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Low-Temperature Deformation of Mixed Siliciclastic & Carbonate Fault Rocks of the Copper Creek, Hunter Valley, and McConnell Thrusts

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Honors Research in Geology

Oberlin College
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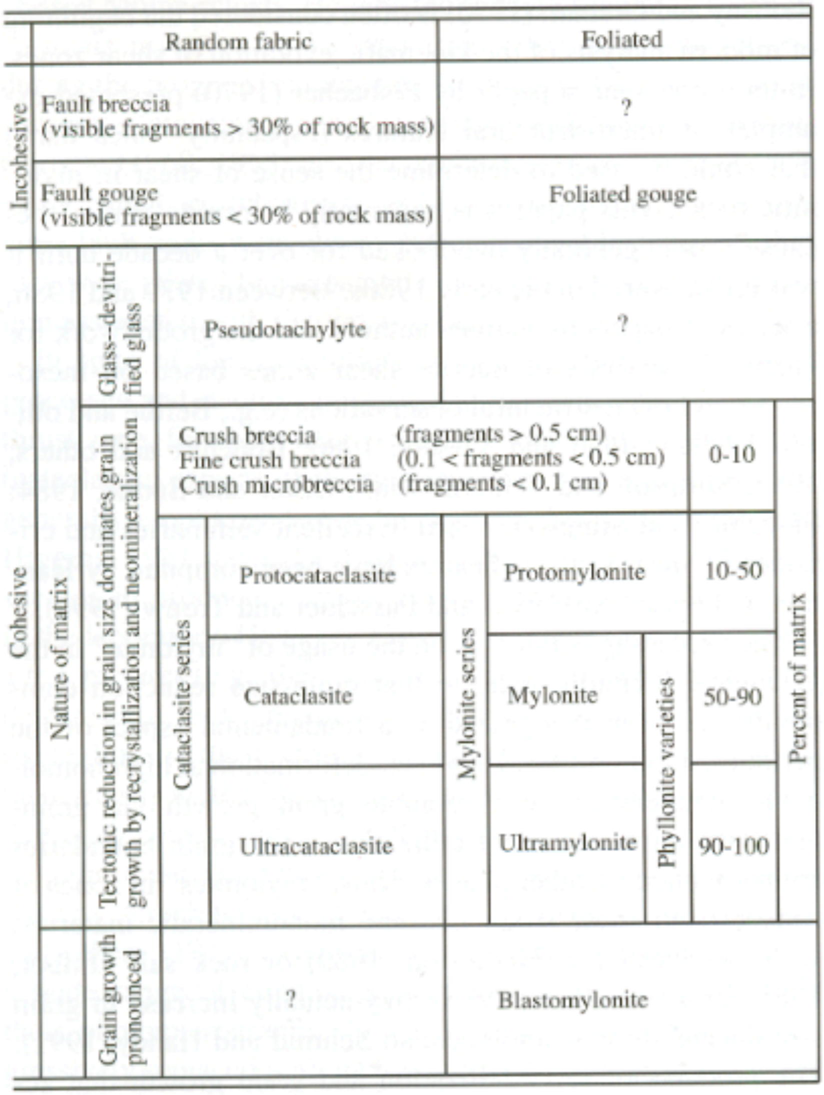
ABSTRACT

This study analyzes the low-temperature deformation of fault rocks associated thrust faults. Each fault has dominantly carbonate rocks in one wall and dominantly siliciclastic rocks in the other. The rocks from the Hunter Valley and Copper Creek thrusts of the Southern Appalachians, and McConnell thrust of the Canadian Rockies, were analyzed using data extracted at the thin section and SEM scale. The rocks, all of which featured a fine-grained carbonate matrix surrounding larger carbonate and siliciclastic carbonates, all experienced general shearing, but deformed by different deformation mechanisms. The Hunter Valley and McConnell samples showed evidence of cataclasis, diffusive mass transfer, diffusion accommodated grain boundary sliding and, in the case of the Hunter Valley fault rocks dislocation creep. The Copper Creek samples, by contrast, deformed primarily via plastic processes such as diffusion mass transfer and dislocation creep, and showed no evidence of cataclasis. Within the Hunter Valley and McConnell fault rocks, brittle processes such as cataclasis seemed to dominate at the thin section scale but SEM data supported ductile deformation of the fine matrix material. In each case, analysis of fabrics defined by grain orientations found that the rocks were deformed under general shear conditions and moderate convergence angles, although the Hunter Valley rocks showed evidence for a strong simple shear component of strain and relatively low (37° to 48°) while rocks from the Copper Creek and McConnell thrusts experienced roughly equal pure and shear strain components and showed evidence for higher convergence angles (51°to 59° and 61° to 68°, respectively). The findings of this study highlight the complicated nature of fault rock deformation as well as the difficulty of situating fault rocks within schemes of fault rock nomenclature, which are largely genetic in nature.

INTRODUCTION

Fault zones in the mid- to upper crust can be distinguished from analogous shear zones in the deeper crust by the processes that accommodate movement in these zones. In the lower crust, high temperatures and pressures favor viscous deformation mediated by recrystallization, dislocation creep and grain boundary sliding, while in fault zones in the upper crust are distinguished by the dominance of frictional deformation mechanisms. (Snoke et al., 1998) These zones of localized strain produce fault rocks that bear structural artifacts of their formation, and the study of strain in these rocks is significant due to the highly localized strain that tends to occur along faults (Braun et al., 2010) allows large-scale inferences to be made about crustal movement and deformation from very narrow bands of fault rocks. Rocks along relatively low-temperature fault zones tend to be affected by cataclastic processes of grain fracture and granular flow, as well as diffusion mass transfer. The fault rocks produced in mid to upper- crustal faults are termed cataclasites, and bare structural markers of the fault zones in which they were formed. They are differentiated from mylonites formed in the lower crust, which bear signs of ductile deformation.

Cataclasites are fault rocks that, as a category, are difficult to define. The very name implies a genetic process of cataclasis, which consists of fracture of rock constituents and the relative movement, in theory by frictional sliding, of those fractured constituents. However, other processes, such as diffusion mass transfer and diffusion-mediated grain boundary sliding, can be feasibly achieved at relatively low temperatures, particularly in areas with sufficiently high fluid content (Blenkinsop, 2000). Further complications arise from the practical requirement that the term must be useful in both the field and the laboratory. The mechanisms of fault rock formation must be inferred from structures within the rock itself, and scientists cannot rely on microstructural analysis when classifying rocks in the field. This presents a challenge to the creation of a classification scheme for fault rocks, and a particular challenge to schemes that are either implicitly or explicitly genetic in nature. Genetic classifications of fault rocks have generally distinguished between brittlely deformed cataclasites from ductilely deformed mylonites (Wise et al. 19884, Schmid & Handy 1991), a distinction that can be difficult or impossible to determine at the hand sample and outcrop scales. Sibson (1977) proposed a system that makes the distinction between foliated mylonites from random-fabric cataclasites (fig 1), but this classification fails to differentiate between foliated fault rocks formed at low temperatures, including those formed by cataclastic processes (Chester et al., 1985) from those formed at high temperatures. Furthermore, though his system was designed to be non-genetic, it emphasizes foliation, a hallmark of continuous deformation, and retains the term cataclasite, which implies a genetic origin. Thus, Sibson's classification system can produce confusion, particularly when applied to foliated fault rocks produced cataclastically and non-foliated rocks deformed by diffusion mass transfer and grain-boundary sliding, both of which ought to be considered in any classification scheme of fault rocks (Snoke et al., 1998).



	Nature of matrix		Random fabric		Foliated		Percent of matrix
Incohesive			Fault breccia (visible fragments > 30% of rock mass)		?		
			Fault gouge (visible fragments < 30% of rock mass)		Foliated gouge		
Cohesive	Glass--devitrified glass		Pseudotachylyte		?		
	Tectonic reduction in grain size dominates grain growth by recrystallization and neomineralization		Crush breccia (fragments > 0.5 cm) Fine crush breccia (0.1 < fragments < 0.5 cm) Crush microbreccia (fragments < 0.1 cm)				0-10
		Cataclasite series	Protocataclasite	Mylonite series	Protomylonite		10-50
			Cataclasite		Mylonite	Phyllonite varieties	50-90
			Ultracataclasite		Ultramylonite		90-100
	Grain growth pronounced		?		Blastomylonite		

Figure 1: Sibson's 1977 Fault Rock Classification

As is the case with most categorizations, the distinction between cataclasites and mylonites are not absolutely discreet groups, but rather represent ideal end members of a spectrum of actual fault rocks. Cataclasites are not formed exclusively via cataclastic deformation. In fact, other deformation mechanisms, such as diffusion mass transfer, or grain boundary sliding accommodated by either diffusion or dislocation creep, can occur at shallow-to-mid-crustal temperatures and, therefore, may be quite common in cataclasites (Snoke et al, 1998), and seemingly brittle processes such as rock fracturing may be facilitated by ductile processes in surrounding material (Mitra, 1978). As a result, cataclasites may not undergo completely brittle deformation, but rather semi-brittle or even semi-ductile deformation. One way to think about the brittle-ductile dichotomy is to equate brittle with geometric discontinuity and ductile with geometric continuity. An ideally ductilely-deformed feature oriented perpendicular to a zone of deformation will follow a smooth curve across that zone, while a brittlely deformed feature will have one or more distinct breaks or fractures (fig 2). When both brittle and ductile deformation occur simultaneously or sequentially, it is possible to discern both continuous and discontinuous features (Gibson & Gray, 1985). As this fact demonstrates, the distinction between cataclasites and mylonites is difficult to make because the two terms do not refer to absolutely discrete groups, but rather represent ideal end members of a spectrum along which actual fault rocks may fall.

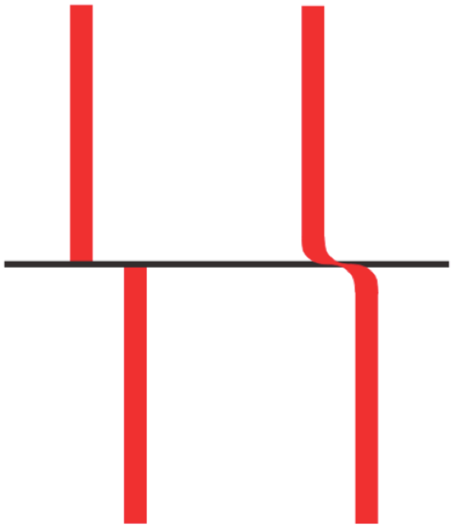


Figure 2: Representation of discontinuous (left) versus continuous (right) deformation

As rocks deform, they can be described as experiencing two-dimensional shearing in a plane perpendicular to the fault surface. A two dimensional component of deformation can be defined as having two ideal end members: pure shear and simple shear. In pure shear, the three principal stretching directions are eigenvectors, i.e. linear features whose orientations are not changed during deformation, although they may change in length. Because of this fact, pure shear is coaxial, meaning that linear features parallel to the axes of the strain ellipsoid maintain a constant orientation throughout shearing (fig 3) By contrast, simple shear is a deformation whose eigenvectors are confined to a single plane (Simpson and De Paor, 1993). As a result, simple shear is noncoaxial, meaning that linear features parallel to the axes of the strain ellipsoid will rotate as shearing progresses (fig 4) (Nicolas, 1987). Rocks undergoing deformation experience exclusively either pure shear or simple shear relatively rarely. Rather, naturally occurring deformation more commonly has both pure and simple shear components, the combination of which produces general shear (Jessop et al., 2007; Bailey et al. 2004; Bailey & Eister, 2003; Lin & Williams, 1997). The relative influence of each component in a

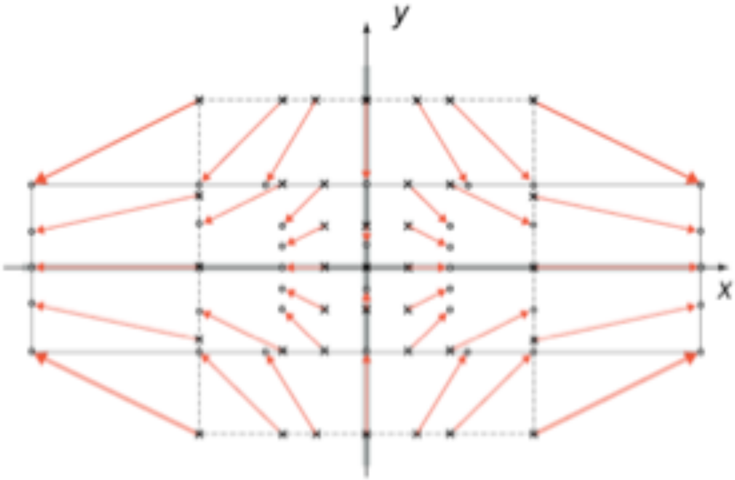


Figure 3: Strain pathways for coaxial deformation; note perpendicular planes of stable orientation; image courtesy of Steve Wojtal

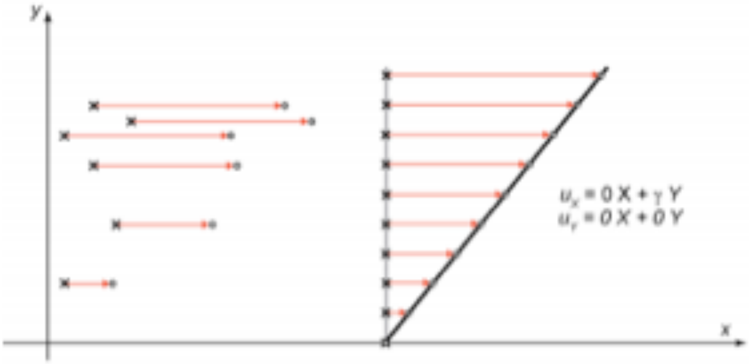


Figure 4: Strain pathways for particles undergoing simple shear; not that deformation is noncoaxial; image courtesy of Steve Wojtal

given rock can be estimated by the mean vorticity number (W_m), although the relationship is not a simple linear one (Passchier, & Trouw 1996).

When describing deformation, shearing is described with respect to an internal reference frame within the deforming rock. Both mylonites and cataclasites are very often host to rigid survivor grains, which may originate in either wall of the fault or in a previously generated fault rock (Snoke et al., 1998). These grains undergo relatively little internal deformation, although they may experience intragranular fracturing or be crosscut by intergranular fractures or veins. Nevertheless, an analysis that assumes grains are entirely rigid can be useful, since survivor grains contribute to the overall deformation of their host rock primarily via rotation. Overall strain is best exemplified by grains with high axial ratios, in that grains with an axial ratio below some critical ratio (R_c) will spin infinitely while those grains with an axial ratio greater than R_c will settle into a stable position (Wallis et al., 1992). The critical ratio is related to the mean vorticity number by the following equation (Equation 1; Wallis et al., 1992):

$$W_m = \frac{{R_c}^2 - 1}{{R_c}^2 + 1}$$

The vorticity number is related to the relative simple and pure shear strain rates by the following equation (Equation 2, Bobyarchik ,1986):

$$W_m = cos\left[arctan\left(2\dot{\varepsilon}_x / \dot{\Upsilon}\right)\right]$$

where $\dot{\varepsilon}_x$ represents the pure shear strain rate and $\dot{\Upsilon}$ represents the simple shear strain rate. Thus, we can find the proportion of pure to simple strain by the equation (Equation 3):

$$\frac{\dot{\varepsilon}_x}{\dot{\gamma}} = \frac{tan[arccos(W_m)]}{2}$$

Finally, vorticity is related to the convergence angle, α , by the equation (Equation 4, Bobyarchik, 1986):

$$\alpha = \arccos(W_m)$$

Such that a pure shear regime has a convergence angle of 90° and a pure shear regime has a convergence of 0°

Studies of mylonites have frequently used these survivor grains to approach an understanding of strain regime (Blenkinsop, 2000; Snoke et al.1998). Because the matrix of cataclasites may also be viscously deformed via a variety of processes (diffusion mass transfer, grain boundary sliding etc.) this method should also be a viable approach for determining for cataclasites. In this study, analysis of the orientations and axial ratios of rigid clasts within foliated cataclasites from the Hunter Valley, Copper Creek, and McConnell thrusts will be used to gain information about the deformation of those rocks.

GEOLOGIC SETTING

The Hunter Valley and Copper Creek thrusts are two (non-adjacent) thrusts in a series of thrust faults that strike northeast to southwest in the Valley and Ridge province of eastern Tennessee and Western Virginia. These faults were probably formed sequentially back to front in a hinterland to foreland fashion during a series of accretions (Woodward & Beets, 1988; Boyer & Elliott, 1982). The Cambrian siliciclastic Rome formation forms the hanging walls of most of the faults in this region. The mineralogy in this region, which consists largely of siliciclastic silts, shales, and sandstones with occasional limestone and dolomite beds (probably trailing continental margin deposits), does not lend itself to reconstructions of deformation environment, but vitronite reflections and conodonts can be used to determine local temperature conditions where they are found (Harris and Milici, 1977). Generally, there is some foliation in the limestones and shales of the region, but markers of high-temperature deformation, such as dislocation creep, are not prevalent along most faults. Both the Hunter Valley and the Copper Creek thrusts dip to the southeast, as is the general trend for thrust fault in this region.

The Hunter Valley samples come from an exposure of the thrust near Duffield, Virginia. Here, Cambrian age Rutledge Limestones have been thrust over Devonian age Genesee Shales (fig 5). The boundary between the two layers is marked by a sharp contrast in color, and the two layers are separated by a medium-gray fault rock, typically 15-20 cm thick, of mixed siliciclastic and carbonate composition. The rock has a prominent foliation roughly parallel to the thrust surface defined by dark banding. Deformation continues several meters into the fractured limestones and shales of the hanging walls and into the heavily folded shales of the footwall.

Figure 5: Hunter Valley collection site; note human for scale. Image courtesy of Steve Wojtal.

The Copper Creek Samples in this study are from Diggs Gap, Tennessee, near Knoxville.

Figure 6: Copper Creek collection site; note pen for scale. Image courtesy of Steve Wojtal.

Here, Rome formation strata, including a shale layer immediately above the fault overlain by dolomite and alternating sand and shale layers, which have been thrust over Ordovician age limestones (fig 6). A band several centimeters thick of light-colored fault rock separates the two layers, although other exposures of the thrust have much thicker (10-20 cm) cataclasite exposures. The fault rocks, composed of a mixture of siliciclastic and carbonate material, is visibly foliated at the hand sample scale with lighter and darker tan layers, and elongated grains are visible, oriented roughly parallel to the thrust surface, and numerous veins cut across the sample.

The McConnell thrust is the leading thrust in the Front Ranges of southern Alberta. The fault, is oriented parallel to hanging wall strata, which dip to the west. The samples in this study were collected at the Mt. Yamnuska exposure of the thrust, west of Calgary, which is near the zone of maximum transport along the thrust (Gretener, 1987). Like the Hunter Valley and Copper Creek thrusts, the McConnell thrust brings material from the basal detachment up to the surface. At this location, the Cambrian age carbonates of the Eldon Formation have been thrust over Cretaceous siliciclastic rocks of the Belly River formation. The thrust has produced a 10-20 cm thick band of dark-colored cataclasite, composed of a combination of siliciclastic and carbonate material, which is easily discernable at the outcrop scale (fig 7). At the hand sample scale, a foliation defined by dark banding roughly parallel to the thrust surface is visible within the rock.

Figure 7: McConnell thrust collection site. Image courtesy of Steve Wojtal.

METHODS

Samples were collected at each locality as follows: three samples were collected each from the Hunter Valley and McConnell thrust from across the exposure. At the Copper Creek thrust only two samples were collected. At each of the three localities, fault rocks are banded but visible lack grain scale deformation in macroscopic grains. Therefore, microscopic analysis is necessary to determine the nature of deformation. For each of the fault rocks under study, samples were analyzed in thin section, producing optical microscopy data that forms the foundation of this study. Thin sections were prepared to be perpendicular to the thrust surface, allowing for a meaningful analysis of deformation in two directions. Using these thin sections, survivor clasts, which were generally rounded and roughly ellipse-shaped in cross-section, were randomly selected using 0.1 mm grid. Grains that coincided with exactly one grid intersection were selected for study. Selected grains were traced using the program EllipseFit, which approximated an ellipse for each selected grain, and allowed us to analyze qualities of each grain including axial ratio, diameter, and orientation with respect to the fault surface. These data were supplemented with clasts measured at a much smaller scale using a scanning electron microscope. These grains at this scale were selected by superimposing a 10 μm grid, and selecting those grains that fell under exactly one intersection of gridlines. These grains were then processed using EllipseFit (Wollmer, 2011). Wallis plots were constructed to determine the vorticity number of at each locality using both grains at both the thin section and SEM scales. Other notable features at the thin section and SEM scale were also noted for each rock. These included intergranular veins and fractures, and intragranular fractures and veins. The orientations of veins were recorded with respect to the thrust surface, and the orientations of intragranular fractures were recorded with respect to both the thrust surface and the long axis of the grain.

RESULTS

Each of the fault rocks is composed of a mixture of siliciclastic and carbonate survivor grains in a fine-grained matrix of mixed composition, and in each case survivor clasts were distinguishable as quartz clasts from sandstones of carbonate clasts from limestones. In the Hunter Valley (fig 8) and McConnell (fig 9) fault rocks, the clasts are composed of quartz or calcite, or may contain multiple smaller grains, also of calcite or siliciclastic composition. The quartz grains often consist of a single crystal while the carbonate samples are limestone fragments that generally contain numerous crystals. Other grains contain multiple smaller clasts surrounded by consolidated matrix. In the Copper Creek fault rocks (fig 10), most of the large clasts are multicrystalline carbonate grains. In the samples rom each fault, the clasts very widely in size, some being as large as several millimeters across, with no sharp drop off in grain size visible at this scale (fig 11)

Calcite-filled veins are also present in the rocks from the Hunter Valley and Copper Creek thrusts, though no veins are visible in the samples from the McConnell thrust. The veins in the Hunter Valley rocks possess two morphologies: some are straight sided and transect

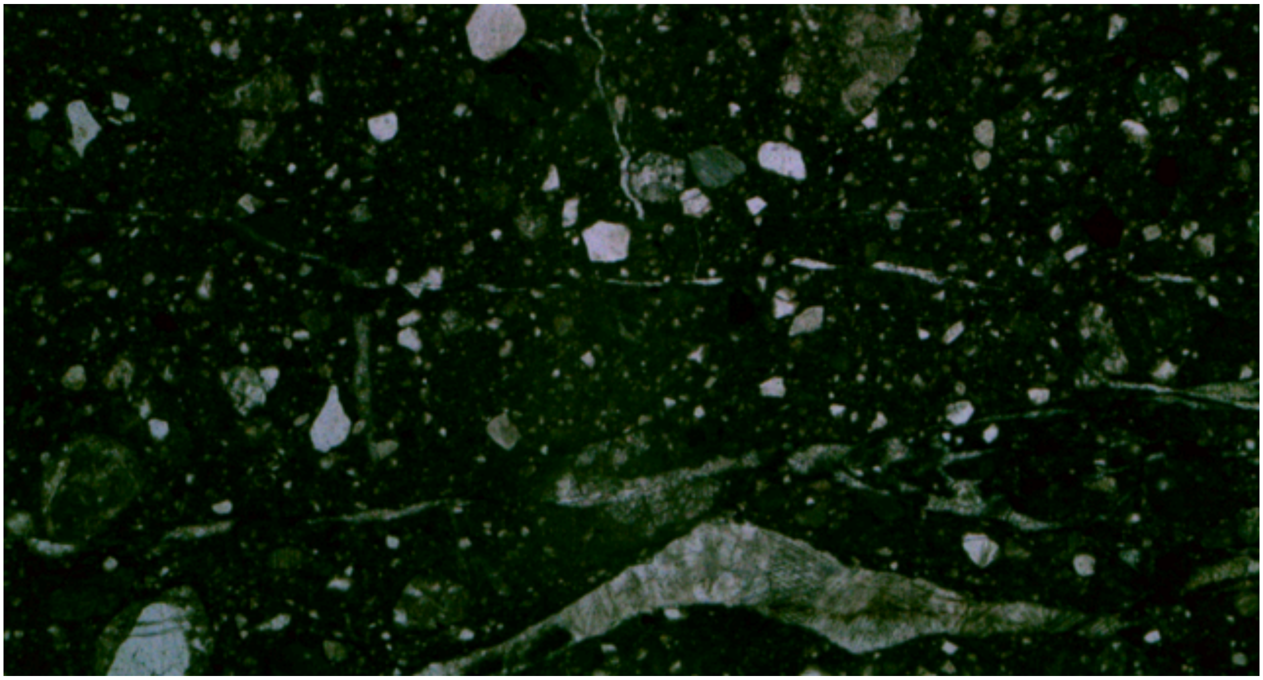


Figure 8: Thin section photomicrograph of Hunter Valley Fault rock; image width represents approximately 3 mm

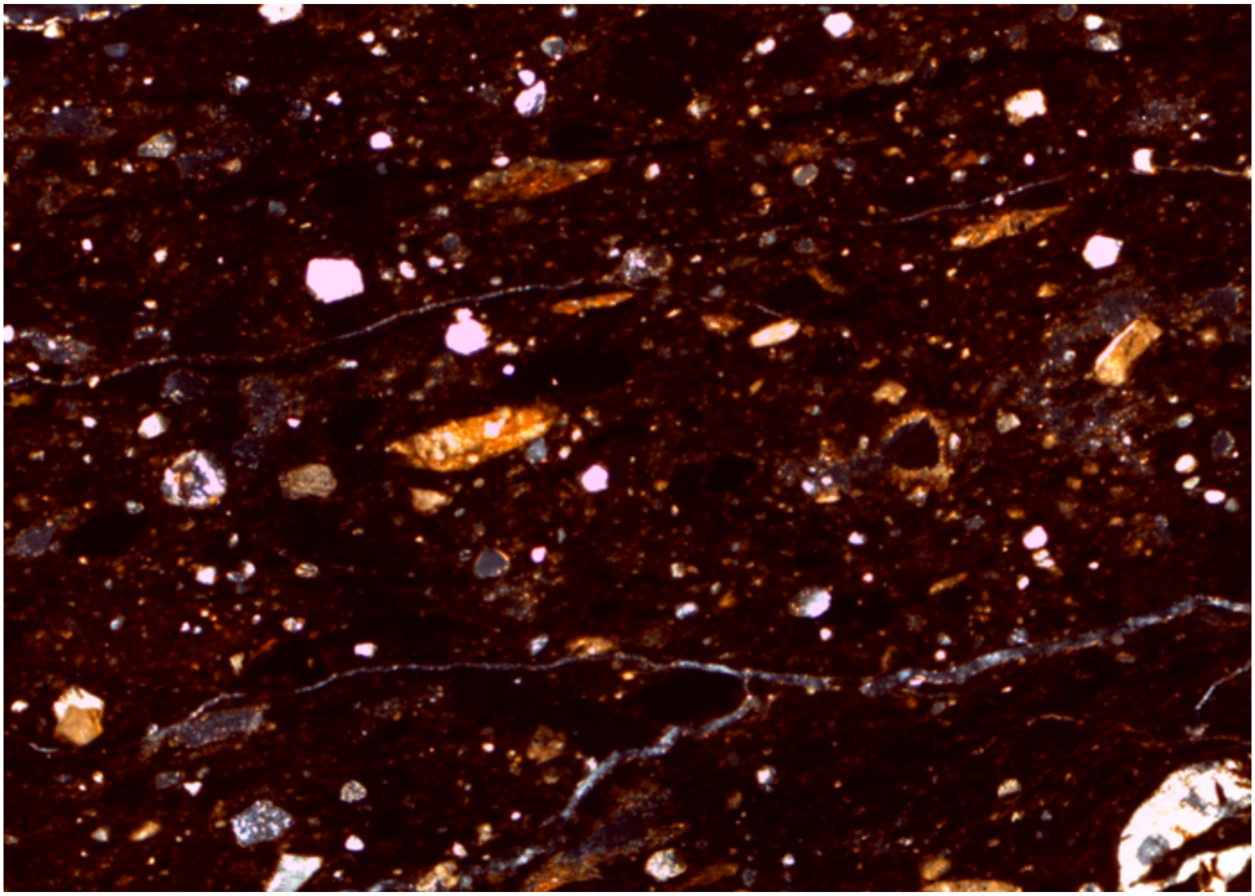


Figure 9: Thin section photomicrograph of McConnell fault rock; image width represents approximately 3 mm

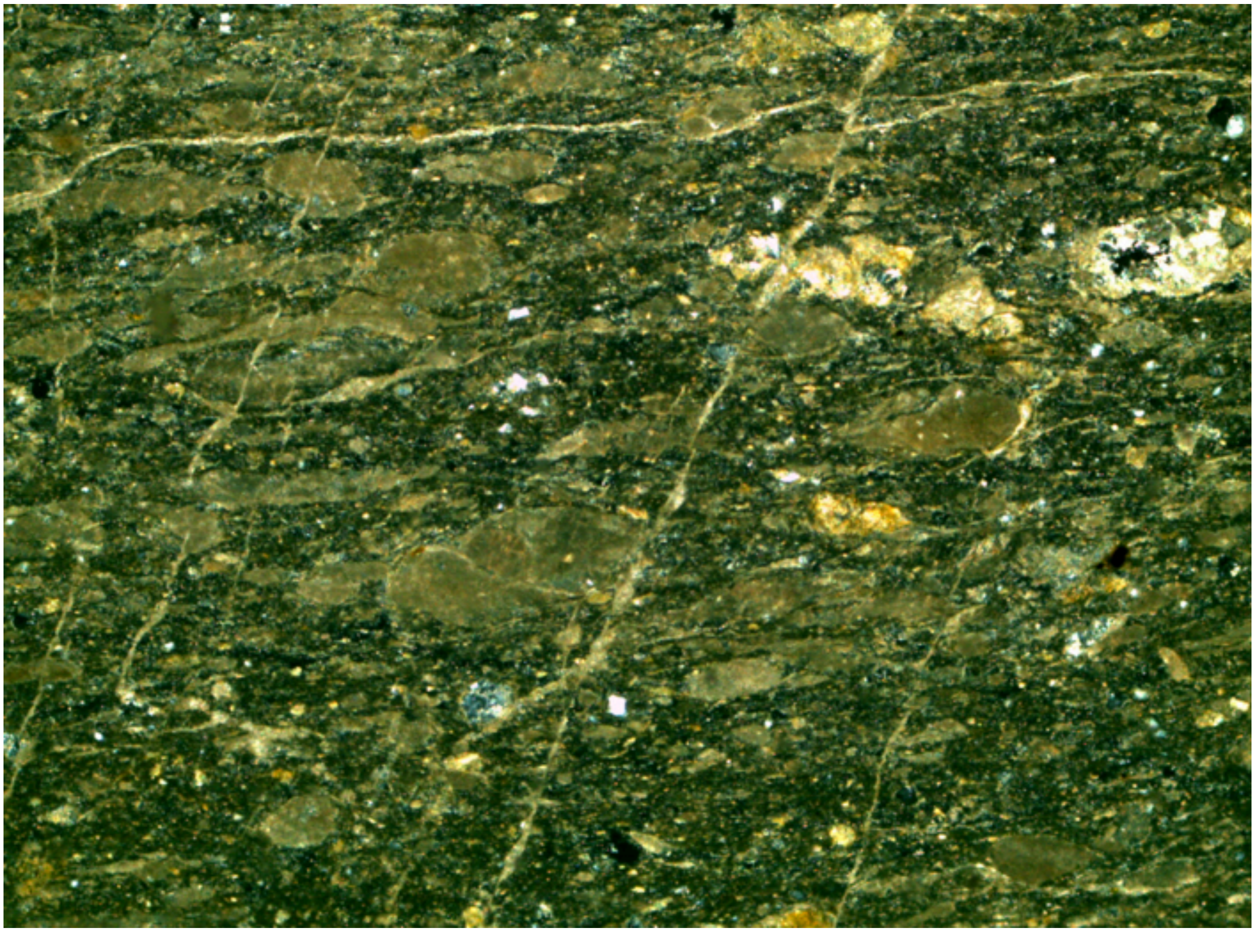
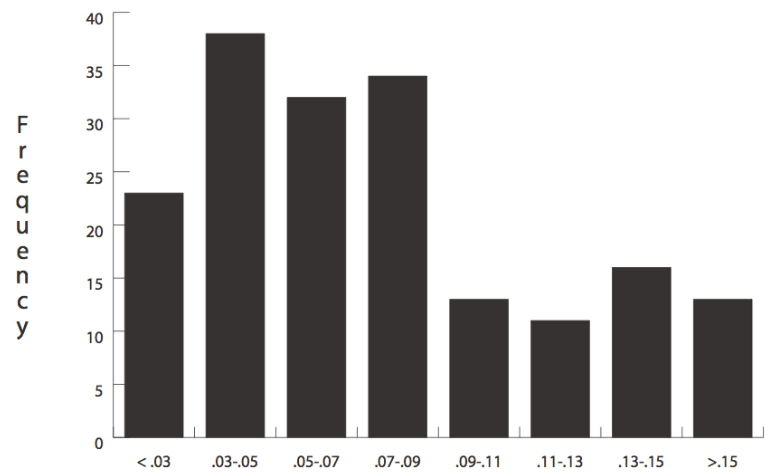
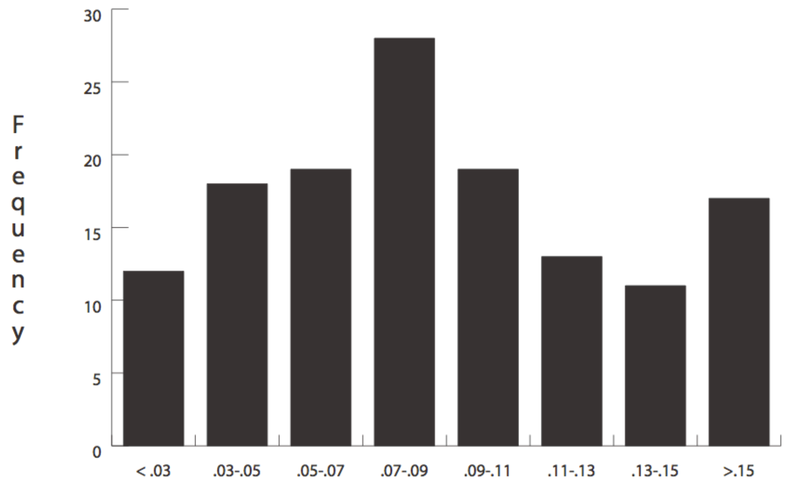


Figure 10: Thin Section photomicrograph of Copper Creek fault rock; image width represents approximately 3 mm


Grain Size Distribution inHunter Valley Fault Rocks, Thin Section Scale


Grain Size Distribution in Copper Creek Fault Rocks, Thin Section Scale

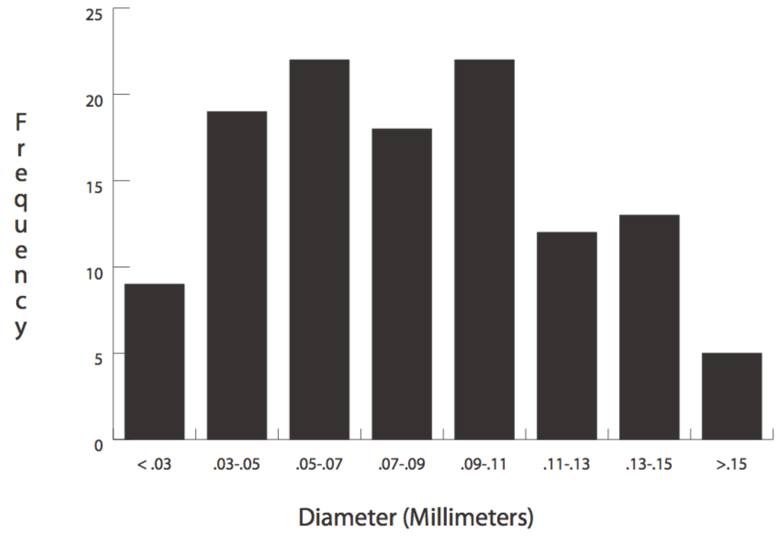

Grain Size Distribution in McConnell Fault Rocks, Thin Section Scale

Figure 11: Thin-section scale grain size distributions for all fault rocks

the whole thin section, while others have taper out and have more irregularly shaped edges, often bordered by selvage material. In both cases twinning is common in the calcite. A plot of the orientation of the veins (fig 12) shows that most of the veins in our sample are oriented at low angles to the thrust surface, but that a significant number are also found at high angles to the fault, with virtually no veins found within the range of thirty to sixty degrees with respect to the thrust surface. When plotted separately (fig 13), the straight-sided veins tend to be oriented at high angles to the thrust while the tapered veins tend to be oriented at low angles to the thrust surface. No clear pattern is visible in the orientations of veins in the Copper Creek fault rocks (fig 14). Other tabular features are also visible in the samples. Numerous dark bands sub-parallel to the thrust surface are visible in hand sample and thin section of all the fault rock samples. Additionally, the McConnell fault rocks are crossed by numerous fractures, some of which contain small amounts of calcite, though none are completely in-filled with calcite. A plot of fracture orientations with respect to the thrust (fig 15) surface shows that most fractures are roughly parallel to the thrust surface, although some are oriented at a higher angle to the fault.

Intragranular fractures are common in the survivor clasts within samples from the Hunter Valley and McConnell thrusts, especially in quartz grains. Cracked grains are more numerous in the Hunter Valley fault rocks than in the McConnell fault rocks. Some of these fractures have divided grains entirely, and many have been filled with calcite. Intragranular fractures are conspicuously absent from the Copper Creek fault rocks. The orientations of intragranular fractures in the Hunter Valley fault rocks with respect to the thrust surface and long axis of the grain are plotted in figure 16. There is a slight concentration of fracture orientations perpendicular to both the long axis of the grain and the thrust surface. When plotted with respect to the thrust surface and the long axes of the grains (fig 17), most intragranular fractures in the samples from the McConnell thrust are oriented oblique to the thrust surface and perpendicular to the long axes of the grains. Some quartz grains in

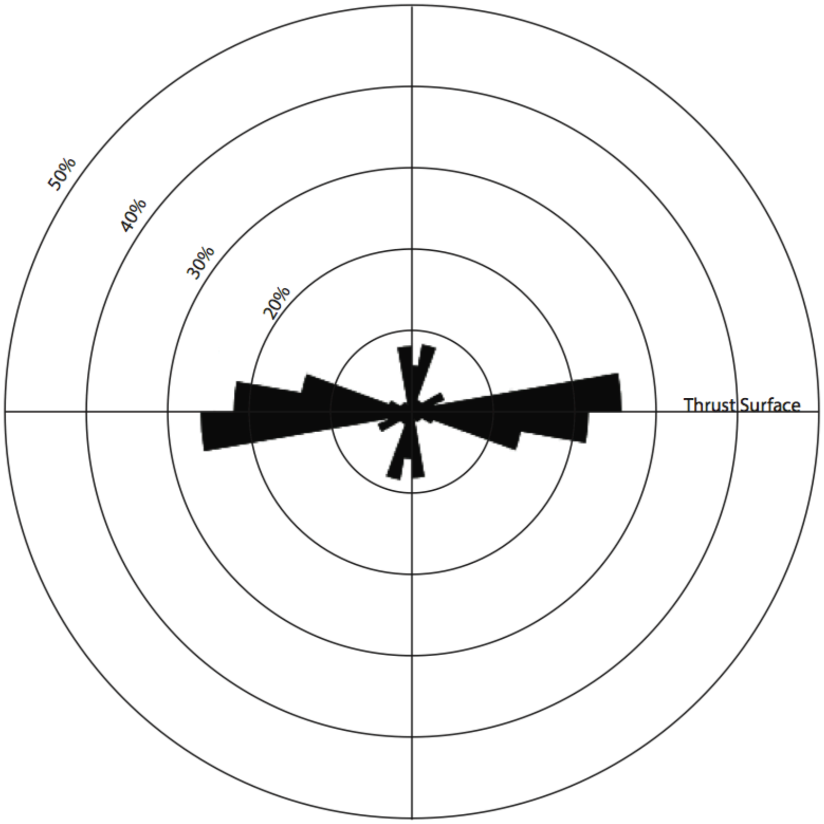


Figure 12: Orientation of all veins in Hunter Valley fault rock with respect to thrust surface

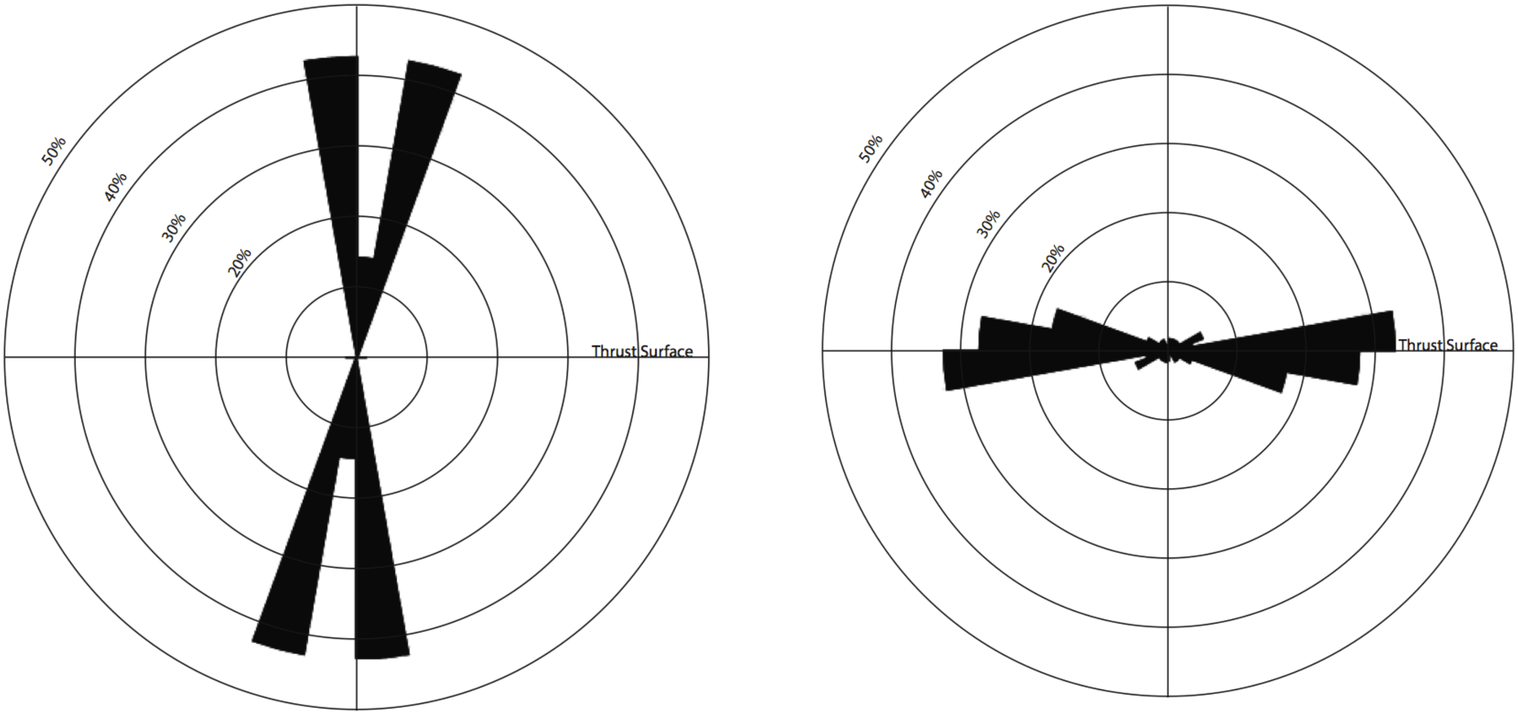


Figure 13: Orientation of straight sided (left) and tapered (right) veins with respect to Hunter Valley thrust surface

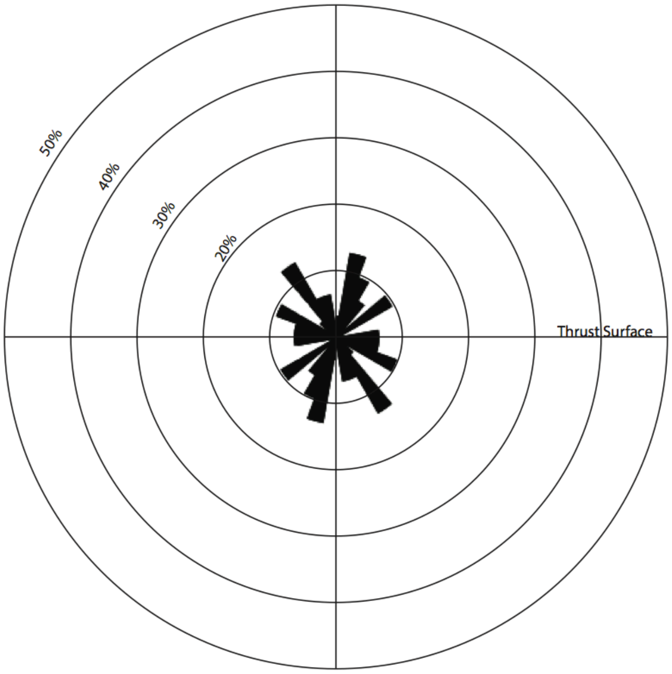


Figure 14: Orientation of veins with respect to Copper Creek thrust surface

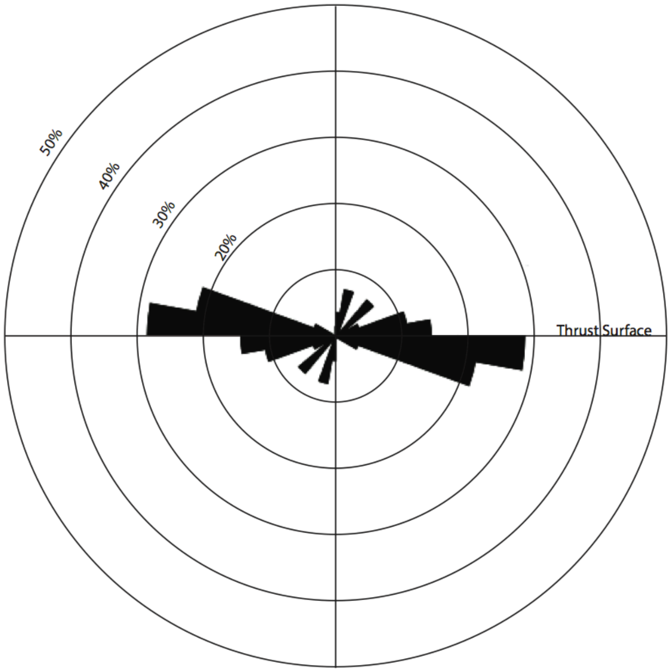
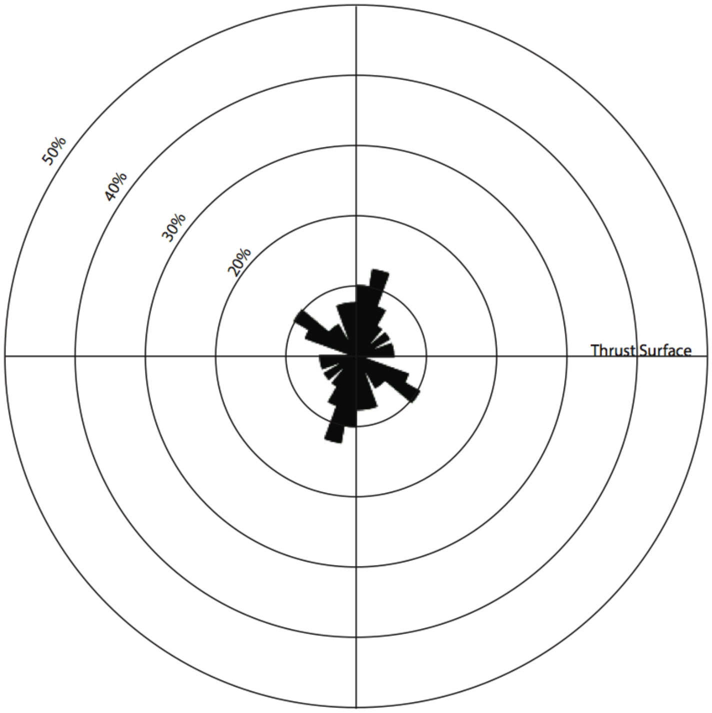


Figure 15: Orientation of unfilled intergranular fractures with respect to McConnell thrust



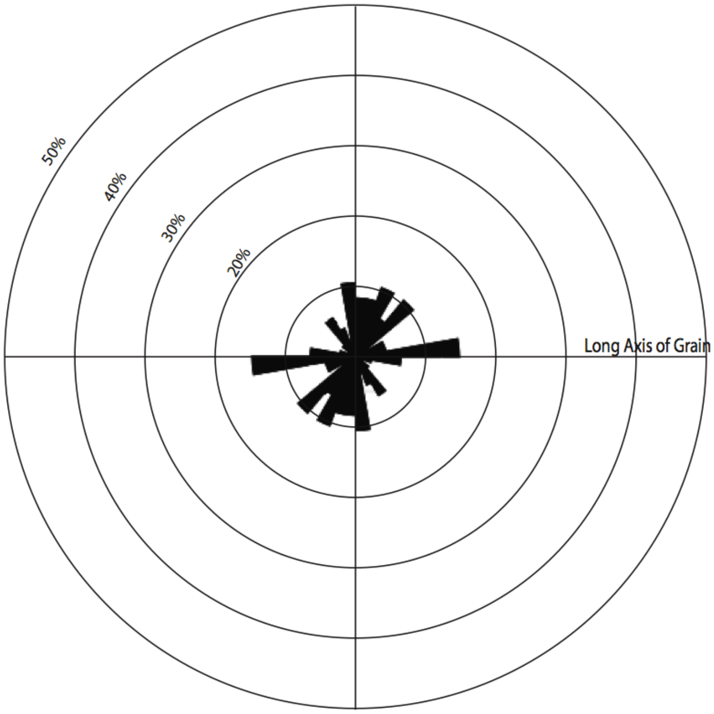


Figure 16: Orientation of intragranular fractures in the Hunter Valley fault rock with respect to the thrust surface (left) and long axis of the grain (right)

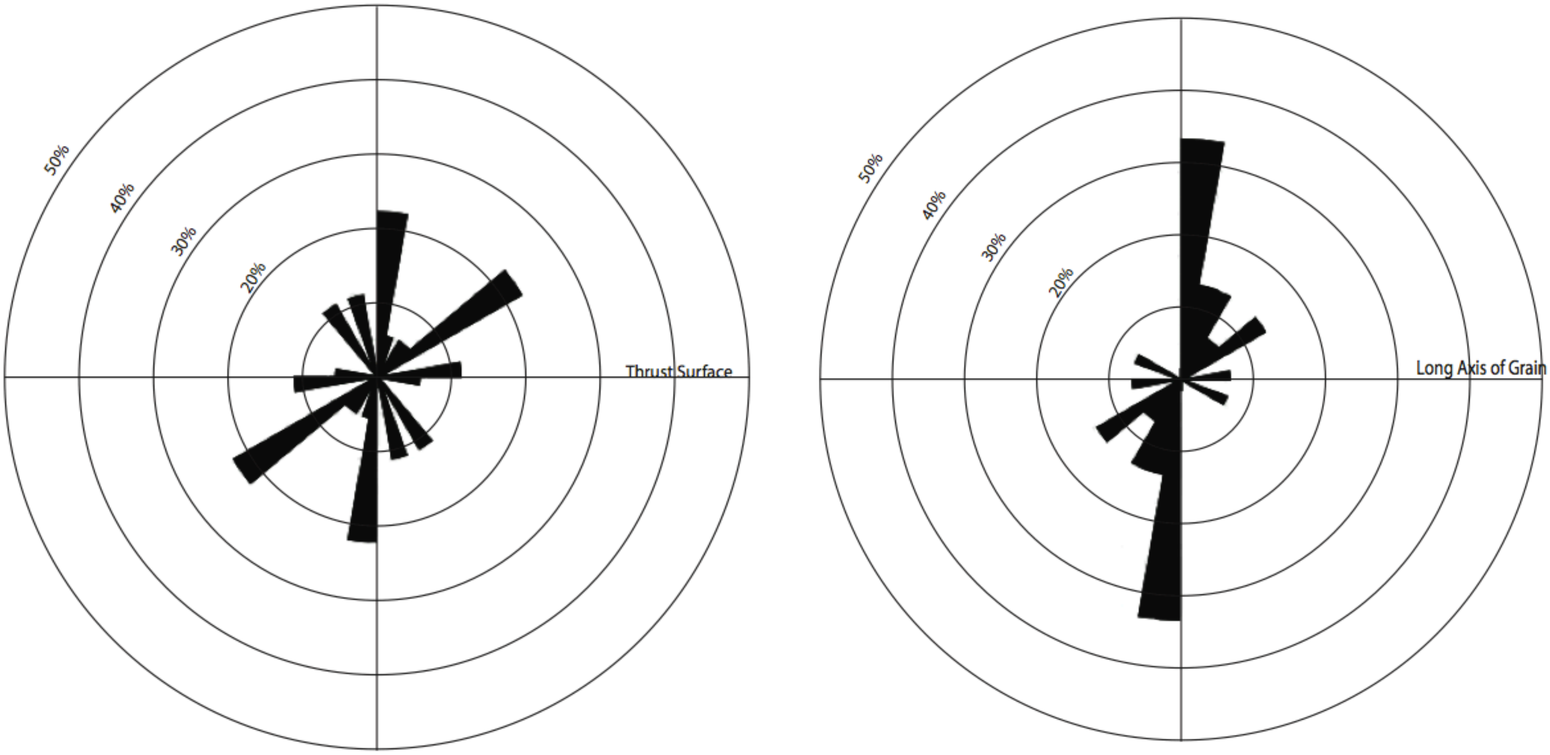


Figure 17: Intragranular fractures of the McConnell fault rock with respect to the thrust surface (left) and long axis of the grain (right)

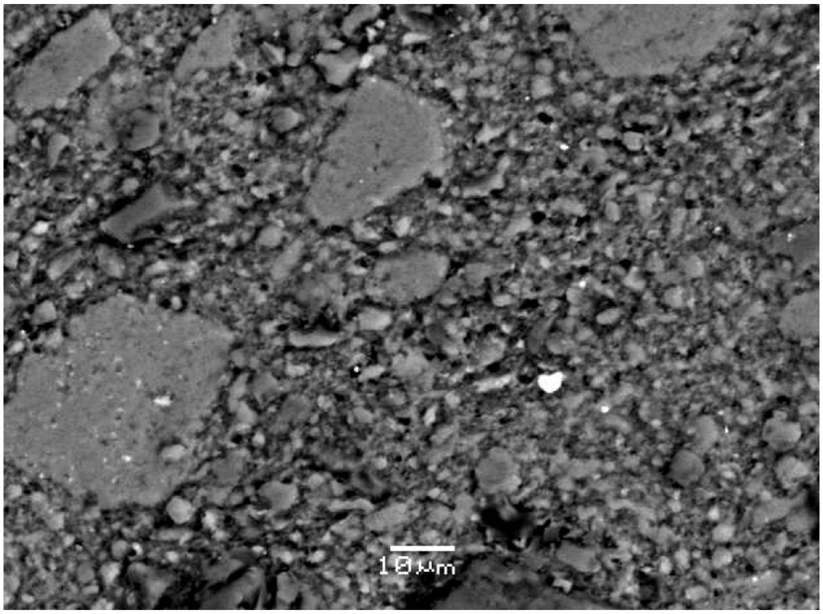


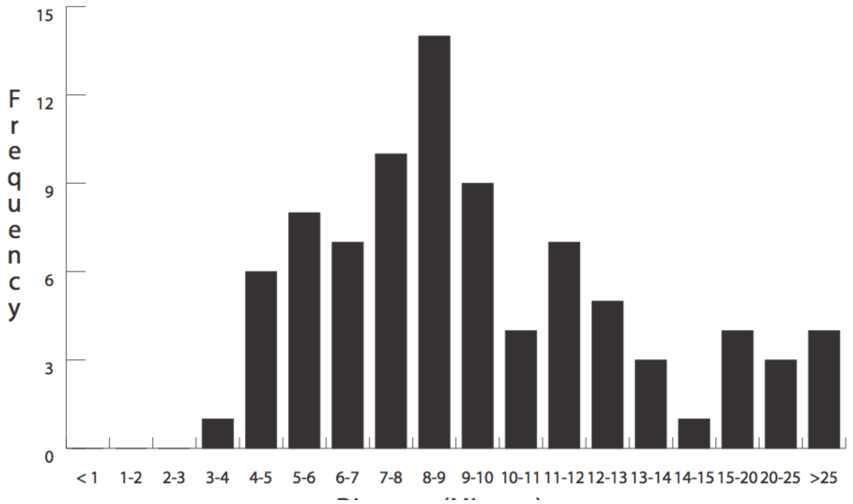
Figure 18: SEM image of Hunter Valley fault rock; note scale bar.

the Hunter Valley fault rocks display slightly undulose extinction, though no grains in the other fault rocks do.

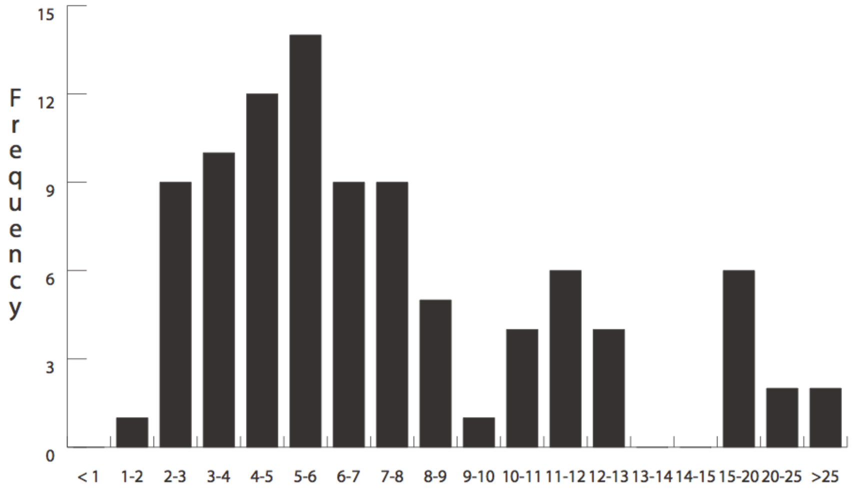
At the SEM scale (roughly .01 - .5 mm), grains are generally more equant in every fault rock than at the thin section scale, and intragranular fractures are much less common (fig 18). Grains tend to have silicate compositions while matrix material is mainly calcite. An interesting feature of the Hunter Valley fault rocks at the SEM scale (less than 30 microns) is the scarcity of grains less than one micrometer across. In the Copper Creek and McConnell fault rocks, no minimum grain size is apparent, although smaller grains are more common, with larger grains separated from each other by numerous smaller grains. Wallis plots for each fault rock display data from both the thin section and SEM scales. A grain size distribution at this scale for each locality is presented in figure 19.The SEM scale grain size data for the Hunter Valley fault rocks shows a sharp drop off in the abundance of survivor grains less than 2 microns in diameter. A similar scarcity of grains below 2 microns is found in the Copper Creek fault rocks, and a scarcity of grains below 4 microns is apparent in the McConnell fault rocks. In each case, much smaller grains are present in the matrix that are beyond the resolving power of the SEM.

In each case, clasts with higher axial ratios tend to be oriented at lower angles to the thrust surfaces. Evaluation of Wallis Plot data can be summarized in Table 1. The Wallis plot for the Hunter Valley fault rock (fig 20) suggests that the critical axial ratio of rotating grains is somewhere between 2.0 and 3.0. Equation 1 yields a mean vorticity number between 0.67 and 0.80, which corresponds with a convergence angle between 37°and 48°. The Wallis plot for the Copper Creek Samples (fig 21) is the most scattered of the data sets in this study, but it does suggest that even grains with relatively low axial ratios are settling into a stable sink orientation, allowing us to tentatively estimate the critical axial ratio, which may be as low as 1.8 to 2.1. These values equate to a vorticity number between 0.52 and 0.63, and a convergence angle between 51° and 59°. The axial ratio for the McConnell thrust (fig 22) can be pinned within a relatively narrow range of 1.5 to 1.7, which corresponds to a vorticity number between 0.38 and 0.48. These values of Wk. are indicative of a convergence angle between 61° and 68°

Grain Size Distribution in Hunter Valley Fault Rocks, SEM scale



Grain Size Distribution in Copper Creek Fault Rocks, SEM scale



Grain Size Distribution in McConnell Fault Rocks, SEM scale

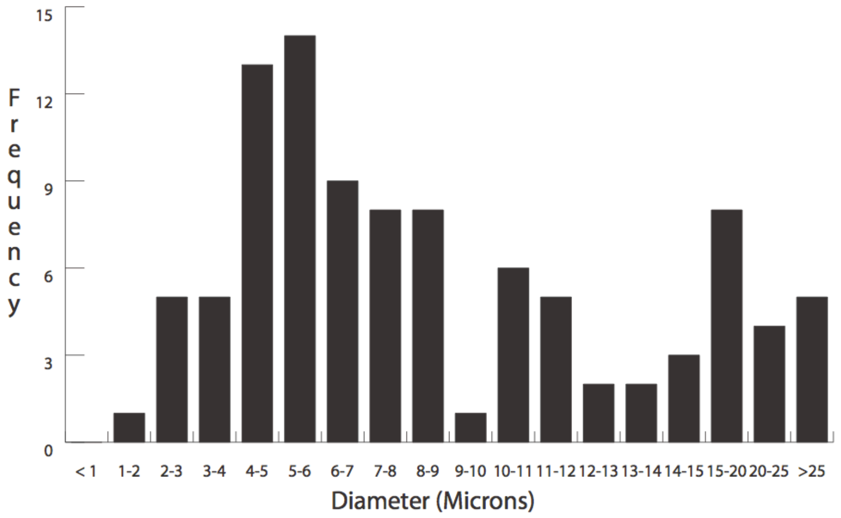


Figure 19: Grain size distributions for all fault rocks at SEM scale

Table 1	Summary of Displacement Field Data		
Associated Fault	Rc	Wk	a
Hunter Valley	2.0 to 3.0	0.67 to 0.80	37 to 48
Copper Creek	1.8 to 2.1	0.52 to 0.63	51 to 59
McConnell	1.5 to 1.7	0.38 to 0.48	61 to 68

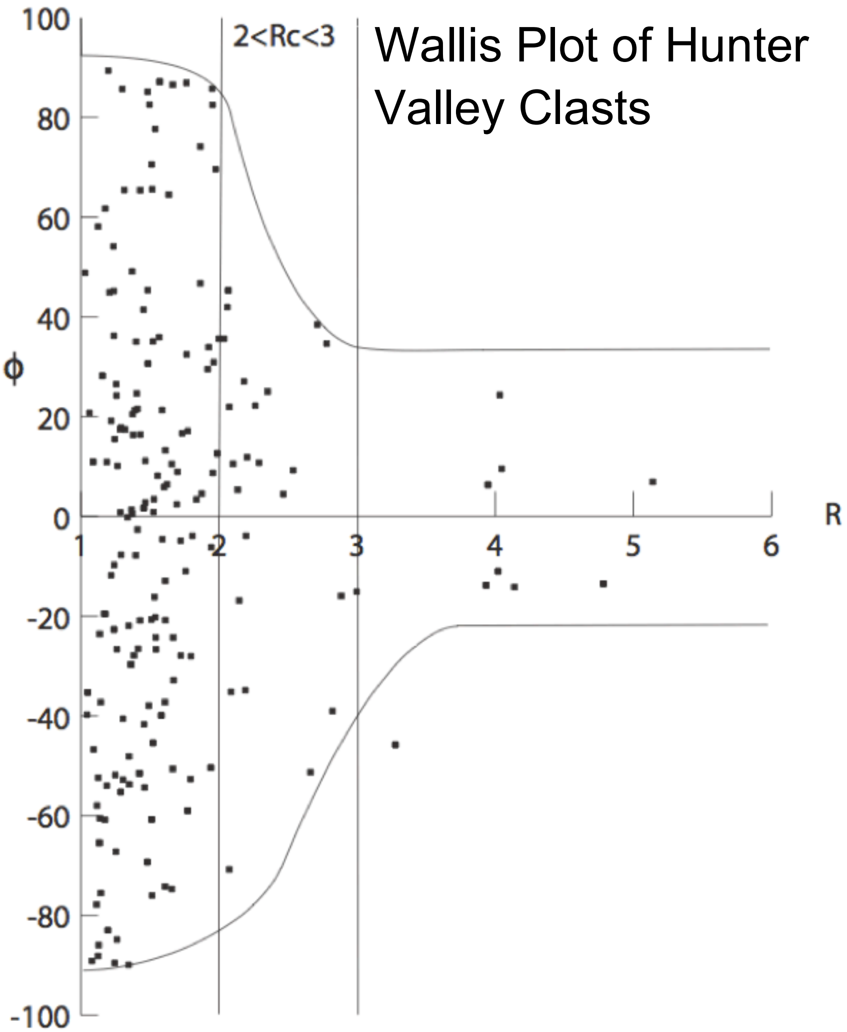


Figure 20: Wallis Plot for Hunter Valley fault rock

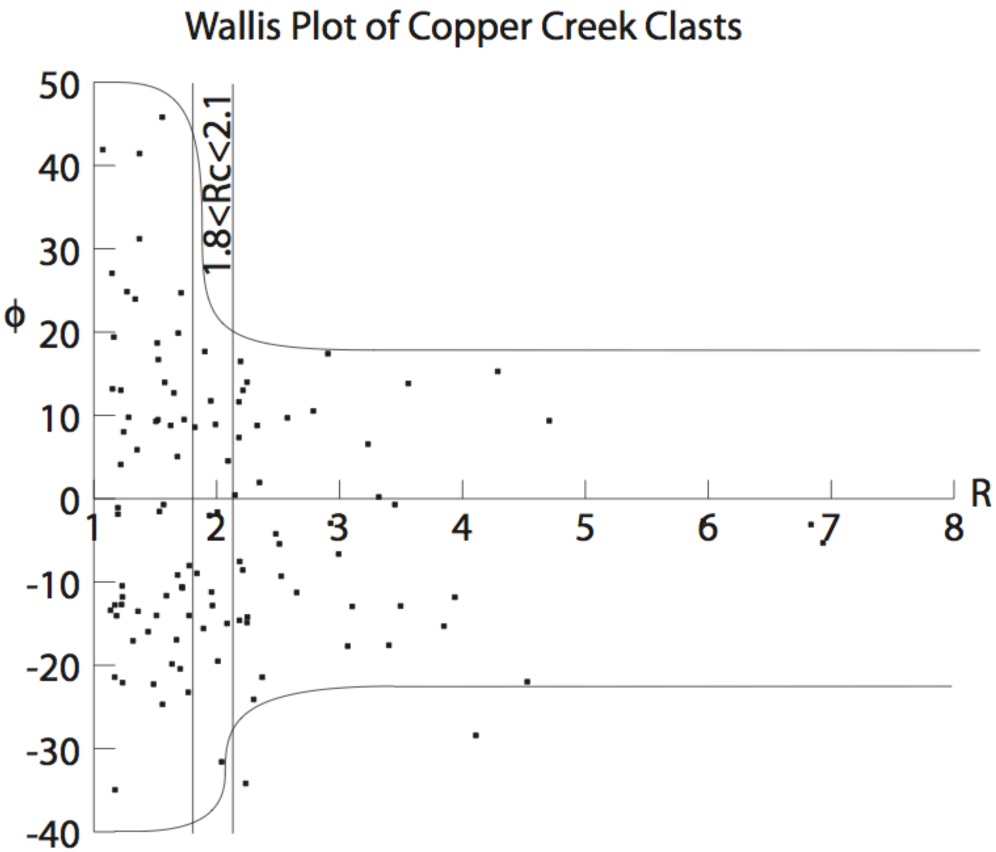


Figure 21: Wallis plot for Copper Creek fault rock

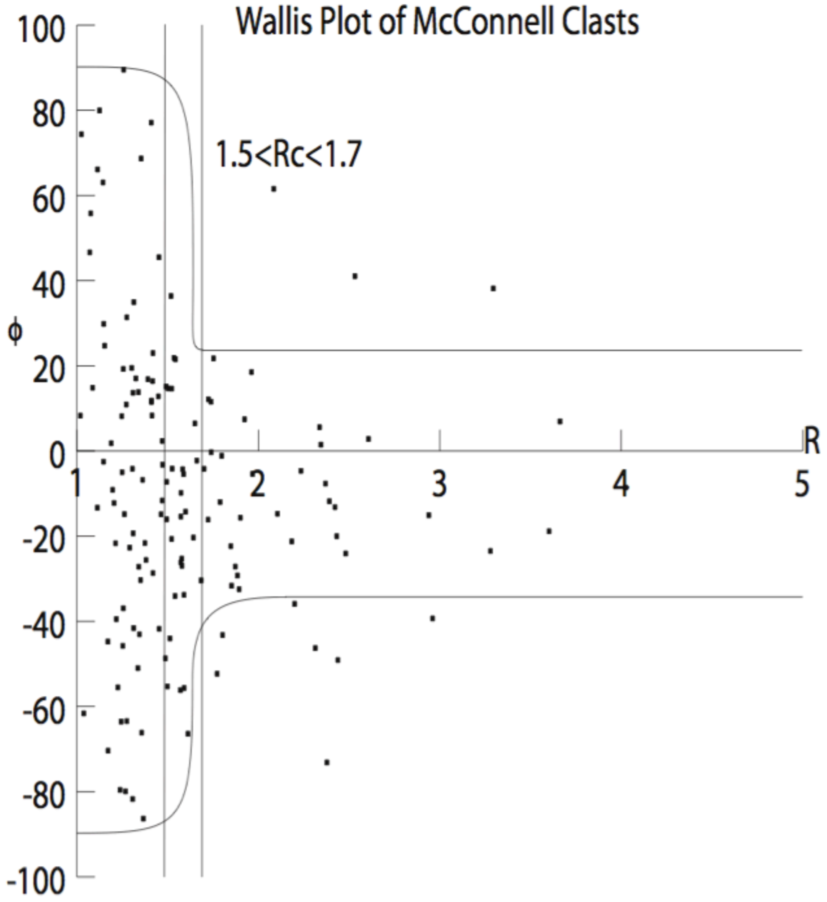


Figure 22: Wallis Plot for McConnell fault rock

DISCUSSION

The large grains that are found in each sample are survivor clasts that have been incorporated into the fault rocks from either surrounding wall rock or previously formed fault rocks. This is evidenced by that fact that in each case, the grains possess a mineralogical composition similar to that either the hanging wall or footwall of the fault, or are fragments of previously formed cataclasites consisting of a combination of siliciclastic and carbonate grains in a consolidated matrix of mixed compositions. These clasts are probably fragments of older fault rocks that have been subsequently broken apart and deformed to produce the fault rocks we see at the present time. At the thin section scale a variety of clast sizes are observed, such that deformation mechanisms are probably not preferentially affecting grains of a size visible at this scale (i.e. larger than 10 μm).

Calcite veins are common in both the Hunter Valley and Copper Creek fault samples. The bimodal orientation of calcite veins roughly perpendicular and roughly parallel to the thrust surface in the Hunter Valley fault rocks is notable. Because the irregular veins with tapered ends were probably deformed and the veins with straight edges probably experienced less deformation, the orientation of the veins suggests that veins were initially formed at high angles to the thrust surface and subsequently rotated to lower angles. The scarcity of veins at moderate angles to the fault suggests that deformation may have occurred in stages, probably related to variations in pore fluid pressure. Initials, high pore fluid pressure facilitated the formation of fractures, which were then in-filled by calcite deposits. This cracking would have decreased pore fluid pressure enough to initiate a period of no vein formation in which existing veins were rotated toward the fault surface as shearing continued. Finally, an increase in pore fluid pressure facilitated the formation of new veins. The process may have repeated multiple times. Though veins were also likely initially formed at high angles to the fault in the Copper Creek samples, and subsequently rotated to positions subparallel to the thrust surface, the presence of veins with a variety of orientations suggests that rotation was continuous rather than occurring in discrete stages. The abundance of veins in these samples provides evidence for deformation by diffusion mass transfer, as well as the presence of fluids, which may only have been present at grain boundaries. The dark bands noted subparallel to the thrust surface in all of the samples is likely selvage material derived from mostly-dissolved grains. These features also provide evidence for diffusive mass transfer in all of the samples, including the McConnell thrust rocks, which lack prominent veins. The fractures in the samples from the McConnell thrust are probably associated with stress relaxation as the rocks as overburden was removed and the rocks were ultimately exposed, and are not products of the deformation that produced the fault rock.

The intragranular fractures in the Hunter Valley and McConnell fault rocks are likely the result of cataclastic processes. The lack of these features in the Copper Creek fault rocks signal that cataclasis probably did not contribute heavily to deformation along the Copper Creek thrust. In cracked grains along the Hunter Valley thrust, fractures have a slight tendency to be oriented perpendicular to both the long axis of the grain and the thrust surface. However, because the long axis of grains tends to be oriented at low angles to the thrust surface, it is difficult to say which factor is controlling fracture initiation. In the McConnell thrust, intragranular fractures tend to be oriented oblique to the fault and perpendicular to the long axis of grains. This suggests that grain shape controls fracture initiation. The fact that elongation occurred parallel to the thrust may account for the lack of intragranular fractures oriented perpendicular to the fault. The undulose extinction in some of the quartz grains in the Hunter Valley fault may indicate the occurrence of dislocation creep, but undulose extinction may have developed prior to inclusion in the fault rock, particularly as most quartz grains do not exhibit undulose extinction.

The vorticity numbers generated from the Wallis Plots reveal information about the type of shearing each rock experienced. Applying these values to equation 3 yields the relative contributions of simple and pure shear in each of the samples. In the hunter valley fault, the proportion of shear pure to simple shear is somewhere between 0.36 : 1.0 and 0.55 : 1.0. In other words, pure shear accounted for between 27% and 35% of total strain, while simple shear accounted for between 65% and 73% of total strain. In the Copper Creek thrust, the ratio of pure shear to simple shear is somewhere between 0.62 : 1.0 and 0.82 : 1.0, meaning that pure shear accounted for between 38% and 45% of total strain, while simple shear accounted for between 55% and 62% of total strain. Finally, in the rocks associated with the McConnell thrust, the proportion of pure to simple shear is somewhere between 0.91 : 1.0 and 1.22 : 1.0, so pure shear accounted for between 48% and 55% of total strain, while simple shear accounted for between 45% and 52% of total strain. All of the rocks in this study experienced general shear, but the Hunter Valley and Copper Creek fault rocks experienced general shear with a greater simple shear component, while the McConnell fault rocks experience a general shear characterized by roughly equal amounts of simple and pure shear.

Although the samples in this study originate from three unrelated thrust faults, they provide some insights into fault rocks as a whole. First, the application of survivor grain analysis produced interpretable results with relatively narrow ranges of Rc (and therefore Wk and a), expanding the versatility of this analytical tool. All of our fault rocks experienced general shear, suggesting that this kind of shearing, rather than pure or simple shear, may be the usual case for upper crustal thrust faults in general. However, not all of the fault rocks experienced the same kind of general shear. Simple shear contributed the greatest component of total strain in both the Hunter Valley and the McConnell fault rocks, while pure shear and simple shear contributed roughly equally to total strain in the McConnell fault rocks. Relatedly, all localities in this study experienced moderate convergence angles, rather than nearly 0^o or nearly 90^o convergence angles. However, there was significant variation between each locality. We may expect to see largely shear strain in thrust zones, but macroscopic fault on either side of the fault indicate initial shortening and later elongation subparallel to the thrust surface, which would suggest at least some pure shear component of strain. Furthermore, fault rocks may thicken and thin throughout deformation, so the whole system may be highly dynamic (Woodward & Beets, 1988)

Another implication of our findings is that rocks of similar chemical composition can experience vastly different modes of deformation. All three faults had carbonate material in one wall and siliciclastic material in the other, and all the fault rocks were each composed of a mixture of carbonate and siliciclastic material. However, each of the rocks accommodated shearing differently. The Hunter Valley and McConnell thrust rocks each displayed evidence for both cataclastic and diffusive properties, while the Copper Creek rocks had no evidence of cataclasis, and likely deformed primarily via diffusion and dislocation creep. The factors controlling these variations are likely some combination of the size and chemistry of hanging and footwall grains, grains of previous fault rocks, mean stress, deviatoric stress, pore fluid pressure, and temperature conditions.

Grain size seems to have played a particularly strong role in the samples in this study, such that the rocks may seem to be deforming ductilely at some scales and brittlely at others. In each sample, the finest grains seemed to be ductilely deforming by diffusion mass transfer and diffusion-accommodated grain boundary sliding. This is supported by the absence of grains less than 2 microns in diameter in the Copper Creek and Hunter Valley fault rocks, and below 4 microns in diameter in the McConnell thrust rocks. Diffusive mass transfer preferentially affects smaller grains, which have proportionally larger surface areas (Blenkinsop, 2000), so grains below these threshold values were probably preferentially affected by diffusive processes, with soluble material either removed from the system or deposited in veins, and insoluble materials accumulating along solution seams. However, in the fault rocks of the Hunter Valley and McConnell thrusts, larger grains seemed to be affected by cataclastic processes as well. This pattern suggests that different processes may dominate matrix grains and larger survivor clasts, and highlights the importance of studying deformation at multiple scales. Because both cataclastic and diffusive processes tend to reduce grain size, while deposition of calcite in veins creates large calcite-rich features that can be broken apart to generate new grains, it is possible that calcitic material in the Hunter Valley and Copper Creek fault rocks is being cycled through a variety of grain sizes.

Another problem highlighted by our data is the complexity of "cataclasite" as a descriptive term. Using Sibson's classification (1977), our samples would have been classified as cataclasites due to the lack of visible signs of high-grade metamorphic processes, brittle processes that classically characterize cataclasites do not seem to predominate in any of the fault rocks in this study. Rather, these fault rocks represent conditions that favor neither brittle nor ductile deformation exclusively. Any future classification scheme of fault rocks ought to recognize the complexities of fault rock formation, especially if that scheme is genetic in nature.

CONCLUSION

All of the fault rocks in this study experienced general shear, both simple and pure shear contributing roughly equally to overall shear. Each set of fault rocks also showed evidence for moderate convergence angles. These findings suggests general shear regimes resulting from moderate convergence angles may be common in thrust faults of orogenic belts. The deformation mechanisms, however, varied significantly between thrusts, as well as between various scales within the same fault rock. Though all rocks seemed to have been deformed by diffusive processes, evidenced by features such as veins and selvage seams, the rocks associated with the Hunter Valley and McConnell thrusts displayed evidence of cataclasis as well, while the rocks from the Copper Creek thrusts did not show any evidence of cataclastic processes. The most important factor controlling these variations seems to be grain size, in particular, may have had an important effect as very fine matrix grains seem to be experiencing different deformation mechanisms(namely diffusion accommodated grain boundary sliding) than the large survivor clasts. Another issue highlighted by our study is the inadequacy of the term "cataclasites" for describing cohesive fault rocks of the mid to upper crust. The word "cataclasite" implies cataclasis as a genetic process. However, the so-called cataclasites in this study seemed to be deforming mostly via diffusion mass transfer, with one rock showing no evidence of cataclastic processes at all.

Further study is needed at the very small scale (<1 micrometer) in the McConnell thrusts, as matrix material is too fine to be observed by the equipment used in this study. Additionally, more research is needed to explain why the mechanics of each of the faults in this study produced general shear rather than simple shear conditions. Additional study of survivor clasts may increase understanding of this phenomenon.

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