## S41B MCC: 3009 Thursday 0800h

### The Energy Budget of the Earthquake Machine I *(joint with G, T, NG)*

***Presiding:*** **R E Abercrombie,** Boston University**; A McGarr,** U.S. Geological Survey

#### S41B-01 0805h INVITED

### Energy Partition and Variability of Earthquakes

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During an earthquake the potential energy (strain energy + gravitational energy + rotational energy) is released, and the released potential energy ($\Delta W$) is partitioned into radiated energy ($E_R$), fracture energy ($E_G$), and thermal energy ($E_H$). How $\Delta W$ is partitioned into these energies controls the behavior of an earthquake. The merit of the slip-weakening concept is that only $E_R$ and $E_G$ control the dynamics, and $E_H$ can be treated separately to discuss the thermal characteristics of an earthquake. In general, if $E_G/E_R$ is small, the event is "brittle", if $E_G/E_R$ is large, the event is "quasi static" or, in more common terms, "slow earthquakes" or "creep". If $E_H$ is very large, the event may well be called a thermal runaway rather than an earthquake. The difference in energy partition has important implications for the rupture initiation, evolution and excitation of long-period ground motions from very large earthquakes. We review the current state of knowledge on this problem in light of seismological observations and the basic physics of fracture. With seismological methods, we can measure only $E_R$ and the lower-bound of $\Delta W$, $\Delta W_0$, and estimation of other energies involves many assumptions. $E_R$: Although $E_R$ can be directly measured from the radiated waves, its determination is difficult because a large fraction of energy radiated at the source is attenuated during propagation. With the commonly used teleseismic and regional methods, only for events with $M_W > 7$ and $M_W > 4$, respectively, we can directly measure more than 10% of the total radiated energy. The rest must be estimated after correction for attenuation. Thus, large uncertainties are involved, especially for small earthquakes. $\Delta W_0$: To estimate $\Delta W_0$, estimation of the source dimension is required. Again, only for large earthquakes, the source dimension can be estimated reliably. With the source dimension, the static stress drop, $\Delta\sigma_S$, and $\Delta W_0$, can be estimated. $E_G$: Seismologically, $E_G$ is the energy mechanically dissipated during faulting. In the context of the slip-weakening model, $E_G$ can be estimated from $\Delta W_0$ and $E_R$. Alternatively, $E_G$ can be estimated from the laboratory data on the surface energy, the grain size and the total volume of newly formed fault gouge. This method suggests that, for crustal earthquakes, $E_G/E_R$ is very small, less than 0.2 even for extreme cases, for earthquakes with $M_W > 7$. This is consistent with the $E_G$ estimated with seismological methods, and the fast rupture speeds during most large earthquakes. For shallow subduction-zone earthquakes, $E_G/E_R$ varies substantially depending on the tectonic environments. $E_H$: Direct estimation of $E_H$ is difficult. However, even with modest friction, $E_H$ can be very large, enough to melt or even dissociate a significant amount of material near the slip zone for large events with large slip, and the associated thermal effects may have significant effects on fault dynamics. The energy partition varies significantly for different types of earthquakes, e.g. large earthquakes on mature faults, large earthquakes on faults with low slip rates, subduction-zone earthquakes, deep focus earthquakes etc; this variability manifests itself in the difference in the evolution of seismic slip pattern. The different behaviors will be illustrated using the examples for large earthquakes, including, the 2001 Kunlun, the 1998 Balleny Is., the 1994 Bolivia, the 2001 India earthquake, the 1999 Chi-Chi, and the 2002 Denali earthquakes.

#### S41B-02 0825h INVITED

### Friction Falls To Zero At Seismic Slip Rates

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Determination of the resistance to slip on faults in the Earth's crust during earthquakes is an important unsolved problem in earthquake mechanics. Knowledge of coseismic slip resistance is critical for understanding the magnitude of shear-stress reduction and hence the near-fault acceleration that can occur during earthquakes, which affects the amount of damage that earthquakes are capable of causing. To investigate the frictional properties of rocks during coseismic slip, we conducted a series of high-speed frictional sliding experiments in a 1-atm rotary shear apparatus at a normal stress of 5 MPa on quartz rocks. Samples were slid at slip velocities $v$ from 0.001 mm/s to 100 mm/s, for displacements characteristic of large earthquakes (up to 4.5 m). For $0.001 < v < 1$ mm/s, steady-state friction $\mu_{ss}$ decreases slightly with increasing sliding speed ($d\mu_{ss}/d\log_{10}v = -0.04$) and the friction coefficient is $> 0.75$, as has been observed previously in low speed sliding speed experiments. For $3 < v < 100$ mm/s, an extraordinary progressive decrease in frictional resistance of quartz rocks occurs with increasing slip speed ($d\mu_{ss}/d\log_{10}v = -0.2$), with friction extrapolating to zero at seismic slip rates (actually at $v = 1.2$ m/s). Measurements of the temperature close to the slip surface, estimates of the average sliding surface temperatures by numerical simulations, and estimates of flash temperatures at the asperity contacts all indicate temperatures too low to induce melting, even locally. Instead dramatic weakening appears to be due to the formation of a thin layer of silica gel on the fault surface produced by ultracomminution of quartz in the presence of water (i.e. from air humidity and fluid inclusions). The observation that many seismic faults are mineralised with quartz even when the country rock is not quartz-bearing suggests that quartz behaviour could be important for earthquakes in many fault zones and that, during large earthquakes, the Earth's crust might be weaker than is commonly assumed.

#### S41B-03 0845h

### Rupture Dynamics With Energy Loss Outside the Slip Zone

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Energy loss in a damage zone outside the slip zone contributes to fracture energy. Because the thickness of the damage zone increases with rupture propagation distance, fracture energy increases with earthquake size. A rupture front propagating near its limiting velocity has a stress concentration with large shear components at orientations different from that of the slip zone. These components can become large enough to induce non-elastic response (such as micro-cracking). The thickness in which stress reaches a threshold value for damage is proportional to rupture propagation distance in the case of constant stress drop. If non-elastic response in the damage zone can be represented as plastic yielding, then energy loss per unit area of rupture is proportional to the damage zone thickness and therefore to rupture propagation distance. I have performed numerical calculations of rupture on a slip plane with relatively low friction with stress drop occurring as abruptly as can be adequately resolved with the grid spacing. Material off the slip plane is subject to a Coulomb yield condition with a larger coefficient of friction. As rupture on the slip plane grows with constant stress drop, both peak slip velocity and off-fault stress components increase until stress in elements next to the fault reaches the Coulomb yield condition. As the rupture continues to grow, the thickness of the yielded material increases while peak stress and peak slip velocity remain constant. Rupture velocity is somewhat less than its limiting value, consistent with the increasing total fracture energy. Although stress on the slip plane is prescribed to drop quickly, slip velocity remains near its limiting value for a longer time while off-fault material is yielding. Slip velocity behaves as if the slip plane were subject to slip-weakening friction with larger $D_C$ , corresponding to fracture energy that includes the off-fault energy loss. In a mode-2 rupture, confining stress changes in opposite senses on opposite sides of the slip plane, so the Coulomb yielding is not symmetric. Non-elastic extension in the direction of rupture is enhanced on one side of the slip plane, so that there is a net compressive change of normal stress on the slip plane, which has a slight stabilizing effect. These complications do not change the conclusions listed above.

#### S41B-04 0900h

### Co-Seismic Energy Changes Induced by Earthquakes on A Rotating, Gravitating Earth

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Besides operating its own energy budget, an earthquake acts as an agent transferring a much greater amount of energy among the Earth's rotation, elastic field, gravitational field and internal heat. We compute the co-seismic, globally integrated gravitational and rotation changes induced by some 20,000 large earthquakes that occurred in the last quarter century, according to Chao et al. (1995, GJI, 122, 776- 783, 784-789) and using the Harvard CMT catalog. The result confirms an extremely strong tendency for the earthquakes to decrease the global gravitational energy and to increase the spin energy. It is found that energy is being extracted from the Earth's gravitational field by the action of earthquakes at an average rate of about 2 TeraW during the studied period, larger by far than the 7 GigaW for the average rate of the earthquake-induced rotational energy increase and the 5 GigaW for the seismic energy release. Based on energetics considerations and assuming the inability of the Earth to build up elastic energy continuously over time, it is argued that earthquakes, by converting gravitational energy, may make a significant contribution to the global hear flow.

#### S41B-05 0915h

### Cyclical Stress Field Switching and (Total?) Relief of Fault Shear Stress Recorded in Quartz Vein Systems Hosted by Proterozoic Strike-Slip Faults, Mt Isa, Australia

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The Proterozoic Mt Isa inlier ($\sim$50,000 km$^2$) in NW Queensland, Australia, underwent a complex tectonothermal history involving multiple episodes of intracontinental rifting, sedimentation, and magmatism that culminated in the Isan Orogeny (1590-1500 Ma) where strong E-W shortening led to compressional inversion of former rift basins. The resulting metamorphic complex of subgreenschist to amphibolite facies assemblages is disrupted by brittle, late-orogenic (1500-1450 Ma?) strike-slip faults. The faults occur in two mutually cross-cutting sets; a set of dextral strike-slip faults striking NE-SW to NNE-SSW with offsets <20 km, and a conjugate set of sinistral faults striking NW-SE to NNW-SSE. The two contemporaneous fault sets therefore lie at $\pm$45-60$^\circ$ to inferred E-W maximum compression, approaching the expected lock-up angle for 'Byerlee' friction coefficients. The faults commonly outcrop as linear blade-like ridges extending for many kilometres across the semi-arid terrain. Transects across the NE-SW Fountain Range and Overlander Faults which crosscut Corella Formation amphibolite facies assemblages and granites have shown that the fault zones are about 100 m in width with a composite brittle fabric comprising: (1) subvertical silicified cataclastic shear zones (cataclasites plus microbreccias containing vein fragments); (2) innumerable subvertical quartz-veins (cm to m thickness) lying subparallel to the principal shear zones (some retain purely dilational textures; others are multiply recemented fault-breccias with wallrock fragments); (3) highly irregular non-systematic veins; and (4) a systematic set of predominantly extensional, steep planar quartz veins oriented 080-120$^\circ$ at moderate angles to the main faults. Mutual cross-cutting relationships occur between all structural components, indicating broad contemporaneity. Recorded dextral separations along shear fracture components are commonly of the order of 1-10 cm, consistent with small-moderate seismic slip increments. A preliminary interpretation is that the differently oriented systematic vein-sets reflect changing orientations of the local stress field at different stages of the earthquake stress cycle. Minimum compressional stress oblique to the fault through the interseismic interval alternates with minimum compression oriented subperpendicular to the fault immediately postfailure, suggesting that each slip episode was accompanied by near-total relief of shear stress along the fault. The presence of amethystine quartz, openspace filling textures, and calcite-quartz intergrowths in the vein sets are consistent with hydrothermal precipitation occurring within 1-2 km of the former ground surface. Consequently, it is not yet clear whether these extensive vein systems developed under hydrostatic or overpresssured fluid conditions.

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## S41B-06 0930h

### Heat Flow in the SAFOD Pilot Hole and Implications for the Strength of the San Andreas Fault

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As part of an investigation into the physical properties of the San Andreas fault (SAF) and adjacent crust, detailed thermal measurements have been acquired in the 2.2-km-deep pilot hole for the San Andreas Fault Observatory at Depth (SAFOD), located 1.8 km west of the SAF near Parkfield, California. Precision temperature logs have been combined with thermal conductivity measurements on drill cuttings in a detailed vertical profile of heat flow. The temperature at the bottom of the borehole is 92 $^{o}$C, and heat flow from the basement section of the borehole (770 to 2160 m) is 91$\pm$2 mW m$^{-2}$. Within the resolution of the measurements, heat flow is constant across the identified faults that intersect the borehole, suggesting that any active fluid flow along these faults is at rates too low to alter the background conductive thermal regime. Heat flow in the SAFOD pilot hole is significantly higher than the 74 mW m$^{-2}$ average for the Parkfield area reported by Sass et al. (JGR, v. 102, 1997) based on measurements in shallow holes but consistent with five measurements ranging from 84 to 100 mW m$^{-2}$ near the SAF in Pancho Rico Canyon 20 km to the northwest. Reanalysis of the regional heat flow pattern indicates that high heat flow at the SAFOD site reflects an abrupt increase in heat flow along the SAF and within the Coast Ranges northwest of Parkfield. This transition corresponds to a shallowing of the base of seismicity on the SAF and may be related to a change in the mechanical behavior of the fault near the northern terminus of the M6 1966 Parkfield earthquake rupture. The persistence of elevated heat flow at sites more than 40 km west of the SAFOD pilot hole appears to rule out frictional heating on the SAF as a major source of the high SAFOD value. However, the correlation of along-strike variations in heat flow with changes in rupture patterns and fault characteristics may indicate a previously overlooked connection between laterally heterogeneous frictional properties and active thermal processes.

## S41B-07 0945h

### The Parkfield Stress Drop Controversy

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Nadeau *et al.* (1995) found that the seismicity on the San Andreas fault at Parkfield is highly clustered. Individual clusters consist of a sequence of near periodically repeating small earthquakes of similar seismic moment. Nadeau and Johnston (1998) compared the moments and timing of these repeating earthquakes ($M_W < 2$), and some larger events, with the surface creep rate on the fault to estimate the slip and stress drop ($\Delta\sigma$). They obtained conventional values (0.1 to 10 MPa) for the larger earthquakes, but $\Delta\sigma$ increased with decreasing $M_W$ to extremely high values (> 1000 MPa) for the small earthquakes ($M_W < 2$). Such values are just about physically possible, but they are much higher than those estimated by seismic methods for small earthquakes elsewhere (e. g. Abercrombie 1995). These controversial high $\Delta\sigma$ estimates have sparked a number of theoretical and laboratory studies (e. g. Sammis & Rice 2000, Anooshepoor & Brune 2001, Beeler 2001) aimed at investigating whether the observations could result from earthquakes with more normal $\Delta\sigma$ occurring within the unusual tectonic setting at Parkfield. Lane & Nadeau (2000, 2002) considered whether localized patches of high $\Delta\sigma$ would be resolvable by standard seismic methods. However, to date nobody has used seismic methods to determine source parameters for these controversial small earthquakes at Parkfield. We use closely located earthquakes of different sizes (for example, the sub-clusters of cluster CL14, Nadeau *et al.*, 1995, $M_W$−0.2 to 1), recorded on the HRSN borehole network to analyse the source parameters. The smaller earthquakes are used as empirical Green's functions to resolve source processes of the larger events. Preliminary results from the earthquakes in cluster CL14 result in a source dimension of about 25 m and $\Delta\sigma$ of about 1 MPa for the $M_W$1 earthquakes, assuming that rupture velocity is the same as that for large earthquakes. We also resolve source-time functions for these earthquakes at most stations and so we can investigate the directivity and velocity of the rupture. Finally we compare the source parameter estimates from the seismic modeling, with those from recurrence and creep rate, and assess the validity of the various proposed models.

# S41C MCC: Level 1 Thursday 0830h

## Stress Transfer, Triggered Earthquakes, and Time-Dependent Seismic Hazard V Posters *(joint with G, T, NG)*

***Presiding:*** **J Lin,** Woods Hole Oceanographic Institution**; C Marone,** Pennsylvania State University

## S41C-0083 0830h POSTER

### Forward modelling of Coulomb stress: Does mu matter?

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The clear correlation between Coulomb stress perturbations and the spatial distribution of aftershocks suggests that it may be possible to make real time Coulomb maps delineating areas likely, or unlikely, to experience aftershocks. As part of the PRESAP project investigating this possibility, we have assessed the importance of the coefficient of friction in computing these maps. Although the static coefficient of friction measured in the laboratory is consistently between about 0.6 and 0.8; Coulomb modellers have suggested widely varying values of "effective friction" (i.e. including some unknown fluid effects) ranging from 0.0 to 0.8. Here we investigate the effect of mu on the spatial correlation between the Coulomb map and the aftershock distribution for a number of mainshocks and for varying assumptions of the planes upon which the stress should be resolved. For each model, we compute a Boolean correlation coefficient between the stress field and the aftershock distribution, a method that avoids the problem of nodal plane ambiguity. Preliminary results for the Landers earthquake show that the Coulomb maps are insensitive to the coefficient of friction and visual inspection of the maps support this assessment. If this result is supported by the remainder of the analysis, it will be very encouraging from a forward modelling perspective as it means that the predictive capacity of Coulomb maps is independent of the choice of a poorly constrained coefficient of friction.

## S41C-0084 0830h POSTER

### Effects of Variable Normal Stress on Shear Strength and Friction

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Previous work shows that dynamic and quasi-static variations in normal stress may play a key role in earthquake rupture dynamics and frictional stability. In order to improve our understanding of how normal stress changes influence frictional strength and stability we performed laboratory experiments using a servo-controlled, double-direct-shear testing apparatus. This assembly includes three rigid forcing blocks with two gouge layers sandwiched between grooved or smooth steel bounding surfaces. We sheared two 3-mm thick gouge layers of fine-grained quartz powder or smectite clay-quartz mixtures at constant load point velocity. Normal stress pulses and step experiments were carried out to investigate the shear strength response to an abrupt normal stress change. Normal stresses ranged from 10-45 MPa and we studied load point velocities in the range 1-1000 $\mu$m/s. Careful calibration of Poisson coupling within the testing apparatus and sample assembly was performed and these effects were removed from data prior to processing. Normal stress step tests involved a series of normal stress increases and decreases during steady sliding. For each step increase in normal stress, the parameter $\alpha = (\Delta\tau/\sigma)/\ln(\sigma/\sigma_0)$ was calculated, where $\Delta\tau$ is the amplitude of the change in shear strength due to a normal stress step, and $\sigma$ and $\sigma_0$ are initial and final normal stress respectively. We find that $\alpha$ ranges from 0.28-0.35 for our range of experimental conditions, and that $\alpha$ does not change systematically with the variation of driving velocity. After exclusion of Poisson effects, there was generally no instantaneous change in shear strength in response to a step increase in normal stress. Our data show that step decreases in normal stress have the potential to destabilize steady sliding. For normal stresses of a few 10's of MPa, a normal stress reduction of >=1 MPa is sufficient to induce dynamic instability in our experiments. We compare our results to dynamic impact experiments on metals and other materials for which sliding velocity is of order 1-10 m/s. Those experiments consider only normal stress reductions and find that shear strength does not exhibit a sudden change in response to a step change in normal stress.

## S41C-0085 0830h POSTER

### The Effect of Dynamic Stress on Shear Strength and Stability in Laboratory Faults

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Recent studies show that earthquake-induced stress changes can trigger fault slip, change seismicity rates, and possibly cause additional damaging earthquakes. Investigations of stress transfer often focus on changes in the static stress state. However, dynamic stressing can lead to destabilization of creep motion and resonant behavior including stick-slip instability, both locally and at greater distances from the earthquake event. Studies of stress transfer commonly find that earthquake triggering occurs from small changes in stress and is delayed relative to the arrival of maximum stress. This phenomena cannot be explained by the Coulomb failure model, which predicts a constant failure threshold independent of stressing rate or time. We test the effects of dynamic shearing, using oscillations of shear loading rate and we compare results to theory. Using a double direct shear configuration, we sheared 3mm thick layers of glass beads (size distribution 105-149 microns) at room temperature. Glass beads are an ideal substance for these tests due to the repeatability of stick-slip events in terms of their magnitude and recurrence interval at constant velocity. The samples were loaded to quasi-periodic failure under a normal stress of 5 MPa (eliminating any changes in stick-slip behavior with displacement) and a background shear loading rate with a sinusoidal oscillation superimposed. Amplitude and frequency of the sine wave were varied, along with background shear loading rate, to determine any systematic shear stress response. We studied amplitudes ranging from 1-30 microns/sec, frequencies ranging from 0.01-10 Hz and load rates of 0.1-20 microns/sec. Although loading rate changes sign, shear stress remains positive throughout the experiment. Shear stress response was determined by studying systematic variations in stick-slip properties, e.g. amplitude of stress drop, frequency, and phase of the stick-slip stress drops compared to the imposed loading rate oscillations. Laboratory results of frictional response are compared to forward models of the rate and state friction laws. Preliminary results indicate that velocity oscillations lengthen the stick-slip recurrence interval and create generally larger instabilities; lower frequency oscillations create longer recurrence intervals than higher frequency oscillations. The phase of the stress drop relative to the velocity oscillation varies with oscillation frequency. During 0.1Hz oscillations, stress drops occur before the maximum loading velocity is reached whereas during 1Hz oscillations stress drops are delayed relative to the maximum velocity.

## S41C-0086 0830h POSTER

### The Role of Stress Interaction in Thrust and Subduction Earthquakes

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Key features of thrust earthquake triggering, inhibition, and clustering can be explained by Coulomb stress changes. Whereas slip on surface-cutting thrust faults drops the stress in most of the adjacent crust, slip on blind thrust faults increases the stress on some nearby zones, particularly above the source fault. Blind thrusts can thus trigger slip on secondary faults at shallow depth, and typically produce broadly distributed aftershocks. Short thrust ruptures are effective at triggering earthquakes of similar size on adjacent thrust faults. We calculate that during a progressive thrust sequence in central California during 1982-1985, the Mw=6.7 Coalinga earthquake brought the subsequent