Shipton, Z.K and Evans, J.P. and Abercrombie, R.E. and Brodsky, E.E. *The missing sinks: slip localization in faults, damage zones, and the seismic energy budget.* In Abercrombie, R. (Eds) *Earthquakes: Radiated Energy and the Physics of Faulting*, pages pp. 217-222. Washington, DC.: AGU (2006)

The Missing Sinks: Slip Localization in Faults, Damage Zones, and the Seismic Energy Budget

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The majority of work done during an earthquake may be consumed by dissipative processes that occur within geometrically and mechanically complex fault zones, rather than radiated as seismic waves. Many processes are likely to act as dissipative energy sinks in a three-dimensional faulted volume: slip along the principal slip zone is likely to be accompanied by deformation in the surrounding damage zone volume. Examination of exhumed fault zones in granite, which are meters to tens of kilometers long, shows thin principal slip zones developing on the smallest faults. As slip is accumulated on progressively larger faults, the principal slip zones remain less than 10 cm wide, but there is increasing complexity in the damage zone of the larger faults. By considering the amount of energy required to crush fine-grained gouge in the principal slip zone, and the grain size of gouge reported from other (seismogenic) faults, we conclude that principal slip zones must remain relatively thin for all sizes of rupture. Any energy consumed by dissipative processes in the damage zone will therefore tend to make the principal slip zone thinner, and will reduce the energy available to propagate the rupture.

1. INTRODUCTION

The majority of fault slip is often concentrated on a narrow principal slip zone (PSZ), within a highly strained fault core zone, surrounded by a volume of deformed rock called a damage zone [*Chester and Logan* 1986; *Caine et al.*, 1996, their Figure 1; *Schulz and Evans*, 1998]. Although coseismic slip may occur in the damage zone, seismic ruptures are likely to propagate along the PSZ of seismogenic faults [*Sibson*, 2003]. Determining 3-D fault zone structure is important for geologic and seismological considerations [see *Heermance et al.*, 2003; *Wibberley and Shimamoto*, 2003; *Faulkner et al.,* 2003]. For instance, the ability for a rupture to cross structural barriers will decrease if the other energy sinks are high, for instance in damage zones with high fracture density.

The energy radiated from an earthquake (E_R) is a relatively small fraction (5% to 20%) of the total energy released (E_T) [*Lachenbruch and McGarr*, 1990, *McGarr* 1999]. This poses a significant question: how is the other 80-95% of the energy partitioned among different fault zone processes during an earthquake? There must be a suite of geological processes that consume the bulk of this energy. Seismologists commonly consider the fracture energy needed to create new surface area, E_G, and the frictional energy to slide along that surface, E_F, as separate terms [e.g., *Scholz*, 2002]. However when considering the geological processes that act along fault zones during a slip event, it is not possible to separate these two energy terms.

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Earthquakes: radiated Energy and the Physics of Faulting
Geophysical Monograph Series 170
10.1029/170GM22

Slip along the 10s of meters long fault in Figure 1a occurs in a zone a few millimeters thick accompanied by the formation of fractures at the perimeter (tip line) of the slipped zone [e.g., *Martel* 1990]. Displacement along these faults has been accompanied by microfracturing, dissolution and growth of minerals (Figure 1b), which are all affected by the presence and flow of fluid through the fault. In larger faults (10s km long, Figure 1c and d), slip occurs along two or more principal slip zones and is accompanied by deformation within the damage zone [e.g., *Pachell and Evans* 2002]. It is not simple to assign any of these processes to the breakdown of a healed zone (E_G) or to frictional sliding (E_F), and it therefore makes more sense geologically to refer to dissipative energy [*Cocco et al*., this volume].

We consider potential dissipative energy sinks in light of field observations of fault zone structure. We present observations from faults in two field areas exhumed from seismogenic depths in the Sierra Nevada, California, which show that a thin PSZ develops early on in the growth of these faults and that these zones remain thin as slip is accumulated along the larger fault zones. We combine these observations with our understanding of the mechanics of brittle rock deformation to show that PSZs should remain thin on faults of all sizes, and that any other dissipative energy sinks active in a three-dimensional fault zone volume will further reduce the size of the PSZ.

2. OBSERVATIONS OF THE PRINCIPAL SLIP ZONE

Left-lateral strike-slip faults from two areas in the Sierra Nevada, California, represent different stages of growth from small simple fault zones (<10 m long) to large complex fault zones (>10 km long) within a single lithology and tectonic setting [*Martel*, 1990; *Evans et al.,* 2000]. Although without the presence of pseudotachylytes it is not possible to be certain if there has been co-seismic slip on an exhumed fault [*Cowan*, 1999], the Sierra Nevada faults, which slipped at seismogenic depths [*Pachell and Evans* 2002], provide an opportunity to document the development of fault architecture within the seismogenic zone from immature faults to large well-developed structures.

The faults localized on pre-existing joints [*Martel*, 1990], therefore the smallest faults have PSZs 1mm-1cm thick [*Shipton et al.,* this volume]. Faults 5 to 30 m long with tens of centimeters of net slip have a PSZ consisting of foliated chlorite-epidote-quartz assemblages 1 to 4 cm thick (Figure 1a and b) [details in *Lim* 1998 and *Robeson* 1998]. The small faults have damage zones consisting of arrays of parallel tension fractures (Figure 1a). Microstructures show an evolution from mylonitisation of the early brittle fracture fills in the sheared joints, to cataclasis and formation of ultracataclasites with only centimeters of slip in the small fault zones (Figure 1b). These microstructures show that slip-weakening deformation and alteration mechanisms were active along the smallest faults. Mylonites show that at least the early part of the slip along these faults was aseismic [*Di Toro and Pennacchioni,* 2004].

As these faults got longer they developed a more complex geometry but the PSZ remained less than 10 cm thick [*Evans et al*., 2000; *Pachell and Evans*, 2002]. Small faults linked up to form complex fault zones [*Martel*, 1990], consisting of a 2 to 15 m wide fault core bounded by subparallel PSZs 1 to 100 mm wide (Figure 1c). The fault core contains <1mm to 5 cm-thick bands of cohesive cataclasites and breccias, sericite-lined fractures, mineral alteration and shear zones. The microstructures observed in these PSZs are similar for all measured values of net slip up to 130 m (Figure 1d). Slip appears to be further localized on very thin zones of ultracataclasite within Figure 1d. A damage zone consisting of opening mode fractures and minor faults occurs around points where these larger faults linked.

These observations of faults from the Sierra Nevada show that there is little change in the composition and thickness (millimeters to centimeters), and hence physical properties, of the PSZ along faults with increasing slip (Figure 2). Thus, if rupture had occurred along these faults, it would have been confined to narrow PSZs with physical properties independent of rupture size. However the damage zone does increase in complexity and thickness [*Shipton et al.,* this volume]. Using scaling relations in *Wells and Coppersmith* [1994], had these faults slipped along their entire length they could have produced M_w 1 to 6 earthquakes with co-seismic slip ranging from cm to 10 m.

This pattern of extremely localized slip is observed across a large range of scales, and in a variety of host rocks and tectonic settings [see *Sibson*, 2003]. Pseudotachylyte-filled PSZs mapped by *Di Toro et al*. [2005], which may represent "single jerk" earthquake events, are always less than 10 cm wide. Faults with up to 10 m co-seismic slip on the Chelungpu fault, Taiwan, have a PSZ < 1 cm wide both in surface outcrops and in drill core from ~300m deep [*Heermance et al.,* 2003]. Rock bursts in South African mines produced microbrecciation on PSZs less than a few centimetres wide with 60 to 120 mm of slip [*McGarr et al.,* 1979; *Ortlepp*, 2000]. Faults exhumed from near the top of the seismogenic zone (~5 km) associated with the San Andreas fault [*Chester and Logan,* 1986; *Schulz and Evans,* 1998], the Nojima fault, Japan [*Ohtani et al*., 2000], and the Median Tectonic Line, Japan [*Wibberley and Shimamoto*, 2003] show a PSZ less than 10 cm thick surrounded by a diffuse damage zone of smaller faults, fractures, and veins. Some mature faults have several PSZs within a wide and structurally complex fault damage zone up to 1km wide [*Faulkner et al.,* 2003], but the thickness of individual PSZ remains <1cm.

3. DERIVATION OF PRINCIPAL SLIP ZONE THICKNESS

Our observations of fault zone structure could be used to constrain the magnitude of energy sinks represented by slip along a narrow PSZ. The energy required to created a volume, V, of gouge with density, ρ, in a rupture event is

$$E_{gouge} = \gamma\ S\ V\ \rho\ , \quad (1)$$

where γ = specific fracture energy per unit surface area (also called free surface energy) usually taken as 1.0 J m^{-2} [*Scholz*, 2002; *Chester et al.,* 2005], S = surface area per unit mass of gouge created in the rupture event. Assuming a uniform PSZ thickness, t (where A = area, and t = VA), rearranging equation 1 to solve for t gives

$$t = E_{gouge}\ /\ (\gamma\ S\ A\ \rho). \quad (2)$$

In the case where all of the non-frictional dissipative energy, E_{disp}, goes into grain crushing along the PSZ, this value is an *upper bound* on the thickness of the rupture zone, i.e., the maximum possible thickness t_{max} of gouge generated in a single earthquake is

$$t_{max} = E_{disp}\ /\ (\gamma\ S\ A\ \rho)\quad . \quad (3)$$

The values of the parameters in equation 3 are not trivial to determine. *Wilson et al.* [2005] and *Chester et al.* [2005] measured S in exhumed faults ranging from 80 to 160 $m^2\ g^{-1}$ using laser particle size analysis and high-resolution microstructural analysis. *Olgaard and Brace* [1983] measured S values of 0.7 to 2.0 $m^2\ g^{-1}$, from two mining-induced earthquake shear fractures using optical methods. Fault gouge generally has a lower density than its host rock, but is likely to be ≥2000 kg m^{-3}. Post-seismic chemical "healing" and alteration can significantly change the grain size between rupture events [*Evans and Chester,* 1995], decreasing S and increasing ρ. However, it is unlikely that a fault could heal to values of S and ρ equivalent to the undeformed host rock.

The most problematic parameter in Eq. 3 is the total dissipated energy. To connect the geological and seismological observations, we consider the commonly invoked special case where E_{disp} is the seismologically observable breakdown energy [*Kanamori and Rivera*, this volume]. The seismologically observable breakdown energy (i.e., energy expended in rupture propagation) includes creation of new surface area in the fault zone during coseismic slip as well as other components including plastic deformation of the grains and other heat losses [*Cocco et al*., this volume]. In this framework, the breakdown energy is equal to the total dissipated energy less the energy dissipated by a stress, σf, which is equal to the minimum stress during the earthquake. If σf is equal to a slip-independent frictional stress, then E_{disp} is the seismologically measurable fracture energy E_G and the combination E_G/A that appears in Eq. 3 is equal to G as inferred from studies such as *Abercrombie and Rice* [2005] or *Tinti et al.* [2005].

We compare the field observations of PSZ thickness to the predictions of Eq. 3 using the above values and assumptions about frictional processes. If the entire 10-km long Gemini fault mapped by *Pachell and Evans* [2002] ruptured with 1 meter of slip, it would have produced a magnitude 6.7 earthquake [*Wells and Coppersmith,* 1994] with a moment of $1.2x10^{19}$ N m [*Hanks and Kanamori,* 1979]. From *Tinti et al*. [2005, their figure 9] G for this earthquake would be 10^6 J m^{-2}. Assuming S = 80 $m^2\ g^{-1}$, γ = 1J m^{-2}, ρ = 2700 kg m^{-3}, the upper bound to gouge thickness from this single slip event is 4.6 mm (Figure 2). Using the same assumptions, if a 100 m long Gemini fault segment had ruptured with 10mm slip, this would have produced a magnitude 2.9 earthquake with a moment of $2.4x10^{13}$ N m, and G = 10^3 J m^{-2}. In this case the upper bound to gouge thickness is 0.005 mm. The observed thickness of individual bands of ultracataclasite is less than 1 mm (Figure 1d), so the geological observations are consistent with the conventional interpretation of the energy budget outlined above. If any other fault zone processes consume a significant portion of the dissipative energy, less energy will be available to crush material within the fault gouge, and therefore the resulting PSZ will be thinner. Conversely, if the values of S are smaller [*Olgaard and Brace,* 1983] the PSZ will be thicker.

4. WHAT STRUCTURAL PROCESSES EXIST TO PROVIDE DISSIPATIVE ENERGY SINKS?

What potential dissipative energy sinks are suggested by observations of exhumed faults? Radiated energy is measured in the far-field, i.e., at a distance greater than twice the fault length [*Rivera and Kanamori,* 2005]. The dissipative energy terms must include the energy consumed in all parts of this volume, including along the principal slip zone(s), within the fault core and within the surrounding damage zone. Below we list a number of deformation processes that could provide sinks for energy during an earthquake event in a three-dimensional fault volume. Many of these processes involve both fracturing *and* the generation of heat.

At the earliest stages of fault growth (e.g., mining induced ruptures) [*McGarr et al*., 1979; *Ortlepp*, 2000; *Wilson et al.,* 2005] energy will be required to fracture intact rock to form gouge. However, most earthquakes propagate along a pre-existing fault and the rock in the path of the rupture front is not intact: it is pre-"processed" fault gouge or other fault materials. The Sierra Nevada faults have well-developed cataclastic textures at only 10's cm of slip. For a fault that ruptures its entire area and outwards over an annular area around its tip, rupture will not be through intact rock; it will be through a microfracture process zone due to the enhanced stress concentrations at that fault tip from previous slip events [*Scholz*, 2002].

Once a rupture has nucleated, frictional sliding will take place along the fault surface. This could involve re-crushing existing fault gouge [*Wilson et al*., 2005], smoothing of asperities [*Power et al.,* 1988], or creating new fractures along the rupture surface. Melting or formation of silica gel on the fault will also provide an energy sink along the PSZ [*Di Toro et al.,* 2005]. Sliding along a smoother, well-established PSZ will require less energy than along a rough surface [see *Chester et al*., 2005]. From our observations of the Sierra Nevada faults the smallest faults have thin PSZs, and subsequent slip on larger faults is along PSZs with very similar microstructures and hence physical properties. This implies that the energy per unit area required to slide along these surfaces may remain fairly constant as ruptures increase in size, though the total ruptured area will increase.

There is a range of processes active in the damage zone of faults that could act as energy sinks. Damage zone deformation could be caused by dynamic stress changes during the passage of the rupture front or as events triggered by radiated seismic waves in the near field [*Poliakov et al.,* 2002; *Dalguer et al.,* 2003; *Andrews*, 2005; *Di Toro et al.,* 2005; *Rice et al.,* 2005]. Coseismic fluid movement in the fault zone [*Sibson*, 2001] will also require energy. Mineral alteration in the fault core and damage zone [*Evans and Chester,* 1995; *Schulz and Evans*, 1998; *Jacobs et al.,* this volume] may consume energy (though on timescales of the entire seismic cycle). Although there is no simple relationship between slip and damage zone thickness [*Shipton et al*, this volume], damage zone deformation will tend to accumulate during the lifetime of a fault and therefore larger faults tend to have more complex damage zones. Thus the energy sink provided by the damage zones of mature faults is likely to be larger than that for small faults.

Since the total energy available for a given earthquake is limited, there is a trade-off between damage zone processes and slip zone thickness. If the magnitude of other dissipative energy sinks increases as earthquakes rupture larger faults, grain crushing becomes a progressively smaller contribution to the overall energy budget, so that PSZ thickness should remain low on larger faults. More studies of exhumed faults are required to produce reliable estimates of the magnitude of energy sinks represented by dissipative processes in the fault core and damage zone.

One of the greatest challenges in using exhumed faults to interpret co-seismic processes is that not all deformation mechanisms observed in exhumed faults are due to seismic slip events [*Cowan*, 1999]. Fault zone properties, and therefore dissipative processes, are highly variable in space and time [*Schultz and Evans*, 1998], and may vary between successive earthquakes. Whether any of these processes is active along a given fault depends on factors such as host rock lithology, state of stress, dynamic and static friction values, depth, pressure, temperature and pore fluid pressure, mineralogy of the fault zone and geochemistry of the pore fluid, etc. Further studies of exhumed faults should provide more information on which of these processes is active under what set of circumstances, and enable us to predict what processes may be active in a particular earthquake on a particular fault.

Acknowledgments. We thank S. Martel, A. Bizzarri and G. Di Toro for constructive reviews. Funding was provided by Department of Energy Office, Basic Energy Sciences, Grant DE-FG03-95ER14526. Y. Ben-Zion, A. Friedrich, T. Heaton, H. Kanamori, A. McGarr, and P. Spudich helped to clarify our thinking. We dedicate this paper to the memory of the late Kim Robeson, and we thank him and S. J. Lim for their field observations.

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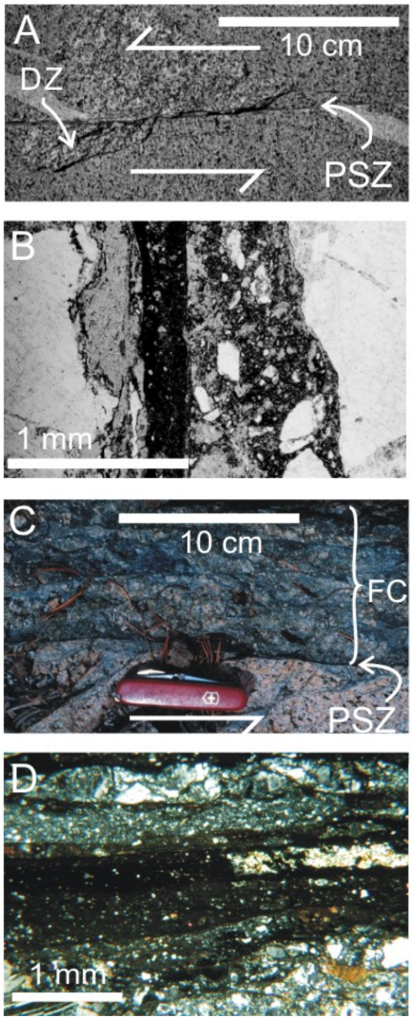

Figure 1. a) Small fault from Bear Creek, Sierra Nevada, with slip of ~ 20 cm. This fault nucleated on a cooling joint filled with chlorite, epidote, and quartz. b) Photomicrograph from fault in Bear Creek, Sierra Nevada, with ~ 60cm slip exhibiting a narrow cataclasite PSZ within a 5 mm thick fault zone c). PSZ with ~ 8 m slip from King's Canyon, Sierra Nevada, localized along the edge of the fault core. d) Photomicrograph of a PSZ from the Gemini fault with 100 m of total slip. Dark fine-grained material is chlorite muscovite foliated gouge with quartz fragments in the matrix.

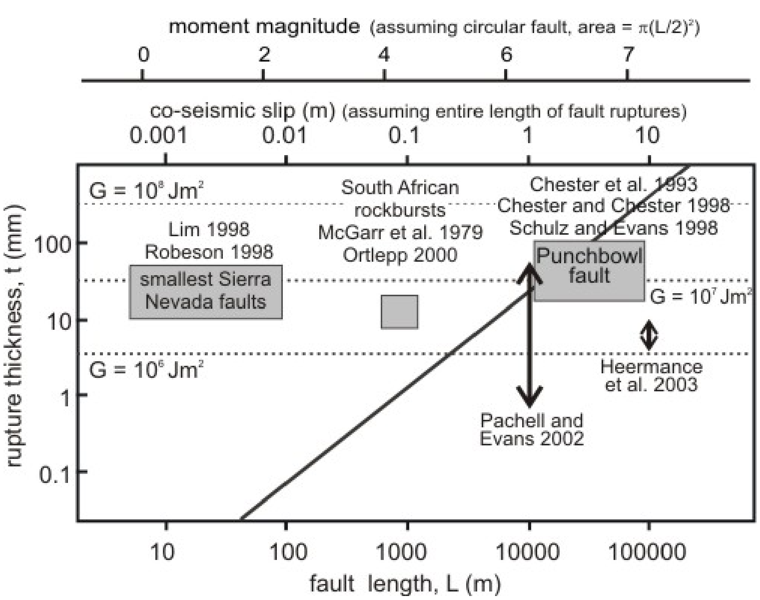

Figure 2. Fault length vs. PSZ thickness. Field data for thickness of the PSZ are represented by arrows where a range of PSZ thicknesses exist for a single fault, and by boxes where a range of PSZ thicknesses were measured on a range of fault lengths. If we assume the entire length of the observed faults slipped in an earthquake the maximum cosesimic slip is calculated using the scaling of fault length and slip from *Scholz* [2002]. Moment magnitudes for these earthquakes are calculated from *Wells and Coppersmith* [1994]. The lines show maximum PSZ thickness as a function of seismic slip calculated from equation 3 using values for S, g and r from the text and assuming that E_{disp}/A is equivalent to G. The solid line uses the empirical relation between G and earthquake size from *Abercrombie and Rice* [2005]. The dotted lines are for constant labeled values of G.