Scaling of fault damage zones with displacement and the implications for fault growth processes

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Knowledge of the spatial extent of damage surrounding fault zones is important for understanding crustal fluid flow and also for understanding the physical processes and mechanics by which fault zones develop with slip. There are few data available on the scaling of the fault damage zone with fault displacement, and of those that exist, deriving scaling relationships is hampered by comparing faults that run through different lithologies, have formed at different crustal depths or tectonic regimes (e.g., normal versus strike-slip movement). We describe new data on the microfracture damage zone width from small displacement fault zones within the Atacama fault zone in northern Chile that formed at ~6 km depth within a dioritic protolith. The microfracture damage zone is shown by an alteration halo surrounding the faults in which the density of the microfractures is much greater than background levels in the undeformed protolith. The data show that damage zone width increases with fault displacement and there appears to be a zero intercept to this relationship, meaning that at zero displacement, there is no microfracture damage zone. This is supported by field observations at fault tips that show a tapering out of fault damage zones. These data, combined with data from the literature, indicate that this same relationship might hold for much larger displacement faults. There is also a distinct asymmetry to the fracture damage. Several processes for the development of the observed scaling are discussed. The widely accepted theory of a process zone predicts that fault damage zone width increases with fault length and thus should always be largest at a propagating fault tip where displacement is lowest. This prediction is opposite to that seen in the current data set, leading to suggestion that other processes, such as damage zone growth with increasing displacement due to geometric irregularities or coseismic damage formation might better explain the spatial extent of damage surrounding even low-displacement faults.


1. Introduction

Faults are composed of a high-strain zone typically containing cataclasite, ultracataclasite, and/or gouge, surrounded by a zone of fractured rock [Chester and Logan, 1986; Faulkner et al., 2010]. The damage zone has received a lot of attention recently, as it is important for the flow of fluids in the crust [Townend and Zoback, 2000] and also is a key component in the energy balance of earthquakes [Rice et al., 2005; Kanamori and Rivera, 2006]. Furthermore, understanding how the damage zone scales with various fault parameters, such as displacement or fault length, helps to understand the physical processes associated with fault growth or the earthquake process.

There are few data on the nature of the damage zone. Studies show that, at least for low-porosity rocks, there is an exponential decay of microfracture density with distance from a fault [Anders and Witschko, 1994; Vermilye and Scholz, 1998; Wilson et al., 2003; Mitchell and Faulkner, 2009]. For faults developed in higher-porosity rocks, the picture is less clear, with some studies [e.g., Anders and Witschko, 1994] showing an exponential decrease in microfracture density with distance from the fault core in Navajo sandstone, whereas others have found no clear relationship [Shipton and Cowie, 2001]. The exponential decay of microfracture density with distance appears to fit with the idea of a decaying stress field with distance as is predicted by fracture mechanics models [Scholz et al., 1993].

Cowie and Scholz [1992] developed a model for the growth of faults based on postyield fracture mechanics. This
made a number of predictions of the scaling relations of faults including the fault length with displacement and the distribution of displacement along the fault length. Many of these relations have support from subsequent field data [Vermilye and Scholz, 1998; Manighetti et al., 2004; Scholz and Lawler, 2004]. Scholz et al. [1993] also made predictions regarding the scaling of the damage zone width with fault length. They predicted that the fault damage zone width should scale linearly with the fault length at the point where the fault tip passed by. They also noted that there was a lack of data on the damage zone width and how it scaled with either fault length or displacement [see Scholz et al., 1993, Table 1]. Since the time that Scholz et al. published their work, there have been very few studies that define the relationship of damage zone width to fault length or displacement. Part of the problem in collecting field data to derive such a relationship is that factors such as the nature of the protolith, depth of faulting, and tectonic environment (e.g., normal, strike-slip or reverse faulting) are likely to affect the damage zone width. Consequently, it is difficult to find a field area where faults can be studied that have a large range in displacement magnitude, run through a single rock type, and have formed at approximately the same depth.

Vermilye and Scholz [1998] presented some data from low-displacement faults that showed the microfracture damage zone width does appear to scale with fault length. Mitchell and Faulkner [2009] showed the relationship between microfracture damage zone and fault displacement for faults contained within a single granodioritic protolith. These data showed a positive correlation that also hinted at a maximum fault damage zone width on the order of 200 m at fault displacements ~5 km. Mitchell and Faulkner fitted these data with a hyperbolic function. However, the data set only included six faults in total, owing to the lack of large displacement structures and time constraints, as collecting oriented samples at various distances from the fault core, sectioning these and performing microfracture counts is very time-consuming.

A laboratory study by Zang et al. [2000] recorded the growth of the microfracture damage zone during quasi-static uniaxial deformation in Aue granite using the location of acoustic emissions (AE) and microstructural analysis. They...
found that the cloud of AEs ahead of the fracture tip increased in size as the length fracture increased, supporting the process zone model.

[7] Recently, Savage and Brodsky [2011] compiled data from a number of faults from the published literature that give the fault damage width, defined by macrofractures, as a function of the displacement. There is inherent scatter in these data, owing to the problems of comparing faults that cut through different lithologies and formed at various depths; however, they again show a positive correlation and also a slowing of the rate of increase of fault damage zone width with displacement. Hence in the few studies that have been made to date, both microfracture and macrofracture density appear to show the same first-order characteristics.

[8] In this work, new field data relating fault damage zone width with displacement are presented. The data were collected from low-displacement strike-slip faults in the Atacama desert of northern Chile and developed in low-porosity crystalline rocks. A key feature of the new data set is that it was collected from faults developed at a particular depth within a single large batholith, thereby removing the complication of comparing faults that cut through various dissimilar rock types and formed at different crustal depths.

[9] The paper first describes the location and nature of the field study area. The faults studied are then described and the measurements presented. The implications of the data set recorded for scaling and also fault growth processes are then discussed.

2. Bolfín Fault Termination, Northern Chile

[10] The faults studied are part of the Atacama fault system (AFS), which is a 1000 km long sinistral strike-slip structure running between Iquique (21°S) and La Serena (30°S) (Figure 1a). The AFS formed during the Early Cretaceous (~125 Ma), toward the end of a magmatic arc that dominated most of the present-day Coastal Cordillera area.

[11] The Atacama fault system in the study area is made of NS-striking master faults and subsidiary NW-striking splay faults are organized into strike-slip duplexes that occur at various scales from meters to tens of kilometers. The Coloso Duplex (Figure 1b) is one such structure [González, 1996; Cembrano et al., 2005]. The strike-slip fault system is excellently exposed at the surface due to the hyperarid
environment of the Atacama desert. The fault has been passively exhumed from depths greater than 3 km, and hence the structures preserved at the surface are representative of those that formed at depth. Minor recent reactivation of the AFS has been attributed to passive responses of the AFS to large subduction earthquakes [González et al., 2003], but this late deformation is easily distinguishable from the deeper-seated one.

[12] In more detail, the Coloso duplex is flanked by two, NNW striking, subvertical master faults (Jorgillo Fault, Bolfín Fault) that splay off the Coloso Fault [Cembrano et al., 2005]. These faults are in turn joined by a set of second-order NW-striking and third-order EW-striking imbricate splay faults (Figure 1b). Both master and subsidiary faults of the Coloso Duplex host spatially and temporally related epidote–chlorite–quartz–calcite veins suggesting a strong link between fluid transport and duplex development.

[13] The study area is in the southern termination of the Bolfín fault (Figures 1b and 2). Here, the fault terminates in a distributed network of low-displacement strike-slip fault zones in a horsetail-type structure. A similar type structure was described in the Sierra Nevada in California by Kirkpatrick et al. [2008]. The faults cut through metadiorites that, although deformed in an earlier and higher temperature (plastic) regime, are relatively isotropic because they have been annealed by a late static recrystallization event [González, 1996]. The metadiorites host meter-wide, amphibolitic, subvertical dykes that lie at a high angle to the later faults and therefore form excellent displacement markers.

3. Faults Studied

[14] The faults studied are part of a population of low-displacement features (less than 3.5 m strike-slip displacement) surrounding the termination of a larger fault. In the field, they are surrounded by a “halo” marked by differential weathering, where immediately adjacent to the fault, the dioritic protolith forms a zone that appears altered in comparison to the surrounding material (Figure 3). In the area, there are a number of fractures with halo zones, and some fractures show no offset. We interpret these as mode I fractures. However, we made measurements on a subset of the fractures with a strike between 120° and 160°. This subset shows subhorizontal slickenlines, strike-slip displacements, and well-developed halo zones. The strike-slip nature of the faults studied has the added advantage that the rocks were more or less at the same crustal level during formation and hence any depth dependency of the damage zone formation will be minimized.

[15] Microstructural investigations show that these halo zones appear to be related to the microfracture damage zone that surrounds the faults (Figure 4). Figure 4a shows a thin section scan of one of the faults, displaying the fault core and associated halo/damage zone. Propylitic alteration of biotite and feldspars to chlorite give the halo zone its overall green color. Figures 4b–4f clearly show chlorite preferentially forming along microfractures, which indicate an interconnected network of microfractures along which fluid was able to flow. Alteration is most extensive in areas where larger intergranular microfractures crosscut many grains, as seen in Figure 4b, where such fractures can be seen in blue where the resin using for thin sample preparation has infiltrated. Presumably such fractures had higher permeability and provided a relatively larger flow of fluids to the surrounding rock mass. Figures 4g and 4h show scanning electron microprobe images of the same sample, where extensive alteration to chlorite can be clearly seen in both the fault core and damage zone. Figure 4h shows a good example of alteration preferentially occurring surrounding a microcrack. The halo zone appears to be related to a higher incidence of microfracturing (e.g., Figure 4c which is an example of damage close to the fault core) that has subsequently been sealed by the chlorite mineralization (Figures 4b–4f). This has resulted in preservation of the microfracture damage zone during exhumation and weathering of the faults at the surface (Figure 3).

[16] Engvik et al. [2005] noted similar features in higher-grade rocks during mode I fracturing when magma was emplaced in dykes. They noted that microfracture densities were an order of magnitude greater within the halo zone than outside of it. In order to verify that the halo zone was a product of the microfracture damage zone, we measured the microfracture density as a function of distance from the fault using a similar methodology as Mitchell and Faulkner [2009] for two of our faults (Figure 5).

[17] In Figure 5 the microfracture densities as a function of perpendicular distance for two faults that were studied microstructurally are presented. Unlike other studies, where quartz has been used as a proxy for the total amount of
Anders and Wiltschko, 1994], the microfractures were counted in all minerals present, as no quartz was present in the diorite protolith. The microfracture density measured is a linear density. The fractures measured by this method are intragranular fractures and the vast majority of them cut right across the grain. Whether or not these fractures continue and cut other adjacent grains is not determined by this method. The rock was composed of relatively equant grains of amphibole and feldspar (15% quartz, 50% plagioclase, 30% amphibole, and 5% biotite). Both these minerals possess a significant fracture anisotropy but, as the rock is isotropic and hence the minerals are randomly oriented, we hoped that any increase in fracture density due to a favorable orientation of the cleavage planes to the stress field would be negligible if enough grains were included in the analysis. Although the results do show scatter, they indicate a clear relationship between the microfractures and the faults, supporting the validity of the approach.

[18] The width of the halo zone measured in the field compares very favorably with the width of the microfracture damage zone measured microstructurally. For fault 2, the halo zone width on one side of the fracture in the field was measured at 70 mm and Figure 5 indicates that this fracture has a microfracture damage zone width of 62 mm. A similar correlation is found for fault 1, where the halo zone width of 23 mm compares with a microfracture damage zone width of 25 mm.

[19] At each measurement locality, the width of the halo zone was measured directly, together with the horizontal displacement of the fault marked by an offset marker, usually a thin leucocratic or amphibolitic dyke. The fill of the fault was noted, as was the orientation of the fault and any slickenlines developed. In all cases where slickenlines were observed, they were subhorizontal (+/−10°), indicating strike-slip movement. Hence the horizontal offset of the displacement markers were taken to represent the total offset on the faults measured.

[20] Two representative measurement localities are shown in Figure 6. They show the displacement recorded by an offset marker and also the associated halo zone. Note that subsidiary fractures can been seen either side of the fault, commonly defining an asymmetric pattern that may indicate the direction of fault propagation [see Scholz et al., 1993].
This asymmetric fracturing is often accompanied by asymmetric damage zone widths (Figure 7). The asymmetry was calculated by dividing the width of the halo on the side of the fault showing the smallest damage zone by the width of the damage zone on the opposite side. This leads to an asymmetry of 1 if the damage is distributed evenly on each side of the fault and zero if the damage is completely asymmetric (i.e., a halo only appears on one side of the fault). The positive numbers correspond to faults that have the widest damage zone on their southwestern side, whereas negative numbers indicate the widest zone on the northeast side.

Figure 8 shows the relationship between the halo zone width with fault displacement. Fault displacement varied from 12 mm to 1.5 m. There is a clear positive correlation. Note the data is plotted on linear axes, as logarithmic axes often appear to show a more clustered relationship. Although the data show some scatter, there may be two relationships in the data, one below ~0.4 m displacement (with a gradient ~1) and one above this, where the rate of increase of damage zone width with displacement is lower. Additionally, the intercept of the data goes through the origin, indicating that at the fault tip, where there is zero displacement, the fault damage zone width would also fall to zero. This inference from the data is also supported by field observations; where fault tips were observed, the halo zone pinches out (Figure 9).

4. Discussion

4.1. Scaling of the Damage Zone With Displacement

The data presented are for low-displacement (<3.5 m) faults developed in a crystalline rock. The problem of making comparisons of the data set with other data is that...
other factors such as rock type, depth of faulting, tectonic environment (e.g., strike-slip versus extensional), and fluid flow control the nature of the fault damage zone; hence different data sets may not be comparable [Faulkner et al., 2010]. Scholz et al. [1993] note that the development of the process zone from a theoretical perspective will be rock-type dependent. One strength of the data set presented in this work is that all the faults are contained within a single lithology and hence direct comparisons may be made. The data may also be reasonably compared with that of Mitchell and Faulkner [2009] as their data was collected in the same region as the present study. The depth of faulting is the same, and the lithology through which the faults cut in the Mitchell and Faulkner study, although different, is comparable (granodiorite versus diorite). The comparison with the Mitchell and Faulkner data set is shown in Figure 10. The data sets are complimentary and appear to show that the relationship shown in this work for low-displacement fractures holds for faults with much larger displacements (up to 5 km).

[23] For comparison, we also show in Figure 10 the distribution of a compilation of data by Savage and Brodsky [2011] for macrofracture damage zone width versus displacement (shaded area in Figure 10). Although these data are macrofracture damage zone widths rather than microfracture damage zone widths and are collected from a wide range of faults from various lithologies, depths, and tectonic environments, they do show a clear relationship. There is a fair degree of scatter in the data, and we note that the data in Figure 10 are presented on a log-log plot. However, the data show the same trend as the data presented in this study and also that of Mitchell and Faulkner [2009] and we tentatively suggest that increasing damage zone width with displacement may be universal.

4.2. Implications for Fault Growth Models

[24] There have been a number of suggestions made for processes responsible for the development of off-fault damage [Wilson et al., 2003; Blenkinsop, 2008; Mitchell and Faulkner, 2009]. These include damage from the coalescence of microfractures, damage from linking of structures [Childs et al., 2009], damage from fault growth involving a process zone [Cowie and Scholz, 1992], damage from continued displacement on “wavy” faults [Chester and Chester, 2000], and coseismic fracture damage [e.g., Rice et al., 2005]. Of these models, we require a damage zone width that increases with increasing fault displacement. The asymmetry of the damage seen (Figure 7) are best explained by the dynamic or quasi-static process zone models detailed below, which would suggest the faults (or increments of movement on existing faults) predominantly propagated from the southeast toward the northwest. This would imply the low-displacement faults appear to have formed at some distance from the termination of the larger Bolfin fault to the northwest. This pattern of development of splay faults has been suggested for areas in California and New Zealand [Scholz et al., 2010]. Scholz et al. [2010] explained this “distal hypothesis” by the stress shadow of the primary fault inhibiting the development of splay faults, thereby forcing the nucleation and growth of these faults at some distance from the primary fault’s termination.

4.2.1. Process Zone Model

[25] The process zone model for fault growth has been widely adopted since it was first suggested by Cowie and Scholz [1992]. The stress at a crack tip is inversely proportional to the radius of curvature of a crack tip; thus in linear elastic fracture mechanics where a mathematically “flat” crack is assumed, the stress is infinite. Clearly, this is an unreasonable assumption, and some yielding of the material around the crack tip must occur in order to limit the stress at the crack tip to the strength of the material and the stress intensity factor to that of the fracture toughness, a material property [Lawn, 1993]. Cowie and Scholz [1992] utilized a postyield fracture mechanics approach along the
lines of Dugdale [1960] to provide a physical explanation of a number fault zone scaling relations.

[26] In the model, the process zone is the region where subcritical yielding of the rock occurs. The reduction of stress from the fault tip to background levels should be governed largely by the elastic properties of the material and are described by the Irwin stress functions, modified to account for the yielding of material around the fault tip [Lawn, 1993]. It is well-established that microfracture damage accumulates in rock at stresses well below the failure stress [Scholz, 1968; Mitchell and Faulkner, 2008] and hence the decay of stress surrounding the fault tip may readily be associated with a decay of microfracture damage that is often observed surrounding faults [Anders and Witschko, 1994; Vermilye and Scholz, 1998; Wilson et al., 2003; Mitchell and Faulkner, 2009]. In a linear elastic fracture mechanics model such as that described above, the size of damage zone around the fault tip should be constant and not scale with either fault length or displacement. However, the zone of "cohesion" behind the crack tip in a postyield fracture mechanics model will scale with fault length [Dugdale, 1960], leading to the prediction that the zone of damage associated with this cohesion zone will scale with fault length (Figure 11). This assumption appears to be supported by some field data [Vermilye and Scholz, 1998]. Furthermore, the orientation of microfractures surrounding low-displacement faults has been shown to fit with those predicted for the propagation of a mode II crack [Vermilye and Scholz, 1998], although the picture is less clear for larger displacement faults [Wilson et al., 2003].

[27] It might be assumed that, as fault length scales with displacement, damage zone width might also scale with displacement. However, displacement varies along the length of a fault, diminishing to zero at the fault tips (Figure 11). Hence for damage zone width scaling with displacement rather than length, the picture is somewhat more complex.

Figure 12 shows two scenarios where faults might be expected to grow in two different ways.

[26] First, faults may grow unilaterally, that is, they nucleate then grow in one direction only away from the nucleation point (Figure 12). In this case, the damage zone width where the fault nucleated, and hence had a very small length, will be correspondingly small. The damage zone width increases toward the other fault tip. In this case, the damage zone width should vary with displacement as shown. Three different length faults are shown in Figure 12, and it can be envisaged how the relationship between process zone width and displacement will look if a single...
of fault damage zones if a fractal distribution of asperities were present along a fault. In the early history of a fault, only the small-scale asperities would interact, producing small damage zone widths. As displacement accumulated, then progressively larger asperities would interact, producing wider damage zone widths. In this model, interacting asperities can result in stresses much greater than the frictional strength of the fault. Hence the extent of the damage zone could be significant. 

The orientation of microfractures surrounding the Punchbowl fault in California were interpreted to best support a fault wear model for their production [Wilson et al., 2003]. One problem with using the wavy fault model to explain the damage zone development observed is that it does not predict any damage asymmetry, whereas it is observed in the data (Figure 7).

4.2.3. Coseismic Damage Models

[32] Off-fault damage produced by the passing of a dynamic rupture pulse might explain the scaling of damage observed. There are several factors that will influence the damage zone width. These include mode of rupture (e.g., crack-like or as a slip pulse) and the rupture velocity.

[33] For earthquakes on preexisting faults, the ratio of slip to length is about $10^{-4}$, as opposed to $10^{-2}$ for faults, with a proportionately lower stress drop [Scholz, 2002]. Consequently, the damage zone formed by the passage of earthquakes along a fault should be much narrower than that formed by the passage of the fault tip through intact rock. Hence, although progressively larger earthquakes on progressively longer faults might result in a positive correlation between fault displacement and dynamic process zone width, the extent of damage should not extend past that formed during fault growth. Note, however, that if fault growth itself occurs by a single seismic event or a series of earthquakes, then coseismic damage will be significant. In this case the stress drop and the dynamic process zone width will be much larger. However, it seems unlikely that each fault represents one earthquake event; the calculated magnitudes from the displacements on the faults here, if each fault formed in one event, range from M5.4 to M7.0 (using relations from Wells and Coppersmith [1994]).

[34] If each of the faults hosted multiple earthquakes, the zone immediately adjacent to the fault should show the superimposed damage from several ruptures. If a significant number of earthquakes occurred, then the smoothly varying, exponentially decreasing microfracture densities shown in Figure 5 could be explained, as population of earthquakes will follow a Gutenberg-Richter relationship. However, if these relatively low-displacement faults only hosted one or two ruptures with varying magnitudes, then the smoothly varying relationship in Figure 5 might not be expected to result.

[35] If earthquake rupture propagates in a crack-like manner, then, as the rupture length grows, the damage zone width will correspondingly increase at the propagating rupture tip. Like the process zone model, the pattern of damage will be affected by unilateral or bilateral growth. The same patterns of damage zone width with displacement are expected as with the process zone model (Figure 12). Early small earthquakes will produce narrow damage zones, and subsequent earthquake slip will increase total displacement on the same section of the fault but will produce much narrower zones of damage for the reasons stated above.
It is possible that earthquake ruptures propagate as a slip pulse rather than an expanding crack [Heaton, 1990]. In this case, the rupture pulse will reach a maximum length that will limit the damage zone width. This mode of rupture has only been recognized for large ruptures [Heaton, 1990] and it is not presently clear if low-displacement faults such as those measured in this study might be subject to ruptures that reach a steady state length.

During an earthquake, the damage zone width is a function of the fracture energy, the strength drop and the rupture velocity of an earthquake [Rice et al., 2005]. If the fracture energy and the strength drop stay constant, the damage zone width might be expected to scale with rupture velocity [Engvik et al., 2005]. This process of damage production would fit the scaling of the data presented here if earthquake damage resulted from an accelerating, unilaterally propagating rupture that reaches a peak velocity, then decelerates before arrest. Similarly, for a bilaterally propagating rupture, if peak velocity is reached very rapidly followed by deceleration, the damage zone width would, in general, reduce toward the fault tip.

In summary, earthquake rupture could result in the damage zone scaling observed by some combination of unilateral or bilateral propagation, rupture mode, or rupture velocity variations. If formed by coseismic damage, it appears, from the measured fracture density variations, most likely that the faults formed by a single earthquake, although the slip displacements would imply quite large earthquakes. However, it is very difficult to constrain any of these parameters from the field data and consequently it is very difficult to assess whether there is some consistent combination of coseismic processes that result in the observed scaling.

In summary, it is clear that all the models discussed above have predictions that are either in conflict with the data or seem physically unlikely. Additional, more detailed, field studies, such as the one presented here, are required to expand the data sets and resolve these issues.

5. Conclusions

We present new data on the scaling of fracture damage zones with fault displacement. The data are derived from faults that run through the same lithology and were formed at approximately the same depth. Fault displacements range from 12 mm to 1.5 m. There is a clear positive relationship between displacement and fault damage zone width, which for these faults is shown by a halo zone of microfracture damage surrounding the fault core. The intercept of this relationship is approximately through the origin. The data imply that fault damage zone width increases with fault displacement. These data are compared with other fault data from the region of study where displacements up to 5 km occur and also with a data set for fault damage zone width defined by macrofractures compiled from the literature for a variety of faults by Savage and Brodsky [Savage and Brodsky, 2011]. The same general relationship is observed.
at all scales, in spite of the inherent problems associated with comparisons of faults from a variety country rocks, depths, and tectonic regimes.

[41] The data are not well explained by a process zone model for fault growth. They can be explained by faults accruing damage through the interaction of asperities with displacement, although a coseismic origin cannot be ruled out. A fractal distribution of asperities is required, with smaller asperities producing damage early in the faults’ history, and the interaction of progressively larger asperities producing wider damage zones at higher fault displacements.

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FAULKNER ET AL.: SCALING OF FAULT DAMAGE ZONES