

Thickness of the Seismic Slip Zone

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Abstract This article reviews geologic and other evidence constraining the thickness of the principal slip zone (PSZ) that accommodates the bulk of coseismic shear displacement during an individual rupture event. Surface deformation from rupturing may occupy swaths tens of meters or more in width, but trenches across active faults generally reveal that incremental slip is accommodated by a PSZ that is tens of centimeters or less in thickness. Geomorphic evidence, coupled with the observations from trenching, suggest a PSZ may stay well localized for distances of several kilometers through many rupture episodes. Mine exposures and exhumed fault zones demonstrate that PSZs separating different lithologies within the “fault core,” although contained within “damage zones” of variably fractured rock ranging up to hundreds of meters in thickness, often comprise just a few centimeters of gouge/ultracataclasite that have accommodated large finite displacements (>1 km). Microstructural studies demonstrate incremental slip localized still further down to 1–10 mm, as do other fault-rock assemblages (slickensides and slickenfibers, fault-veins of pseudotachylite friction-melt, intravein septa in hydrothermal fault infills). The accumulated evidence indicates that localization of coseismic shearing to less than 10 cm on planar faults is widespread throughout the crustal seismogenic zone, with extreme localization to less than 1 cm not uncommon. However, some distributed coseismic shear may also develop, especially at rupture irregularities.

Coseismic reduction of shear resistance from friction-melting ($\Delta T \sim 1000^\circ\text{C}$) or from transient thermal pressurization of aqueous fluids ($\Delta T \sim 100^\circ\text{C}$) requires slip during moderate-to-large earthquakes ($u > 1$ m) to be restricted to narrow zones, respectively a few centimeters or tens of centimeters in thickness. Given the evidence for slip localization, the apparent scarcity of pseudotachylite suggests either that seismic friction-melting is a rare phenomenon, or that pseudotachylite is only rarely preserved in recognizable form within mature hydrated fault zones.

Introduction

Modern seismological techniques are capable of resolving relative microearthquake locations to within a few meters and defining tabular bounding envelopes to microseismically active shear zones of comparable thickness (e.g., Nadeau and McEvilly, 1997). Additionally, trapped waves can be used to define the thickness of brittle damage zones associated with major crustal fault zones (e.g., Li *et al.*, 1998). However, no direct seismological constraints have so far been placed on the thickness of the seismic slip zone during rupturing, t_s , a parameter that has considerable significance for energy dissipation, rupture processes, and seismic efficiency (Heaton, 1990; Brune *et al.*, 1993; Kanamori and Heaton, 2000; Ben-Zion, 2001; Brodsky and Kanamori, 2001). This note reviews geological observations constraining the thickness of principal slip zones (PSZs) that accommodate the bulk of coseismic displacement throughout the upper crustal seismogenic zone. It focuses on the thickness

of the slip zone active during individual moderate-to-large earthquake ruptures ($M > 6$) within mature, large-displacement (>1 km) fault zones. The discussion has the dual purpose of acquainting the seismological community with evidence from near-surface exposures of rupture traces, geomorphology, and fault-rock assemblages bearing on this matter and provoking new research into this area of fundamental relevance to source mechanics. Those unfamiliar with fault-rock terminology and petrographic characteristics should refer to the comprehensive photographic atlas of fault rocks compiled by Snoke *et al.* (1998).

Energy Considerations

For constant shear resistance, τ_f , during a slip increment, u , the heat generated per unit area of the fault is

$$Q = \tau_f u \quad (\text{J/m}^2), \quad (1)$$

so that at a representative seismic slip rate of 1 m/sec, the power dissipated per unit area of the fault surface lies in the range 10–100 MW/m² for $10 < \tau_f < 100$ MPa, representing the likely range of fault strengths in the upper crust. For rise times of a few seconds, heating will be essentially adiabatic for slip zones thicker than a few millimeters. On the assumption of uniform adiabatic shearing within a shear zone of thickness t_s , the resulting temperature rise is then approximated by

$$\Delta T = \frac{\tau_f \cdot u}{c_p \cdot \rho \cdot t_s} \quad (^\circ\text{C}), \quad (2)$$

where ρ is rock density and c_p is the specific heat. Here, we use $\rho = 2500$ kg/m³ and $c_p \sim 1000$ J/kg °C (a little high for most rocks, but this value helps to account for the latent heat of fusion). In Figure 1, anticipated temperature increases are plotted against shear zone thickness, t_s , for coseismic displacements $u = 0.1, 1, 5$, and 10 m against constant shear resistances of 10 and 100 MPa, roughly equivalent to depths of 1 and 10 km for hydrostatic fluid pressures and “Byerlee” rock friction coefficients, $0.6 < \mu_s < 0.85$ (Byerlee, 1978).

A temperature increase of $\sim 1000^\circ\text{C}$ would be sufficient to induce partial melting in most crustal rock types, allowing for variations in ambient rock temperatures, latent heats of fusion, and so on (Wenk *et al.*, 2000). Such a temperature increase would result from a moderate seismic slip of 1 m localized to less than 4 mm and less than 4 cm against constant shear resistances of 10 and 100 MPa, respectively. The expectation, therefore, is that this degree of shear localization would commonly lead to friction-melting within the slip zone (Jeffreys, 1942; McKenzie and Brune, 1972; Cardwell *et al.*, 1978).

Evidence for friction-melting in the form of fault-hosted pseudotachylite vein networks has, however, only rarely been identified in exhumed fault zones, certainly not in proportion to the expected dominance of seismic slip. Other limited evidence exists for temperature increases localized along faults: for example, Bustin (1983) has inferred temperature increases of several hundred degrees from increased vitrinite reflectance in carbonaceous material along some thrust faults. One possible explanation for the apparent absence of widespread friction-melting is that in mature, fluid-saturated fault zones, a temperature increase, ΔT , of $\sim 100^\circ\text{C}$ from initial power dissipation during slip is sufficient to boost existing fluid pressures to near-lithostatic values, thereby reducing effective normal stress across the fault and any further capacity for heat generation during the remainder of the slip episode (Sibson, 1973, 1980a; Lachenbruch, 1980; Mase and Smith, 1987). This 100°C temperature increase for “thermal pressurization” of fluids could be achieved from 1 m of slip localized within 4-cm- and 40-cm-thick shear zones, respectively, against shear resistances of 10 and 100 MPa (Fig. 1).

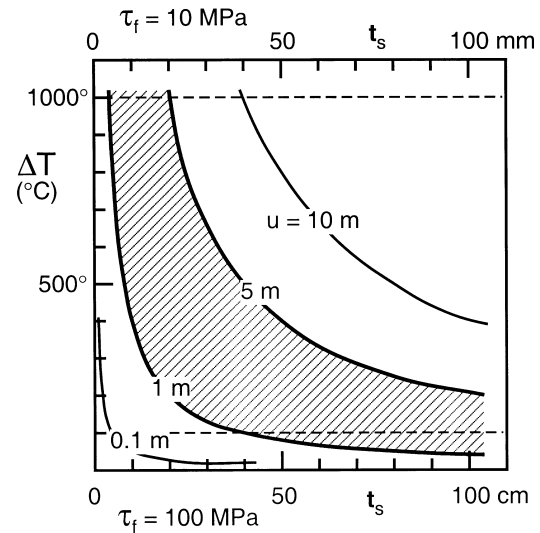


Figure 1. Expected temperature increase, ΔT , from uniform adiabatic heating for various values of coseismic slip, u , plotted against shear zone thickness, t_s , for constant shear resistances, $\tau_f = 10$ MPa (corresponding to ~ 1 km depth) and $\tau_f = 100$ MPa (corresponding to ~ 10 km depth), calculated for specific heat, $c_p = 1000$ J/kg °C, and density, $\rho = 2500$ kg/m³.

On the basis of these mechanical considerations, it seems clear that earthquake rupture mechanics may be profoundly influenced by the degree of slip localization at different levels within crustal fault zones.

Near-Surface Observations

Earthquake Rupture Traces

The width and complexity of surface rupture zones is affected by the mode of faulting, whether reverse, normal, strike-slip, or oblique; by the presence or absence of alluvial cover and its thickness above the bedrock expression of the fault; and by free surface effects at low confining pressure. For example, deformation along the surface rupture zone of the 1999 M 7.6 Chi-Chi, Taiwan, earthquake on the Chelungpu fault ranged in width from a few meters to ~ 200 m (Lin *et al.*, 2001b). A trench exposure through the rupture zone at one location revealed, however, that near-surface deformation involving subsidiary folding and thrusting that extended ~ 60 m across strike was largely induced by ~ 4 m of reverse slip on a discrete (< 5 cm thick) fault that dipped $\sim 34^\circ\text{E}$ at only a few meters depth (Lee *et al.*, 2001). Such observations are in general accord with other paleoseismic trench investigations for a range of fault types, where most of the fault slip in surficial material is accommodated within shear zones that are commonly less than 10 cm thick at depth but sometimes range up to a meter or so in thickness (McCalpin, 1996).

Strike-Slip Rupture Zones. These have special significance because maps of strike-slip rupture traces are generally or-

thogonal to subvertical faults and reveal irregularities transverse to the slip-vector. In alluvium, strike-slip rupture zones typically comprise a “mole-track” array of en echelon primary Riedel shears with linking compressional rolls and minor thrusts. Dextral mole-tracks along the surface rupture zones of the 1966 **M** 6.1 Parkfield, 1979 **M** 6.6 Imperial Valley, and 1987 **M** 6.5 Superstition Hills earthquakes in California, away from fault intersections and major irregularities, are generally less than 1–2 m in width along much of their length, giving way in places to discrete tabular shear zones less than a few centimeters thick (Brown *et al.*, 1967; Sharp *et al.*, 1982, 1989). In the case of the 1968 **M** 6.5 Borrego Mountain earthquake, which generated a 31-km surface rupture zone in late Cenozoic–Holocene sediments, surface mole-track deformation accommodating up to 0.4 m dextral displacement ranged in width from less than 1 m to more than 100 m (Clark, 1972). For approximately two-thirds of the rupture zone, this distributed surface deformation was concentrated within a swath less than 50 m wide. Trench exposures at only a few meters depth revealed, however, that the bulk of displacement through successive ruptures had been localized to one or more subvertical tabular gouge zones only a few centimeters thick (Clark *et al.*, 1972). Likewise, Sharp (1979) cited evidence from the sinistral rupture zone of the 1976 **M** 7.5 Guatemalan earthquake that mole-tracks arise from the presence of cemented soil horizons (duricrust) at the Earth’s surface, with the en echelon fractures converging helicoidally downward into a narrow planar rupture at depths of only a few meters.

A notable contrast between the localization of strike-slip deformation in alluvial cover and bedrock was evident following the 1968 **M** 7.2 Dasht-e Bayaz earthquake in northern Iran. The surface rupture zone accommodating up to 4.5 m of sinistral strike slip was traced over 80 km through both Quaternary alluvium and bedrock (Tchalenko and Ambraseys, 1970; Tchalenko and Berberian, 1975). Surface deformation along straight segments of the fault in alluvium comprised a systematic array of Riedel shears interspersed with compressional ridges. The width of this surface rupture zone was commonly ~10 m (ranging from 2 to 100 m) but broadened correspondingly in the vicinity of major dilational step-overs with cross-strike dimensions greater than 1 km. However, a qanat (underground aqueduct) exposure at 30 m depth in the alluvial cover beneath one of the “straight” fault segments revealed a single discrete fault ~10 cm in thickness (R. Bilham, personal comm., 2001). Likewise, where the near-linear rupture trace was exposed in Mesozoic bedrock, field mapping revealed that most of the strike-slip displacement was restricted to a shear zone less than 40 cm wide (Tchalenko and Berberian, 1975). Similar contrasts between the surface expression of fault rupture in alluvium and bedrock were observed following the 1992 **M** 7.3 Landers, California, earthquake. This rupture was notable for the distributed character of surface deformation within a complex segmented zone ~85 km in length that accommodated up to 6 m dextral strike slip (Sieh *et al.*, 1993). Again, the

broadest zones of distributed surface deformation were associated with major step-overs (>2 km across strike). Broad bands of subsidiary shearing (50–200 m wide) developed in the alluvial cover along straight segments of the rupture trace, but the bulk of the dextral displacement (>70%) was localized in bounding shear zones less than 5 m wide, which narrowed to less than 50 cm wide in consolidated bedrock (Johnson *et al.*, 1994; Lazarte *et al.*, 1994). Such observations are also in accord with the deformation noted in the railway tunnel at Wright Station near the southern end of the 470-km-long rupture formed during the 1906 San Francisco earthquake. Prentice and Ponti (1997) suggested that while some permanent shear strain may have occurred across a zone up to 400 m wide, more than 60%–85% of the estimated dextral coseismic slip of 1.7–1.8 m at this locality was restricted to a discrete near-vertical slickensided fault plane in sandstone.

Together, these near-surface observations on strike-slip faults suggest that the thickness of rupture zones near the surface of the Earth is strongly affected by the presence of the free surface, by the depth of alluvial cover together with its state of consolidation and near-surface cementation, and, in particular, by the thickness of undeformed alluvium that has accumulated since the preceding rupture episode. At depths of only a few meters, most of the slip is commonly localized to a PSZ only centimeters to tens of centimeters thick.

Longer-Term Slip Localization. Geomorphic expression of active strike-slip fault zones provides longer-term evidence for slip localization. For example, in the dextral strike-slip fault system of New Zealand, there are many instances of progressively displaced flights of postglacial river terraces. Lensen (1968) provided a comprehensive description of progressive dextral strike slip on the Wairau fault (the northern continuation of the Alpine fault) at Branch River, with offset increasing progressively from the youngest terrace riser to the oldest. The sharp geomorphic expression of the fault trace demonstrates slip localization to within a few meters, at most, over a period of ~15,000 years (perhaps 10–20 rupture events). The remarkably linear character of the fault trace over many kilometers also implies localization extending to comparable depths. The trace of the dextral Wellington fault is likewise constrained by offset terrace flights and has also been trenched for paleoseismic studies at several sites to reveal steep gouge zones, generally less than 50 cm thick, cutting alluvial deposits; this PSZ has apparently accommodated most of the strike-slip displacement over the past several thousand years (Berryman, 1990; Van Dissen *et al.*, 1992). In neither case has any geomorphic evidence been documented suggesting significant distributed permanent strain away from the main fault trace.

Aseismic Shear Zones

Shear localization also occurs along creeping segments of the San Andreas fault system. Distortion of monument

alignment arrays along the creeping segment of the San Andreas fault over periods of 2–11 years reveals that aseismic shearing is accommodated by a mixture of distributed shear zones and planar discontinuities (Burford and Harsh, 1980). Most of the displacement is accommodated by simple shear within zones ranging in thickness from meters to tens of meters (most commonly <15 m) at shear strain rates in the range $10^{-9}/\text{sec} < \dot{\gamma} < 10^{-11}/\text{sec}$. Some minor slip (sometimes oscillatory) is localized along discrete fracture planes. Boundaries of the active shear zones and the zones of most intense shear localization change with time, sometimes abruptly. Similarly, along the Hayward fault, aseismic creep at up to 9 mm/yr is largely accommodated by shear zones ranging in thickness from a few meters to a few tens of meters at the surface, with some evidence for downward narrowing to shear zones less than 1 m thick at depth (Lienkaemper *et al.*, 1991; Bilham and Whitehead, 1997).

On rock mechanics grounds, higher strain rates associated with rupture propagation ($\dot{\gamma} > 10^{-5}/\text{sec}$) would be expected to promote more intense shear localization (i.e., more brittle behavior) than slow aseismic shearing. The widths of these aseismic shear zones therefore place a likely upper bound on the thickness of coseismic PSZs.

Brittle Fault-Rock Assemblages in Bedrock

General Brittle Infrastructure of Bedrock Fault Zones

A picture of the internal structure of large-displacement brittle fault zones developed in bedrock has emerged from surface, mine, and borehole observations on both ancient and active structures (Wallace and Morris, 1986; Evans and Chester, 1995; Caine *et al.*, 1996; Ohtani *et al.*, 2000; Schultz and Evans, 2000; Tanaka *et al.*, 2001). A major difficulty in all such studies is establishing the original depth at which particular fault-rock assemblages developed (Sibson, 1986). The studies generally reveal a cataclastic damage zone of varying thickness (meters to hundreds of meters) containing distributed fractures with subsidiary, often anastomosing, shears variably affected by hydrothermal alteration (Fig. 2). Cataclastic deformation (brittle fragmentation by macroscopic fracturing and grain comminution) intensifies toward a fault core comprising one or more tabular deformation zones of gouge or ultracataclasite (centimeters to meters thick), within which bands of intense grain-size reduction define PSZs usually only 1–10 cm thick that may separate contrasting lithologic assemblages (e.g., Chester and Chester, 1998). In some instances, localization of a throughgoing PSZ appears to have occurred very early in the evolution of the fault zone (Shipton and Cowie, 2001).

Individual PSZs can rarely be traced for more than a few hundred meters from surface and underground exposures, but fault-trace geomorphology suggests their continuance over many kilometers in some instances. Disposition of damage zone and fault core is often asymmetric: it is quite common to find a PSZ localized close to one of the bound-

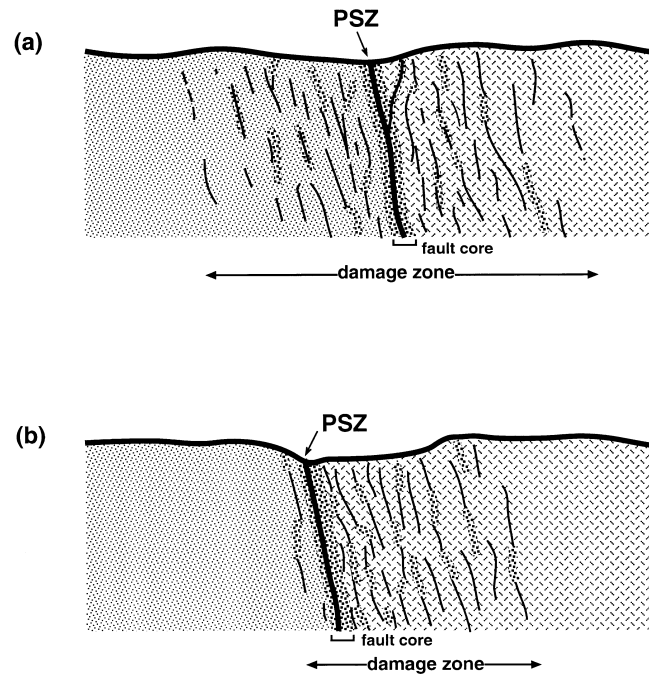


Figure 2. Schematic representations of brittle fault zones in the upper crust illustrating relationships of principal slip zone (PSZ), fault core, and damage zones: (a) approximately symmetric disposition; (b) PSZ localized at margin of damage zone. The coarse stipple denotes distributed cataclastic deformation and hydrothermal alteration of varying intensity, and lines represent subsidiary fractures.

aries to the damage zone (Fig. 2). Slip localization to thin (several millimeter to several centimeter) cataclastic PSZs at the boundaries of tabular fault-fracture zones (tens of centimeters to meters thick) has also been noted for strike-slip faults accommodating 10–100 m displacement in Sierra Nevada granitoid assemblages (Martel *et al.*, 1988; Martel 1990). Analogies may be drawn with the tendency for strike-slip ruptures along the San Andreas fault to follow one of the margins to the geomorphically defined ~1-km-wide fault zone (Brown *et al.*, 1967). Comparison can also be made with the tendency, during experimental shearing of gouge layers in the laboratory, for stick-slip sliding to be localized at the gouge–wallrock interface (Engelder *et al.*, 1975; Moore *et al.*, 1989).

Based on frictional wear theory and data from a mixture of fault types exhumed from a range of depths, Scholz (1987) proposed a simple scaling law,

$$t_d \sim 0.01d, \quad (3)$$

relating thickness of the cataclastic gouge zone, t_d , to fault finite displacement, d . However, serious reservations have been expressed on the validity of this relationship (e.g., Blenkinsop, 1989; Evans, 1990), and no systematic scaling relationships have yet been established for thicknesses of damage and core zones around different fault types. It is

noticeable, for instance, that despite expectations of higher frictional shear resistance along thrust faults compared with other faults at the same depth and fluid-pressure level (Sibson, 1974), in terms of general damage distribution the reverse appears to hold true. Many brittle foreland thrusts with up to 100 km displacement display “knife-edge” fault contacts between contrasting lithologies (Price, 1988) with damage zones commonly less than a meter or so in thickness (Hubbert and Rubey, 1959; Elliot, 1976; Bustin, 1983; Ghisetti *et al.*, 2001; Kirschner and Kennedy, 2001). For example, the famous Glarus overthrust in the Swiss Alps has accommodated more than 35 km displacement at a depth of more than 6 km on a “calc-mylonite” layer ~ 1 m thick, with the last increments of displacement apparently restricted to a planar septum of carbonate gouge less than 1 cm in thickness (Schmid, 1975). Badertscher and Burkhard (2000) have recently reinterpreted the calc-mylonite as recrystallized cataclastic material derived from repeated fracturing episodes.

Fault-Rock Assemblages

Slickensides and Slickenfibers. Polished fault surfaces (slickensides), often striated by various frictional wear processes, are widely associated with PSZs in surface and underground mine exposures of fault zones (Wallace and Morris, 1986; Petit, 1987; Power and Tullis, 1989; Doblas *et al.*, 1997). Spray (1989) showed that the mirrorlike “polish” of artificial slickensides induced in sandstone by an excavator was a glass-bonded gouge layer formed from surface melting less than $150\ \mu\text{m}$ thick, but such material is unlikely to be preserved over long periods on natural fault exposures. Carbonate footwalls of normal faults commonly display spectacular striated and grooved surfaces that demonstrate slip localization to less than 1–10 mm over very large areas ($<10,000\ \text{m}^2$) (Hancock and Barka, 1987; Stewart and Hancock, 1991; Jackson and McKenzie, 1999). From the extent of the surface and mine exposures of slickensided surfaces, it is apparent that such slip localization extends to depths of at least a few kilometers (Power and Tullis, 1989; Hadizadeh *et al.*, 1991; Doblas *et al.*, 1997).

In environments where fault slip is associated with solution transfer, fault surfaces are commonly coated with slickenfibers, stepped arrays of crystal fibers precipitated from hydrothermal solution and tracking the incremental slip direction (Durney and Ramsay, 1973; Elliot, 1976). Although calcite and quartz fibers are the most widely developed, other fiber minerals (e.g., gypsum, laumontite, chlorite, talc, tourmaline) may develop on faults throughout the seismogenic crust as a function of host rock and pressure-temperature environment, provided conditions are appropriate. A common association with extension veins developed in fault wallrocks suggests that slickenfiber development may be diagnostic of fluid overpressuring to meet the hydraulic fracture criterion (Sibson, 1980a). While the continuity of the fibers has led many to infer growth from steady aseismic shearing, the presence in some cases of “crack-seal” fiber textures (Davison, 1995; Petit *et al.*, 1999; Lee

and Wiltschko, 2000; Koehn and Passchier, 2000) does provide evidence for submillimeter to millimeter growth increments, possibly arising from microseismic slip episodes. As with slickensided surfaces, the thickness of slickenfiber coatings generally demonstrates localization of slip to a few millimeters, at most.

Gouge-Breccia-Cataclasite Zones. These common rock products of faulting throughout the seismogenic zone have formed largely by macroscopic fracturing, frictional wear processes, and cataclastic comminution. They include incohesive gouge and fault breccia, and cohesive fault rocks of the cataclasite series (protocataclasite $\rightarrow$ cataclasite $\rightarrow$ ultracataclasite) reflecting progressive reduction in grain size and in porphyroclast content. Ultracataclasites, with matrix grain size typically reduced toward micron dimensions and few surviving mineral or lithic porphyroclasts, characteristically have a black, flinty appearance, occasionally preserving laminar color banding and substructure on the millimeter scale, indicating multiple slip episodes (Streit, 1998). Sometimes there is evidence for additional deformation mechanisms involving solution transfer in areas of intense grain-size reduction (Sibson, 1986). Recently, there has been increased recognition of overprinting of primary cataclastic textures by other (aseismic) deformation mechanisms in fault rocks derived from regions near the base of the seismogenic zone (e.g., McNulty, 1995; Badertscher and Burkhard, 2000; Takagi *et al.*, 2000).

Because of their relevance to understanding deformation at depth along major strike-slip fault zones such as the San Andreas, detailed studies have been made of damage zone and fault core structures of the inactive subvertical Punchbowl and San Gabriel strike-slip faults exhumed from depths of 2–5 km at various localities within the crystalline basement complex of the San Gabriel Mountains, California (Anderson *et al.*, 1983; Chester and Logan, 1986; Chester *et al.*, 1993; Evans and Chester, 1995; Chester and Chester, 1998; Schultz and Evans, 1998, 2000). Dextral offset across different splays of the San Gabriel fault ranges from ~ 20 to 40 km, and across the Punchbowl fault is up to 45 km. The general picture that emerges from these studies is of a PSZ in the fault core defined by a band of dark, flinty ultracataclasite that may reach up to a meter or so in thickness but is commonly only 1–10 cm thick, often flanked by foliated cataclasite up to a few meters thick, enclosed within a damage zone ranging from a few tens to a few hundreds of meters thickness. Textural evidence for repeated episodes of hydrothermal neomineralization and reshear within the fault core material is widespread (Chester *et al.*, 1993). A very detailed study of the north strand of the Punchbowl fault, juxtaposing arkosic Punchbowl sandstone of Miocene age against a crystalline igneous/metamorphic complex, is particularly revealing. Chester and Chester (1998) have shown that a damage zone ~ 100 m wide enclosing the ultracataclasite core has accommodated less than 100 m of the 10+ km of dextral strike slip across the fault strand. The

fault core is defined by two lithologically distinct ultracataclasite layers derived from different protoliths, together averaging ~30 cm in thickness but separated by a PSZ less than 2 cm thick across which at least 2 km of strike slip is inferred to have occurred.

Comparable slip localization has been observed elsewhere in strike-slip fault zones developed within the crystalline basement. For example, in Yellowknife, northwest Canada, a metamorphosed Archean assemblage of pillow lavas and mafic intrusives intruded by granitic plutons is disrupted by the Proterozoic West Bay fault, along which a series of offset markers indicate ~5 km of predominantly sinistral strike slip (Henderson and Brown, 1966). The subvertical fault is well exposed in glaciated outcrops and in open-pit mines, revealing a highly brittle character defined by a cataclasite PSZ mostly less than 10 cm in thickness, with little visible in the form of a distributed damage zone. Streit (1998) has described cataclastic strike-slip faults overprinting an older mylonitic shear zone fabric in King Island, Tasmania. Sharply defined lamellar substructure within the ultracataclasites suggests localization of slip down to the millimeter scale. Likewise, Hadizadeh *et al.* (1991) have described thin, millimeter-scale cataclasite bands developed subparallel to mylonitic foliation in the Towaliga fault zone of the Appalachians; the bands are inferred to have developed by localized brittle shearing during progressive exhumation from the subseismogenic ductile flow regime.

Pseudotachylyte Friction-Melt. Dark aphanitic veins of pseudotachylyte, usually hosted within crystalline rocks and preserving microscopic evidence of melting, have been reported from slip surfaces in exhumed ancient fault zones (e.g., Camacho *et al.*, 1995; Fabbri *et al.*, 2000) and also from some active structures with a substantial dip-slip component, such as the Alpine fault of New Zealand (Sibson *et al.*, 1979; Lin, 1994; Boullier *et al.*, 2001). Characteristically, planar veins of pseudotachylyte lying along slip surfaces (fault-veins) are associated with irregular injection veins leading into the wallrocks, with the orientation of slip surfaces often controlled by existing planar anisotropy (e.g., mylonitic foliation) within the host rocks (Sibson, 1975; Grocott, 1981; Swanson, 1992; Curewitz and Karson, 1999). The presence of a strong planar anisotropy in the rock-mass (e.g., schistosity, gneissose layering, mylonitic foliation) may help to localize rupturing along near-discrete planes. Preserved glass or quench textures sometimes provide definitive evidence of a former melt phase, but in many cases the fine-grained groundmass is extensively altered or recrystallized (Maddock, 1992; Magloughlin, 1992; Wenk *et al.*, 2000). Cataclastic comminution appears as an essential precursor to melting (Magloughlin, 1992; Spray, 1995), and there is a common association of fault-generated pseudotachylyte with cataclasite series material, but the former is generally vastly subordinate in volume (e.g., Fabbri *et al.*, 2000).

Fault-veins of pseudotachylyte that developed during a

single slip episode (on the evidence of preserved chill margins) commonly have thicknesses of 1–10 mm, in general accord with McKenzie and Brune's (1972) estimates of likely melt-layer thicknesses formed by friction-melting during seismic slip, but may locally attain a thickness of 10 cm or more. Variations in fault-vein thickness are attributable to lensing from slight waviness in fault surfaces and to local loss of pseudotachylyte into injection vein complexes. Local "reservoir" sites with abnormal thicknesses of pseudotachylyte tend to be localized at dilational step-overs between echelon fault segments. Vein geometries and textural characteristics of fault-generated pseudotachylyte are remarkably similar to friction-melts generated by high-power dissipation associated with landslides (e.g., Lin *et al.*, 2001a) and at major bolide impact sites, although in the latter case the melt volumes are orders of magnitude greater (Magloughlin and Spray, 1992; Spray, 1997). In fact, the type pseudotachylyte was described from the Vredefort Dome in South Africa (Shand, 1916), now recognized as a Proterozoic impact structure.

Inferred depths for pseudotachylyte generation by seismic slip on faults span most of the upper crustal seismogenic zone, ranging from less than 2 km (Seward and Sibson, 1985; Lin, 1994) to as much as 15–20 km (Camacho *et al.*, 1995; McNulty, 1995; Boullier *et al.*, 2001; O'Hara, 2001). There is also increasing recognition of pseudotachylyte veins (<10 mm thick) formed along transient rupture discontinuities within mylonitic shear zones deforming under greenschist facies metamorphic conditions near the base of the seismogenic zone and then becoming "smeared out" into ultramylonite bands by aseismic crystal plastic flow (Sibson, 1980b; Passchier, 1982; McNulty, 1995; White, 1996; Goodwin, 1999; Takagi *et al.*, 2000). In addition, Austrheim and Boundy (1994) have recognized pseudotachylyte formed during eclogitization of deep crustal material at depths greater than 60 km.

The significance of these pseudotachylyte occurrences is their demonstration that, at least in some instances, seismic rupturing is localized to less than 1 cm through the full depth of the seismogenic zone, with temperature increases leading to melting consistent with the simple analyses of energy dissipation and frictional heating portrayed in Figure 1. Careful petrographic studies of fault-rock assemblages have led to increased recognition of fault-generated pseudotachylyte in recent years, but in most cases the quantities are comparatively minor compared with other cataclastic fault rocks. However, Camacho *et al.* (1995) have estimated that a 1-km-thick high-grade mylonitic shear zone associated with the Woodruffe Thrust in central Australia contains ~4% pseudotachylyte, equivalent to a layer of solid pseudotachylyte ~40 m thick. In addition, earlier suggestions that pseudotachylytes form by friction-melting only in "dry" environments may need to be reexamined in the light of recent evidence that some pseudotachylytes result from water-rich melting (Magloughlin, 1992; Lin, 1994; Boullier *et al.*, 2001).

The critical question is whether pseudotachylyte friction-melt is generated only rarely in the brittle regions of fault zones, perhaps because of some physical effect such as thermal pressurization of fault fluids, or is commonly generated but only rarely preserved in recognizable form because of cataclastic overprinting and hydrothermal alteration of reactive material. As previously discussed, comparable localization of slip to less than 1–10 cm is also evident in the ultracataclasite fault cores of major fault zones without any associated recognizable pseudotachylyte. But the question remains as to whether some of the very fine grained ultracataclasite rich in hydrothermal alteration products described by Chester *et al.* (1993) could be derived from extensively reworked and altered pseudotachylyte.

Intravein Septa. Laminated mesothermal quartz veins (ribbon-texture) infill faults over considerable vertical intervals (<2 km) in certain tectonic settings and are sometimes exploited for their mineral (usually Au) content (Robert and Brown, 1986; Cox, 1995; Robert *et al.*, 1995). The vein material was deposited episodically from hydrothermal solutions usually with temperatures in the 250–400°C range at depths of 10 ± 5 km, toward the base of the seismogenic zone. The origin of such veins has been attributed to episodic postseismic discharge of overpressured hydrothermal fluids along fault rupture zones through fault-valve action (Sibson *et al.*, 1988; Boullier and Robert, 1992). The ribbon texture comprises laminations of quartz separated by thin selvages of wallrock that commonly range up to a few millimeters in thickness. A standard interpretation is that successive ruptures occur along the margin of the existing fault-vein, detaching thin slivers of the wallrock with a fresh layer of quartz precipitated from hydrothermal fluid discharging along the new rupture (Brown and Bruhn, 1996). The inference again is of slip localization to a few millimeters, albeit under strongly fluid overpressured and, hence, more brittle conditions.

Discussion

Observations constraining the thickness of seismic slip zones for mature, large-displacement faults are summarized in Figure 3. Note, again, the poor constraints on the depth-range estimates. Apart from the width of surface rupture zones, which are attributable in part to free surface effects and to young cover sequences of previously undeformed alluvium, there is evidence for localization of individual slip events in PSZs to less than 10 cm and, in many cases, to less than 1 cm at all depths through the upper crustal seismogenic zone. The fact that seismic slip zones at depth tend to be more localized than aseismic shear zones along creeping fault segments also correlates with expectations from laboratory rock mechanics that the high strain rates associated with rupturing should lead to more brittle (i.e., more localized) behavior. The PSZs are generally contained within, or localized at one or other margin to, damage zones with sub-

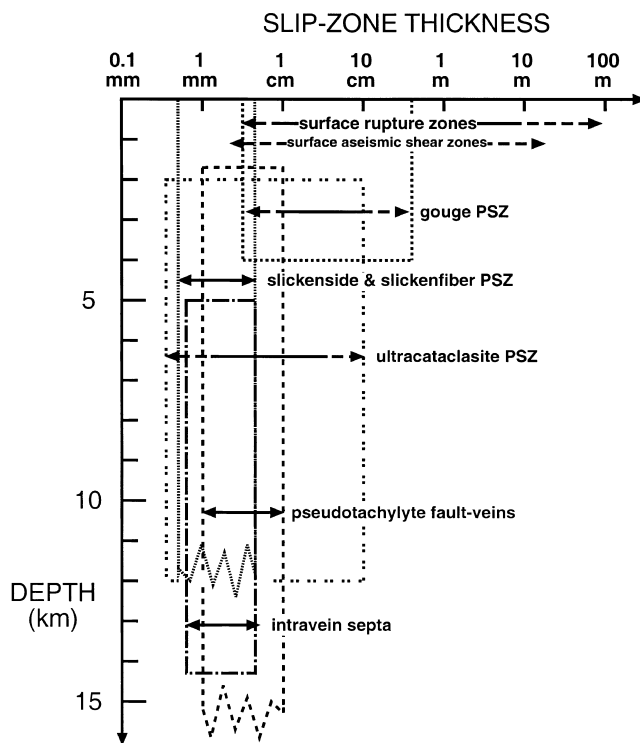


Figure 3. Geological estimates for the thickness of the seismic slip zone over various depth ranges as discussed in the text.

sidary cataclastic fracturing and hydrothermal alteration of varying intensity. These damage zones may range up to hundreds of meters in thickness and likely serve as the wave guides responsible for fault-zone trapped waves.

These observations of well-defined PSZs do not rule out the possibility that varying amounts of distributed permanent shear strain also develop coseismically at depth, although the work of Chester and Chester (1998) seems to negate this for the segment of the Punchbowl fault they have studied in detail. My own experience of working in exhumed fault zones of various types suggests that essentially planar fault segments with well-defined PSZs are commonly linked through en echelon step-overs and bends by zones of distributed cataclastic deformation with no clear throughgoing structure (Fig. 4). Analogies may be drawn with aftershock distributions around strike-slip ruptures: aftershocks tend to be few where the fault is planar but plentiful and diffusely distributed around rupture irregularities, which tend to develop as fragmentation barriers (King, 1986).

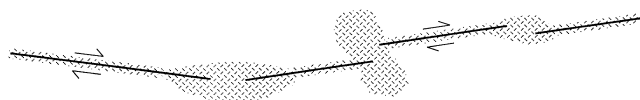


Figure 4. Schematic of polysegmented fault zone with individual PSZ and associated damage zones interlinked through zones of distributed and heterogeneous cataclastic fracturing.

The knife-edge appearance of many thrust faults with thin associated damage zones has long been attributed to near-lithostatic fluid overpressures counteracting confining pressure and, by lowering shear resistance, contributing to slip localization (Hubbert and Rubey, 1959; Badertscher and Burkhard, 2000). It remains to be established whether comparable slip localization on other fault types likewise results from fluid overpressuring, either widespread or concentrated in the cores of the fault zones (Hickman *et al.*, 1995).

The apparent scarcity of pseudotachylite friction-melt in exhumed brittle portions of crustal fault zones remains an important issue for rupture dynamics. If the scarcity is genuine and does not merely reflect poor preservation, it seems unlikely that inadequate slip localization alone is responsible for the lack of melting. Other possibilities include low static levels of shear resistance (≤ 10 MPa) from elevated fluid pressure, or low kinetic shear resistance that may arise, either from transitory thermal pressurization of fault fluids (Sibson, 1973) or perhaps from interface separation accompanying dynamic reduction of normal stress during rupture propagation (Brune *et al.*, 1993; Ben-Zion, 2001).

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