but point out that numerous events where failure barely occurs are more likely. Microscopic strain energy, surface free energy, and porosity work against lithostatic stress are comparable. Microscopic strain energy builds up until the amount regenerated in each event balances the amount that relaxes between events. Thereafter, further pulverization becomes inefficient.

[1] Sleep, N. H. (2005) Physical basis of evolution laws for rate and state friction, *Geochem. Geophys. Geosyst.*, *6*, Q11008, doi:10.1029/2005GC000991. *SCEC contribution number 896.*

[2] Sleep, N. H. (2006) Real contacts and evolution laws for rate and state friction, *Geochem. Geophys. Geosyst.*, *7*, Q08012, doi:10.1029/2005GC001187. *SCEC contribution number 991.*

[3] Sleep, N. H. (2006) Frictional dilatancy, *Geochem. Geophys. Geosyst.*, *7*, Q10008, doi:10.1029/2006GC001374. *SCEC contribution number 1030.*

[4] Frankel, A. D., D. L. Carver, and R. A. Williams (2002) Nonlinear and linear site response and basin effects in Seattle for the M 6.8 Nisqually, Washington, earthquake, *Bull. Seism. Soc. Am.*, *92***,** 2090–2109.

[5] Beresnev, I. A. (2002) Nonlinearity at California generic soil sites from modeling recent strong-motion data, *Bull. Seismol. Soc. A., 92*, 863-870.

[6] Hartzell, S., L. F. Bonilla, and R. A. Williams (2004) Prediction of nonlinear soil effects, *Bull. Seismol. Soc. Am., 96*, 1609-1629.

[7] Bonilla, L. F., R. J. Archuletta, and D. Lavallée (2005) Hysteretic and dilatant behavior of cohesionless soils and their effects on nonlinear site response: Field data observations and modeling, *Bull. Seismol. Soc. A., 95*, 2373-2395.

[8] Tsuda, K., J. Steidl, R. Archuleta, and D. Assimaki (2006) Site-response estimation for the 2003 Miyagi-Oki earthquake sequence consider nonlinear site response, *Bull. Seismol. Soc. Am., 96*, 1474-1482.

[9] Poupinet, G., W. L. Ellsworth, and J. Frechet (1984) Monitoring velocity variations in the crust using earthquake doublets: An application to the Calaveras fault, California, *J. Geophys. Res.* **89**(B7), 5719-5731.

[10] Rubinstein, J. L., and G. C. Beroza (2004a) Nonlinear strong ground motion in the M_L 5.4 Chattenden earthquake: Evidence that preexisting damage increases susceptibility to further damage, *Geophys. Res. Lett., 31*, L23614, doi:10.1029/2004GL021357.

[11] Rubinstein, J. L., and G. C. Beroza (2004b) Evidence for widespread nonlinear strong motion in the M_W 6.9 Loma Prieta Earthquake, *Bull. Seismol. Soc. Am., 94*, 1595-1608.

[12] Rubinstein, J. L., and G. C. Beroza (2005) Depth constraints on nonlinear strong ground motion from the 2004 Parkfield earthquake, *Geophys. Res. Lett., 32*, L14313, doi:10.1029/2005GL023189.

[13] Peng, Z. G., and Y. Ben-Zion, (2006) Temporal changes of shallow seismic velocity around the Karadere-Duzce branch of the North Anatolian fault and strong ground motion, *Pure Appl. Geophys., 163*, 567-600.

[14] Sawazaki, K., H. Sato, H. Nakahara, and T. Mishimura (2006) Temporal change in site response caused by earthquake strong motion as revealed from coda spectral ratio measurement, *Geophys. Res. Lett, 33*, L21303, doi: 10.1029/2006GL027938.

[15] Brenguier, F. , M. Campillo, C. Hadziioannou, N. M., Shapiro, R. M. Nadeau, and E. Larose (2008) Postseismic relaxation along the San Andreas Fault at Parkfield from continuous seismological observations, *Science*, *321*, 1478-1481.

[16] Wegler, U., H. Nakahara, C. Sens-Schönfelder, M. Korn, and K. Shiomi (2009) Sudden drop of seismic velocity after the 2004 Mw 6.6 Mid-Niigata Earthquake,

Japan, observed with passive image interferometry, *J. Geophys. Res.*, *114*, B06305, DOI: 10.1029/2008JB005869.
[17] Chao, K., and Z. G. Peng (2009) Temporal Changes of Seismic Velocity and Anisotropy in the Shallow Crust Induced by the 10/22/1999 M6.4 Chia-Yi, Taiwan Earthquake, *Geophys. J. Int.*, *179*, 1800-1816.
[18] Wu, C. Q., Z. G. Peng, and D. Assimaki (2009) Temporal Changes in Site Response Associated with the Strong Ground Motion of the 2004 M-w 6.6 Mid-Niigata Earthquake Sequences in Japan, *Bull. Seismol. Soc. Am.*, *99*, 3487-3495.
[19] Zhao, P., and Z. G. Peng (2009) Depth extent of damage zones around the central Calaveras fault from waveform analysis of repeating earthquakes, *Geophys. J. Int.*, *99*, 1817-1830.
[20] Fischer, A. D., C. G. Sammis, Y. L. Chen, and T.-L. Teng (2008a), Dynamic triggering by strong motion P- and S-waves: Evidence from 1999 Chi-Chi, Taiwan Earthquake, Bull. Seismol. Soc. Am., 98, 580 – 592, doi:10.1785/0120070155.
[21] Fischer, A. D., Z. G. Peng, and C. G. Sammis, (2008) Dynamic triggering of high-frequency bursts by strong motions during the 2004 Parkfield earthquake sequence, Geophys. Res. Lett., 35, L12305, doi:10.1029/2008GL033905.
[22] Fischer, A. D., and C. G. Sammis (2009) Dynamic driving of small shallow events during strong motion, *Bull. Seismol. Soc. Am.*, *99*, 1720-1729.
[23] Aoi, S., T. Kunugi, and H. Fujiwara (2008) Trampoline effect in extreme ground motions. *Science* **332**, 727-730.
[24] Sleep, N. H., and S. Ma (2008), Production of brief extreme ground acceleration pulses by nonlinear mechanisms in theshallow subsurface, *Geochem. Geophys. Geosyst.*, *9*, Q03008, doi:10.1029/2007GC001863.
[25] Wechsler, N., T. K. Rockwell, Y. Ben-Zion (2009) Application of high resolution DEM data to detect rock damage from geomorphic signals along the central San Jacinto Fault. *Geomorphology*, 113, 82–96.
[26] Elkhoury, J. E., E. E. Brodsky, and D. C. Agnew, Seismic waves increase permeability, *Nature*, *441*(7097), 1135–1138, 2006.
[27] Sleep, N. H. (2009) Depth of rock damage from strong seismic ground motions near the 2004 Parkfield mainshock. Bull. Seismological Soc. America, 99(5), 3067–3076, doi: 10.1785/0120090065. SCEC contribution number 1278.
[28] Sleep, N. H. (2010) Nonlinear behavior of strong surface waves trapped in sedimentary basins. Bull. Seismological Soc. America, 100(2), in press, doi: 10.1785/0120090150. SCEC contribution number 1327.
[29] Graves, R.W., B.T. Aagaard, K.W. Hudnut, L.M. Star, J.P. Stewart and T.H. Jordan (2008) Broadband simulations for Mw7.8 southern San Andreas earthquakes: Ground motion sensitivity to rupture speed, *Geophys. Res. Lett.* **35**, L22302, doi:10.1029/2008GL035750.
[30] Olsen, K. B., and 12 others (2009) ShakeOut-D: Ground motion estimates using an ensemble of large earthquakes on the southern San Andreas fault with spontaneous rupture propagation, *Geophys. Res. Lett.* **36**, L04303, doi: 10.1029/2008GL036832.
[31] Joyner, W. B. (2006) Strong motion from surface waves in deep sedimentary basins. *Bull. Seismol. Soc. Am.* **90**(6B), S95-S112.
[32] Olsen, K. B., S. M. Day, J. B. Minster, Y. Cui, A. Chourasia, M. Faerman, R. Moore, P. Maechling, and T. Jordan (2006) Strong shaking in Los Angeles expected

from southern San Andreas earthquake. *Geophys. Res. Lett.* **33**, L07305, doi:10.1029/2005GL025472.
[33] Sleep, N. H. (2010) Sudden and gradual compaction of shallow brittle porous rocks. *J. Geophys. Res.*, in press. SCEC contribution number 1339.
[34] Beeler, N. M., T. E. Tullis, and D. L. Goldsby (2008), Constitutive relationships and physical basis of fault strength due to flash heating, *J. Geophys. Res.*, *113*, B01401, doi:10.1029/2007JB004988.
[35] Noda, H., E. M. Dunham, and J. R. Rice (2009), Earthquake ruptures with thermal weakening and the operation of major faults at low overall stress levels, *J. Geophys. Res*., *114*, B07302, doi:10.1029/2008JB006143.
[36] Chester, F. M., J. S. Chester, D. L. Kirschner, S. E. Schulz, and J. P Evans (2004) Structure of large-displacement, strike-slip fault zones in the brittle continental crust. In: *Rheology and Deformation in the Lithosphere at Continental Margins*, Edited by Karner, G. D., B. Taylor, N. W. Driscoll, and D. L. Kohlstedt, Columbia University Press, New York, pp. 1-26.
[37] Chester, J. S., F. M. Chester, and A. M. Kronenberg (2005) Fracture surface energy of the Punchbowl fault, San Andreas system, *Nature*, *437*, 133-136.
[38] Sleep, N. H., and P. Hagin (2008), Nonlinear attenuation and rock damage during strong seismic ground motions, *Geochem. Geophys. Geosyst.*, *9*, Q10015, doi:10.1029/2008GC002045.
[39] Marsan. D. (2005) The role of small earthquakes in redistributing crustal elastic stress. *Geophys. J. Int., 163*, 141-151.
[41] Rockwell, T., M. Sisk, G. Girty, O. Dor, N. Wechsler, and Y. Ben-Zion (2009) Chemical and physical characteristics of pulverized Tejon Lookout Granite adjacent to the San Andreas and Garlock Faults: Implications for earthquake physics. *Pure Appl. Geophys.*, *166*, 1725–1746.
[42] Dor, O., J. S. Chester, Y. Ben-Zion, J. N. Brune, and T. K. Rockwell (2009) Characterization of damage in sandstones along the Mojave section of the San Andreas Fault: Implications for the shallow extent of damage generation. *Pure Appl. Geophys.*, *166*, 1747–1773.
[42] Doan, M.-L., and G. Gary (2009) Rock pulverization at high strain rate near the San Andreas fault. *Nature Geoscience*, *2*, 709-712, DOI: 10.1038/NGEO640.