Cataclasis and the Generation of Fault Gouge

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ABSTRACT

Cataclasis, a friction-dependent mechanism of deformation involving fracture and rigid-body rotation, occurs during faulting of sandstone in the upper crust. Two stages of cataclasis of a sandstone are represented by (1) mildly deformed cataclastic sandstone that is shattered but contains many original grains that have not been fragmented and (2) gouge so severely deformed that the few surviving grains are almost surrounded by a fine-grained matrix of crushed grains. Gouge is restricted to shear fractures and larger slip planes within the natural fault zones, whereas cataclastic sandstone usually pervades the fault zone. Grain size and sorting of gouge decrease as a function of increasing confining pressure and increasing displacement along a shear fracture. In cataclastic sandstone associated with gouge, microfractures are strongly oriented parallel to the maximum principal compressive stress. These microfractures, which are extension fractures, may be used to determine the orientation of the stress field during faulting. Rigid-body rotation is important during cataclasis, and grains rotate in a manner that agrees with the sense of shear on the fault plane. *Key words: structural geology, experimental petrology, cataclasis, fault gouge.*

INTRODUCTION

Cataclasis, a friction-dependent mechanism of brittle deformation involving both fracture and rigid-body rotation (Borg and others, 1960; Griggs and Handin, 1960), is a mechanism of both faulting and macroscopic flow in the upper crust (Stearns, 1969). Fault gouge is a common product of cataclasis at low pressures and temperatures. Cataclasis also occurs at depths where neomineralization and recrystallzation are competing deformational processes during the generation of mylonite and blastomylonite (Higgins, 1971). Because this paper focuses on cataclasis, attention is given to the generation of fault gouge rather than higher temperature-pressure types of cataclastic rock in which other deformational effects mask effects due to cataclasis.

Work is expended to overcome frictional resistance in the cataclastic deformation of rocks along the fault contact. Estimates of the frictional resistance of faults are made using experiments on rocks with planar sliding surfaces on which a limited amount of cataclasis occurs (Jaeger, 1959; Byerlee, 1967). However, natural faults usually contain much greater thicknesses of gouge than that generated during laboratory experiments (Handin, 1972). In light of this discrepancy between experimental and natural faults, attempts to refine laboratory data on the frictional properties of faults must take into account the effect of cataclasis and the generation of fault gouge.

This paper describes cataclastic deformation by documenting the (1) fabric and texture and (2) generation and deformation of quartz fault gouge through field, microscopic, and experimental observations of natural and experimentally produced fault zones in quartzose sandstone. Natural textures and fabrics discovered in this study are used as a control in designing geologically reasonable sliding friction experiments with quartz gouge. In another paper, the experimentally determined frictional characteristics of sandstone sliding on quartz gouge are presented in detail (Engelder, 1974).

Quartz gouge and faults in sandstone were studied for several reasons: the quartz gouge is easier to work with in the laboratory compared to clay and shale; it is monomineralic; its optical properties simplify petrographic observations; it is a common type of gouge in nature; and stick-slip sliding, a possible mechanism for shallow earthquakes, occurs on fractures in quartzose rocks (Brace and Byerlee, 1966; Logan and others, 1973).

CHARACTERISTICS OF NATURAL QUARTZ GOUGE

Specimens from four fault zones were used to characterize the texture and fabric of quartz gouge: (1) the Bonita fault, a normal fault near Tucumcari, New Mexico, with gouge in the Mesa Rica Sandstone (Cretaceous); (2) the Muddy Mountain fault, a low-angle thrust near Glendale, Nevada, with gouge in the Aztec Sandstone (Jurassic); (3) the Hurricane fault, a high-angle fault near Pintura, Utah, with gouge in the Coconino Sandstone (Permian); and (4) a high-angle reverse fault on the north flank of the Uinta Mountains near Manila, Utah, with gouge in a sandstone of the Uinta Mountain Group (Precambrian). Based on field and subsequent petrographic work, quartz gouge is described relative to the mechanism of generation, grain size and sorting, generation during displacement, and orientation of microfractures within the fault zone.

Cataclastic Deformation

The primary mechanism for the generation of quartz gouge is cataclasis — the granulation of individual grains by fracturing and the rigid-body rotations of grains and fragments. There is no evidence of gliding or recrystallization flow in any of the natural quartz gouges examined. Any sandstone containing highly fractured grains has a cataclastic texture (Fig. 1A); however, the term gouge is restricted to those sandstones within which cataclastic de-

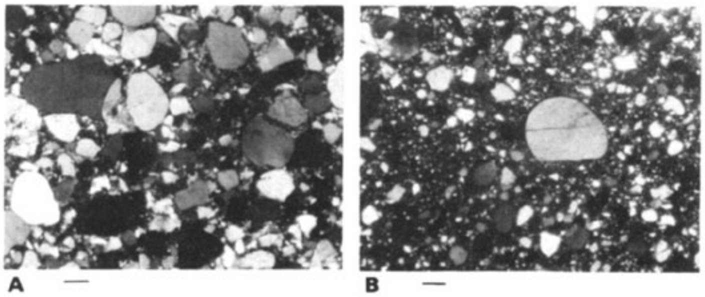

Figure 1. Aztec Sandstone with cataclastic textures. A, Cataclastic sandstone. B, Quartz fault gouge. Scale lines are 0.02 cm; crossed polarized light.

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Geological Society of America Bulletin, v. 85, p. 1515–1522, 14 figs., October 1974

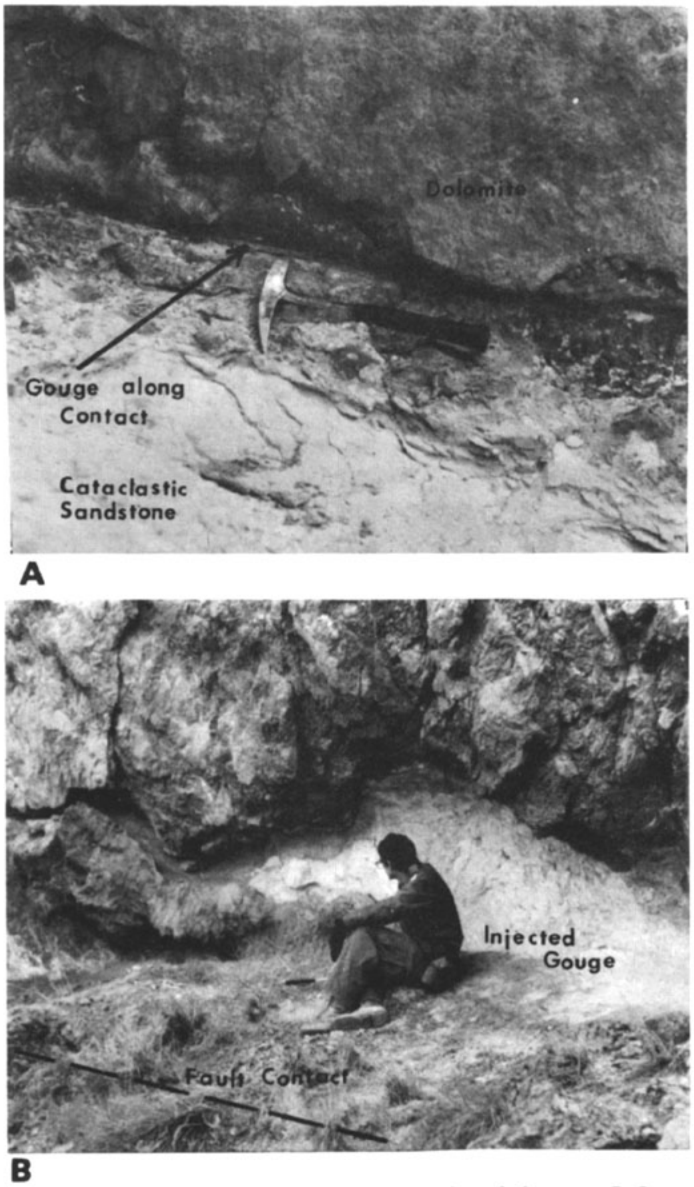


Figure 2. Muddy Mountain thrust fault zone. A, Planar fault contact. B, Quartz gouge injected into upper plate.

formation is so severe that any surviving grains are nearly surrounded by a fine-grained matrix of crushed grains (Fig. 1B). It is shown in Appendix 1 that natural gouge generated from sandstones whose median grain size is initially 200 μm consists of less than 30 percent by volume of fragments larger than 100 μm. The term cataclastic sandstone is used for sandstones that have a cataclastic texture but are less severely deformed than gouge. This distinction between cataclastic sandstone and gouge is equivalent to Higgins' (1971) classification of cataclastic rocks without post-faulting cohesion; a fault breccia has more than 30 percent by volume of coarse fragments (that is, original fragments and grains), whereas a fault gouge has less than 30 percent.

Grain Size and Sorting

Cataclastic deformation of the Aztec Sandstone in the vicinity of the Muddy Mountain thrust fault is typical of the four faults listed above. The late Mesozoic Muddy Mountain thrust fault has placed Cambrian Goodsprings Dolomite in the upper plate over Jurassic Aztec Sandstone or a forethrust debris in the lower plate (Longwell and others, 1965; Fig. 2A). The total slip on the fault is a minimum of 24 km. The zone of deformation (that is, fracturing and cataclasis) associated with this fault extends as much as 75 m down into the Aztec Sandstone and more than 100 m up into the Goodsprings Dolomite. However, the major cataclastic deformation and shear displacement along the fault is restricted to a gouge zone 5 to 20 cm thick at the fault contact (Fig. 2A). This planar contact with a narrow gouge zone is visible for several hundred meters of outcrop.

The nature of cataclastic deformation in the vicinity of the Muddy Mountain thrust fault is illustrated by the cumulative frequency curves in Figure 3. (The method for determining cumulative frequency curves, as well as a justification for using just five data groups for plotting the curves, is discussed in Appendix 1.) Undeformed Aztec sandstone (curve I) contains well-rounded quartz grains, few of which are less than 100 μm in diameter. Cataclastic fragments are found in the sandstone as much as 75 m from the fault contact (curve II). In this case, the poorer sorting of the finer portion indicates a cataclastic sandstone. Within a meter of the fault contact, cataclasis pervades the sandstone, as indicated by a well-developed fine-grained matrix (curve III). The surviving large grains are angular and contain several fractures (Fig. 1A). The poorly cemented sample taken right at the contact (Fig. 3, curve V) is even finer grained, and it represents a fault gouge. Although the zone of cataclastic deformation extends well down into the sandstone, the zone of intense shearing is rarely more than 1 m and generally only 5 to 20 cm thick. Curve V for gouge at the contact shows that no more than 6 percent of the original 200-μm grains have survived the deformation.

Mobility of fault gouge is demonstrated by its injection upward into cracks in the dolomite of the upper plate (Fig. 2B). This material (Fig. 3, curve IV) contains the largest percentage of fragments of less than 25 μm. Evidently, the movement of gouge from its source favors the concentration of finer fragments because either the injected material is subjected to more cataclastic deformation during movement, or the flow process acts as a filter that somehow partially excludes the coarser fractions.

Cataclasis is so intense near the Muddy Mountain thrust fault contact that gouge in shear fractures is not distinct from the surrounding cataclastic sandstone. (In this context, a shear fracture is any fault with a displacement arbitrarily less than 10 cm.) In the Bonita fault zone, gouge along shear fractures in the fault zone may be distinguished from that found in genetically related cataclastic sandstone.

The Bonita fault, located about 25 km southeast of Tucumcari, New Mexico, is a normal fault with a throw of about 150 m (Stearns, 1972). Its zone is as much as 60 m wide in the Mesa Rica Sandstone, and it consists of the main fault, some subsidiary faults with throws of less than 10 m, and many shear fractures.

Cumulative frequency curves for the Mesa Rica Sandstone at Bonita fault further illustrate the textural changes accompanying gouge development. Cataclastic deformation is observed within 40 m of the fault contact (Fig. 4, curve II). The median grain size decreases, and the sorting becomes poorer as more gouge develops within a subsidiary fault 30 m from the main fault contact. The median grain size of the gouge within this small subsidiary fault with about 5 m of displacement (curve III) is nearly the same as that within a shear fracture with only 2 cm of offset (curve IV), and the finer portion of curve III possesses the same distribution as curve IV. However, gouge within shear fractures has a smaller volume of grains larger than 50 μm than gouge samples from larger faults within the Bonita fault zone.

Generation of Gouge during Displacement

Generation of quartz gouge may be related to displacement of a shear fracture or fault. However, the random measurement of gouge thickness along shear fractures does not indicate a clear relation between thickness and displacement, as illustrated in Figure 5.

One reason for the scatter in gouge thickness as a function of displacement is that shear fractures often bifurcate into subfractures that may also bifurcate. Bifurcating shear fractures are called braided shear factures primarily because subfractures can be seen crossing several times in the outcrop (Fig. 6). At points where the fracture divides into subfractures, the over-all distance across the zone of subfractures is not the true measure of gouge width; intact sandstone is found between the subfractures. In addition, because of the bifurcation, random sampling of a braided shear fracture would occur at a point with an unknown fraction of the maximum gouge thickness.

Indications are that the sum of gouge thicknesses across the location of maximum number of subfractures is the *true* maximum gouge thickness. But direct measurement of the gouge thickness within each subfracture is impractical because individual subfractures are too narrow to measure accurately in outcrop, and sampling for thin sections on a plane surface is nearly impossible. For these reasons, the generation of gouge during displacement is assessed by counting the maximum number of subfractures in one cross section of a shear fracture exposed in the face of an outcrop. The maximum number of subfractures in the length of an exposed braided shear fracture is representative of the generation of gouge because it gives a reasonable indication of the thickness of gouge generated within a fracture.

Subfracture counts were made within the Hurricane fault zone and on the north flank of the Uinta Mountains. Near Pintura, Utah, the Coconino Sandstone of the Hurricane fault has been stably folded over the eastern uplifted block of the Hurricane fault. The folded section of the Coconino Sandstone dips as much as 64° to 85° to the west, and it has been thinned by extension. Within the attenuated portion, domains of shattered sandstone are separated by less deformed domains that contain conspicuous shear fractures. Although the offset of fractures may not represent total displacement, fractures offset other fractures; these offsets were used to measure displacements within both domains.

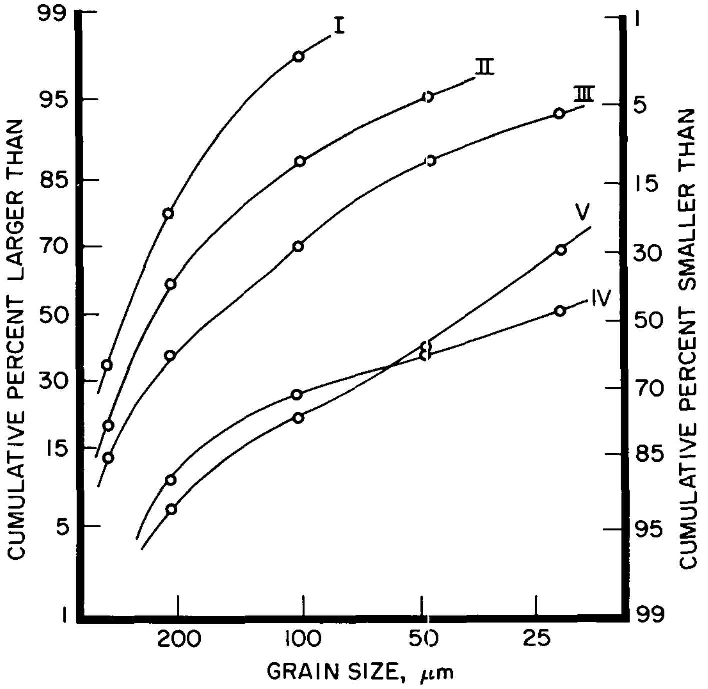


Figure 3. Cumulative frequency curves for Aztec Sandstone in vicinity of Muddy Mountain thrust fault. Each curve is based on 300 apparent long axes. Curve I, undeformed Aztec Sandstone; curve II, cataclastic sandstone 75 m from fault contact; curve III, cataclastic sandstone 1 m from fault contact; curve IV, fault gouge injected into upper plate of thrust fault; curve V, fault gouge at fault contact.

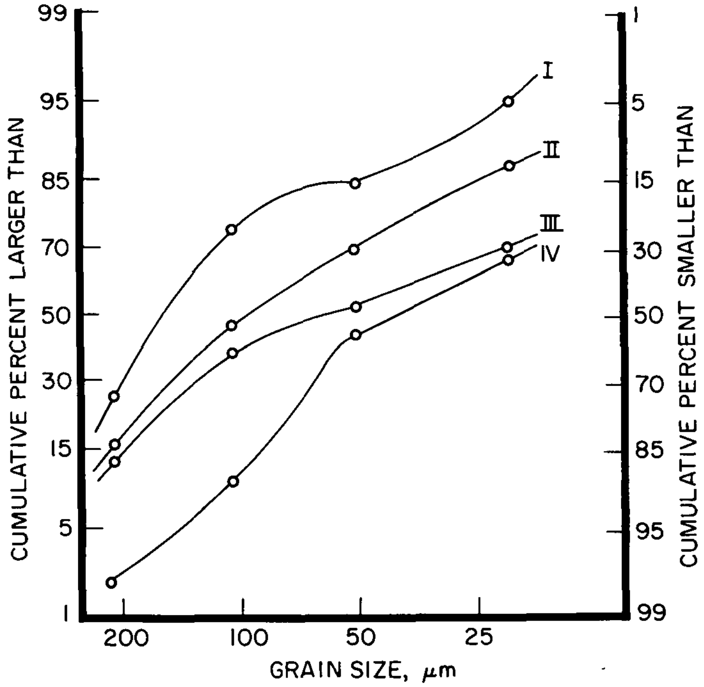


Figure 4. Cumulative frequency curves for Mesa Rica Sandstone in vicinity of Bonita normal fault. Curve I, undeformed Mesa Rica Sandstone; curve II, cataclastic sandstone 1 m from minor fault in fault zone; curve III, gouge along minor fault in fault zone; curve IV, gouge within a shear fracture with 2 cm of offset.

Sandstone of the Uinta Mountain Group is folded over a high-angle reverse fault in Sheep Creek Canyon on the north flank of the Uinta Mountains. In this case, the folded section is not shattered, but numerous shear fractures could be found. Here, braided shear fracture displacement was measured using bedding plane offsets.

There is a direct relation between the number of subfractures and total displacement in shear zones observed along these faults (Fig. 7). If it is assumed that each subfracture represents the generation of a given thickness of gouge, it can be argued that the volume of gouge increases directly with displacement up to at least 5 cm. These observations agree with experimental work, but they contrast with some field observations that show no relation between the amount of displacement (>10^3 cm) and the volume of gouge (Handin, 1972). However, the earlier results relate to major faults,

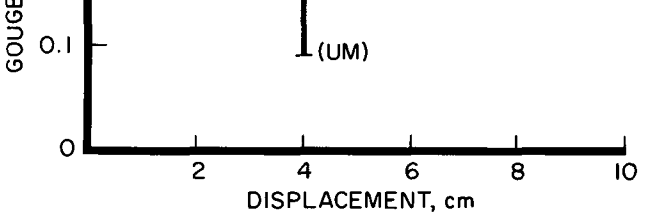


Figure 5. Thickness of natural gouge versus displacement in five sandstones. UM, Uinta Mountain Sandstone; N, Navajo Sandstone, from north flank of Uinta Mountains; C, Coconino Sandstone, from Hurricane fault; MR, Mesa Rica Sandstone, from Bonita fault. Top and bottom of each vertical line indicate maximum and minimum gouge thickness within portion of shear fracture from which thin section was cut.

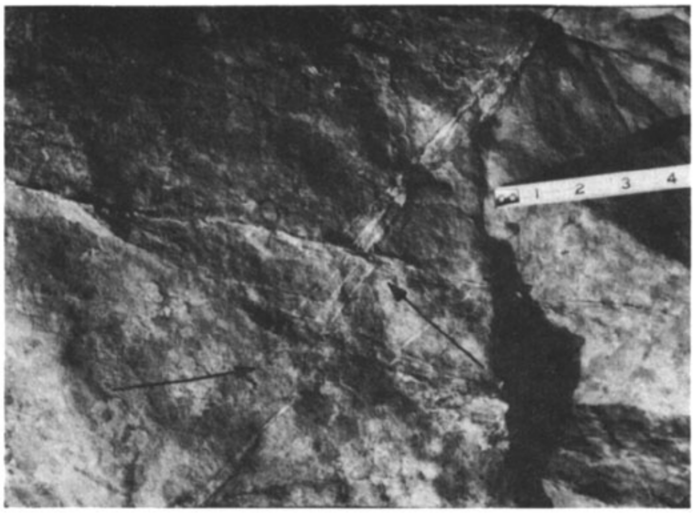


Figure 6. Braided shear fractures from Bonita fault zone. Set of three subfractures within one braided shear fracture is offset several times by second braided fracture (arrows).

whereas the present observations are restricted to shear fractures. Apparently, the volume of gouge increases with increasing displacement to some as yet unknown value.

Microfracture Orientations

The orientations of microfractures associated with cataclastic sandstone and gouge were measured for comparison with the orientation of inferred directions of principal stresses during faulting. Microfracture data from two or three mutually perpendicular thin sections show statistically that one major set of microfractures forms during faulting. This microfracture set is oriented so that it intersects the fault in a line perpendicular to the displacement direction along the fault. Therefore, microfracture data from one thin section, cut perpendicular to the plane of the fault and containing the displacement direction, accurately represents the orientation of the major set. All microfractures within fractured grains are measured unless otherwise specified. Microfractures usually are preserved in larger grains that were not fragmented by cataclasis. For this reason, the microfracture fabrics come from cataclastic sandstone next to gouge zones rather than from the gouge. (For an illustration of experimentally produced microfracture next to a gouge, see Figures 8, 11, and 12 in Dunn and others, 1973).

Near a shear fracture with 3 cm of displacement and a 0.4-cm thick layer of gouge within the Coconino Sandstone adjacent to the Hurricane fault, the microfractures are oriented at 29° to the shear plane (Fig. 8A). These microfractures are within the intact rock and are located within 10 grain diameters (0.2 cm) of the shear plane. They are oriented so that the apices of the acute angles between them and the shear plane point in the correct sense of shear for the fracture. The microfracture planes are generally oriented within 10° of the inferred direction of σ_1, which is oriented vertically for normal faulting such as that found along the Hurricane fault. This preferred orientation of microfractures is common near other shear fractures in the Hurricane and Bonita fault zones.

Microfractures within a cataclastic sandstone are often distributed over a broader range of orientations than those found next to an isolated shear fracture. For example, certain microfractures within cataclastic sandstone next to the Bonita fault are preferentially oriented almost vertically and parallel to the strike of the fault (Fig. 8B). These microfractures are parallel to macroscopic extension fractures whose planes may be traced for many meters on the outcrop face. Macroscopic extension fractures form during faulting but are not necessarily restricted to the immediate vicinity of the fault. Other microfractures, however, are oriented nearly parallel to shear fractures conjugate to the Bonita fault. In general, there is a slight to strong preferred orientation of microfractures within a girdle whose axis is parallel to the strike of the Bonita fault. These data indicate that the microfracture orientation pattern for cataclastic sandstone at the Bonita fault is more complex than that next to a shear fracture from the Hurricane and Bonita faults.

EXPERIMENTS ON THE GENERATION AND DEFORMATION OF QUARTZ GOUGE

Triaxial compression tests were conducted on two types of sandstone cylinders to evaluate the effect of confining pressure and displacement on the texture and fabric of quartz gouge and to gain a better understanding of the observations made on natural quartz gouge. The triaxial apparatus used for these experiments is described in Handin and others (1972).

Cylinders (5-cm diameter by 10 cm) of intact Coconino Sandstone were fractured and shortened in different amounts by sliding along the induced fractures to simulate the natural development of fault gouge from host rock. These tests were done at confining pressures to 0.5 kb and a displacement rate along the fracture of 10^{-3} cm/sec. The ends of the specimens are ground parallel to within 0.001 cm. A 0.6-cm thick steel spacer powdered with MoS_2 on both sides was placed between the specimen and the upper piston to decrease friction between them and improve reproducibility. The 5- by 10-cm specimens were then jacketed by heat-shrink, polyolefin sleeves.

In other experiments, cylinders of Tennessee Sandstone were precut at 35° ± 0.2° to the cylinder axis and ground to ±0.1° with an 80-grit wheel. Quartz grains between 100 and 250 μm in diameter were evenly distributed in a 0.20-cm layer along the preliminary cut by pulling half the precut sample from the jacket, pouring sand on the sliding surface, and replacing the sample. Upon application of the confining pressure and as sliding of the precut cylinder on the quartz grains progressed under differential stress, the quartz grains were cataclastically deformed to form gouge. In contrast with Coconino Sandstone, the Tennessee Sandstone is strong enough so that the precut sample did not deform cataclastically and contribute to the thickness of the gouge. These experiments were used to

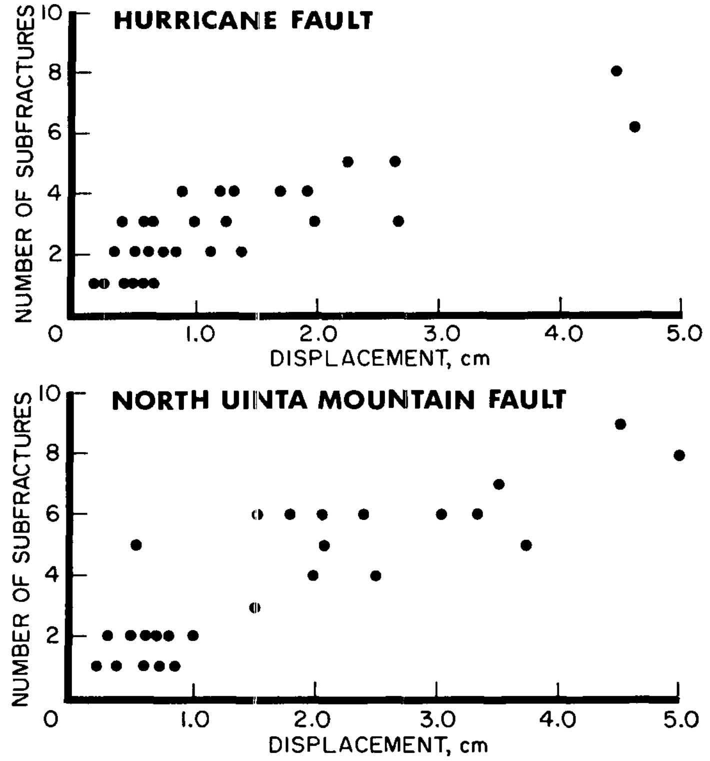


Figure 7. Plot of number of subfractures versus total displacement along shear fracture from Hurricane fault zone and fault on north flank of Uinta Mountains.

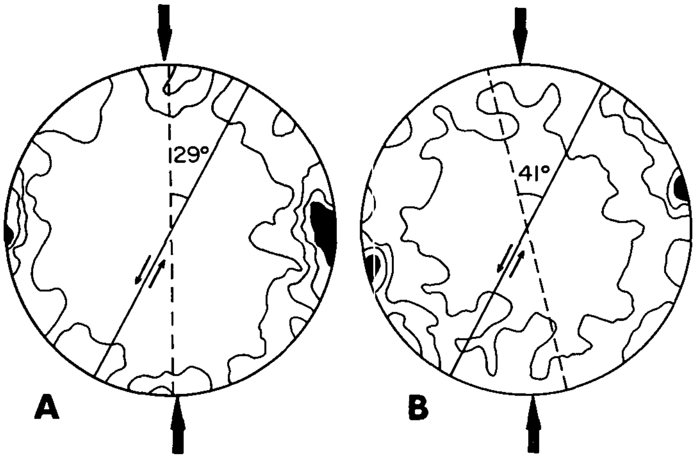


Figure 8. Diagrams illustrate orientation poles of microfractures within grains of naturally fractured or cataclastically deformed sandstone. Plane of each diagram perpendicular to macroscopic shear fracture; data plotted in equal-area, lower hemisphere projection. Contours at 9 percent, 6 percent, 3 percent, and 1 percent per 1 percent area. Solid line represents plane of shear and dashed line represents orientation of maximum concentration of microfractures. Sense of shear indicated along plane of shear. Vertical arrows represent inferred direction of σ_1. A, Normals to 100 microfractures in intact Coconino Sandstone next to shear fracture in Hurricane fault (15 percent per 1 percent area maximum). B, Normals to 168 microfractures in cataclastic sandstone next to Bonita fault (11 percent per 1 percent area maximum).

evaluate the effect of confining pressure to 3.0 kb and displacement to 0.6 cm on a layer of gouge of constant thickness.

Generation of Gouge as a Function of Displacement

In thin sections of experimentally fractured Coconino Sandstone, minimum and maximum thicknesses within the sliding zone were observed to increase systematically with displacement (Fig. 9). This is because quartz grains are continuously torn from asperities on the sliding surface and incorporated in the layer of gouge during sliding. Jackson and Dunn (1974) reached this conclusion concurrently.

If one equates the slope of the line fit to the data for number of subfractures versus displacement in the field (Fig. 7) with the slope of the line for average thickness versus displacement data for experimentally generated gouge in Coconino Sandstone (Fig. 9), each subfracture would have a thickness of about 0.005 cm. This agrees with thin-section measurements of a few natural subfractures that show thicknesses of 0.005 ± 0.002 cm.

A functional relation also exists between the mean thickness of experimentally generated gouge and the shear displacement of the intact specimen (Fig. 9). For Coconino Sandstone fractured at 0.5-kb confining pressure,

$$d_s = 8t,$$

where d_s (cm) is the shear displacement and t (cm) is the mean thickness of the gouge zone. Here the volume (that is, thickness) of gouge increases during sliding because asperities are sheared off, crushed, and incorporated into the gouge. There are practical limits to the usefulness of this linear relation, as illustrated by the Muddy Mountain thrust, which has a displacement of several tens of kilometers. Jackson and Dunn (1974) suggest that when the gouge is thick enough to blanket the largest asperities, no new gouge need be produced.

Grain-Size Distribution in Experimental Gouge

The transformation of sand to gouge between precut surfaces of Tennessee Sandstone at 0.5-kb confining pressure is accompanied by a systematic decrease in grain size and sorting as sliding takes place (Fig. 10). Cataclastic deformation begins upon application of confining pressure (curve H). During initial differential loading, but before sliding begins, there is additional fracturing and crushing (curve 0.00 cm). Once sliding occurs, the grain size decreases still further (as represented by curves labeled 0.11 cm and 0.27 cm of displacement). The steep portions of these cumulative curves indicate the survival of relatively large original grains within the fine-grained gouge. At about 0.44 cm of displacement, the fine-grained fraction of the gouge has been generated. Between 0.44 and 0.64 cm, the grains between 100 and 200 μm in diameter are reduced without appreciably affecting the distribution of those less than 50 μm.

Cataclasis can be expressed quantitatively. A functional relation exists between the median grain size of a 0.12-cm thick layer of experimental gouge and the shear displacement of the precut sandstone at 0.5-kb confining pressure. The median grain size changes rapidly for about the first 0.3 cm of displacement and then asymptotically approaches about 20 × 10^{-4} cm as displacement progresses to 0.7 cm. The curve that approximates this relation between median grain size (M cm) and displacement (d_s cm) is

$$M = 0.0126\, e^{-51 d_s} + 0.0056\, e^{-6 d_s} + 0.0018.$$

This equation reflects the combined effects of at least two events.

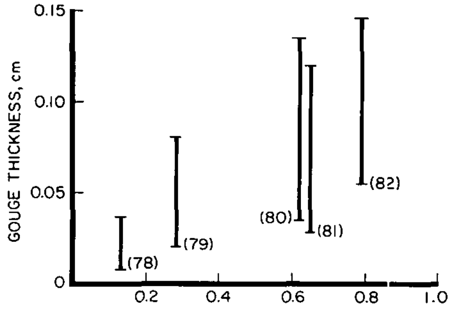


Figure 9. Gouge thickness versus displacement along sliding surface. Maximum and minimum gouge thickness along each shear fracture designated by top and bottom of each vertical line.

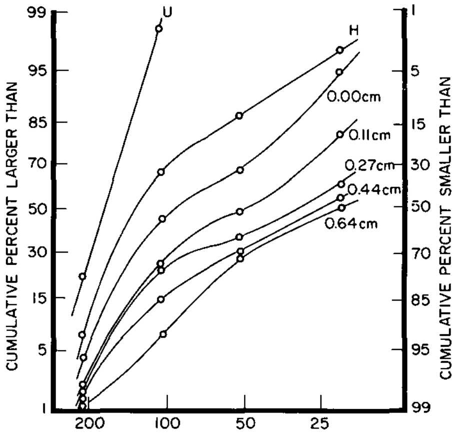


Figure 10. Cumulative frequency curves for development of compacted 0.12-cm thick layer of quartz gouge as function of displacement at 0.5-kb confining pressure. Numerical labels on curves indicate centimeters of displacement of sample under differential load. U, undeformed sand; H, sand loaded hydrostatically.

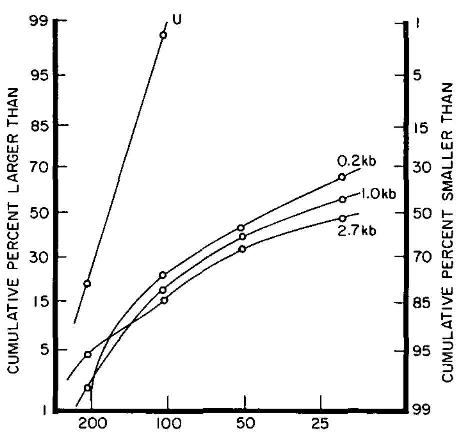


Figure 11. Cumulative frequency curves for development of compacted 0.12-cm thick layer of quartz gouge as function of confining pressure. Numerical labels on curves indicate confining pressure. U, undeformed sand.

Initially, fracturing and milling of grains reduces the size rapidly. Then the translation and rotation of particles as rigid bodies without much milling result in a decrease in rate of change of median size. Qualitative observations of gouge from other experiments indicate that the position of this curve in $M-d_s$ space is probably different for displacements at different confining pressures, gouge thicknesses, and pore fluids.

The grain-size distribution of experimental gouge is sensitive to the confining pressure at which it forms. For a suite of three experiments with the same displacement at 0.14-, 1.0-, and 2.7-kb confining pressure, respectively, the gouge becomes progressively finer grained with increasing confining pressure (Fig. 11). The effect of confining pressure has not been documented in nature because in none of the field areas could overburden pressure and pore fluid pressure be established unequivocally or its effect isolated from other parameters. However, it is possible that with a careful study, a gouge formed under a greater depth of burial may be distinguished by its finer grain-size distribution.

Microfracture Orientation

Microfracture orientations in quartz gouge and cataclastic sandstone next to a shear fracture give an indication of the orientation of the stress field in which the gouge is formed. Microfractures within experimentally fractured Coconino Sandstone are oriented within 5° of σ_1, and they are inclined at 30° to 40° to the plane of the shear fracture (Fig. 12A). These microfractures are probably extension fractures that propagate between grain contacts where high stress concentration occurs and follow the trajectories of σ_1 within porous aggregates (Gallagher, 1971). Micrographs of these fractures are displayed in Friedman and Logan (1970) and Dunn and others (1973). They generally form within ten grain diameters (0.2 cm) away from the shear plane. Many are formed after the initiation of the shear plane, as indicated by a migration of microfractures into the sample as the gouge zone widens with displacement. Microfractures within grains that are starting to tear from the intact rock and, therefore, possibly rotate are not measured.

Within the layer of gouge sheared between precut surfaces of Tennessee Sandstone, microfractures are found within the coarser grains. The finer grains are fragments of coarser ones that have already broken apart along microfractures. Microfractures are oriented statistically between 30° and 50° to the sliding surface, so that their planes are at a small angle to the direction of σ_1. These microfractures are also probably extension fractures that propagate between grain contacts where high stress concentration occurs.

The preferential orientation of the microfractures varies with experimental parameters, particularly displacement. For example, at 0.5-kb confining pressure and a displacement rate of 10^{-3} cm/sec, for 0.27 cm of displacement, the microfractures form a distinct grouping oriented 34° to the sliding surface (Fig. 12B). As displacement progresses to 0.44 cm, the fabric maximum becomes less intense (Fig. 12C). At the same time, the maximum concentration rotates from 34° to 42°. In gouge displaced 0.75 cm, the maximum has rotated to 56° to the sliding surface and reflects the greater displacement. The sense of these progressive rotations of the microfracture maxima agrees with the known sense of shear. As the maximum concentration of microfractures rotates away from the sliding surface, the microfracture orientation pattern becomes progressively more diffuse and forms a broad peripheral girdle. These data indicate that the angle between the microfractures and the adjacent macroscopic shear plane increases with increasing displacement, but that the strength of the microfracture orientation pattern decreases. On the assumption that the microfractures form early and are then rotated, these data document the sense of grain rotation during shearing.

Another experimental parameter that influences the fracture fabric is confining pressure. Within compacted gouge sheared at 1.0-kb confining pressure and displaced 0.38 cm, the microfractures are oriented closer to the shear plane (Fig. 12E) than are those at 0.5 kb and 0.44 cm displacement (Fig. 12C). The maximum concentration of microfractures, formed at 1.0-kb confining pressure but with only 0.25 cm of displacement, has about the same orientation as does the gouge displaced 0.38 cm. Thus at 1.0 kb, the maximum concentration does not rotate with a shear displacement of at least 0.38 cm. This lack of evidence for grain rotation suggests that

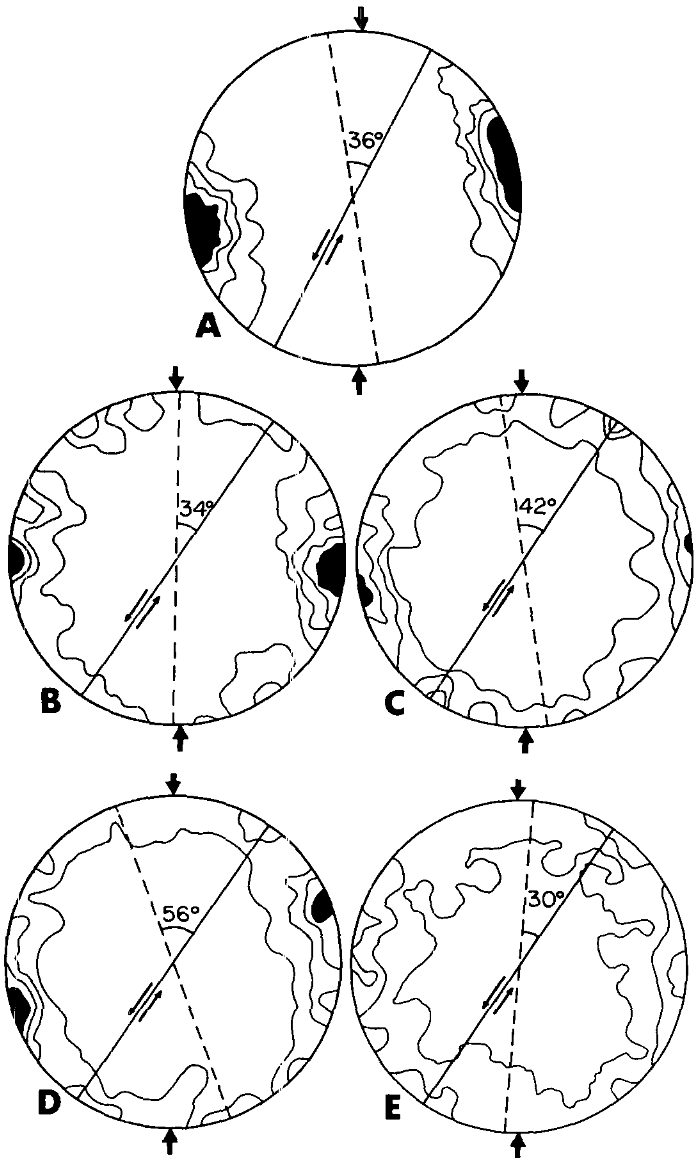


Figure 12. Orientation of sets of microfractures within grains of experimental fault gouge generated from sand grains. Plane of each diagram is perpendicular to macroscopic shear fracture; data are plotted in equal-area, lower hemisphere projection. Contours at 9 percent, 6 percent, 3 percent, and 1 percent per 1 percent area. Solid line represents plane of shear and dashed line represents orientation of maximum concentration of microfractures with angle between lines denoted. Sense of shear indicated along plane of shear. Vertical arrows represent direction of σ_1 at boundary of the specimen. A, Normals to 100 microfractures in intact Coconino Sandstone next to shear fractures (16 percent per 1 percent area maximum). B, Normals to 92 sets of microfractures in gouge generated at 0.5-kb confining pressure with 0.27 cm of displacement of intact sandstone (15 percent per 1 percent area maximum). C, Normals to 152 sets of microfractures in gouge generated at 0.5-kb confining pressure with 0.44 cm of displacement of intact sandstone (10 percent per 1 percent area maximum). D, Normals to 114 sets of microfractures in gouge generated at 0.5-kb confining pressure with 0.75 cm of displacement of intact sandstone (10 percent per 1 percent area maximum). E, Normals to 150 sets of microfractures in gouge generated at 1.0-kb confining pressure with 0.38 cm of displacement of intact sandstone (8 percent per 1 percent area maximum).

grains containing fractures have a higher probability of breakup. The data shown in Figure 11 indicate that larger grains containing microfractures are less likely to survive shearing under 1.0-kb than 0.5-kb confining pressure.

Cataclastic flow within the experimental gouge is suggested by the peeling of an iron oxide stain from large grains within the gouge (Fig. 13). Cataclasis is an abrasive process that removes the oxide cover from the grains. The oxide is distributed within the gouge in a manner suggesting that the finer fragments translate relative to the coarser ones. The direction of flow of the iron oxide also agrees with that expected from the known sense of shear.

DISCUSSION

Process of Cataclasis

The cataclastic deformation of sandstone is defined as the granulation of individual grains by fracturing and the rigid-body rotations of grains and new fragments (Borg and others, 1960). The data presented here demonstrate the role of cataclasis in gouge formation and in the faulting process. The microfracturing is conspicuous to direct observation, and it is also manifest in grain-size and sorting changes and gouge thickness changes. The nature of the rigid-body rotations is evident in the orientations of microfractures generated within grains of the experimental quartz gouge that has been sheared by different amounts between precut surfaces of sandstone. For specimens with less than 0.3 cm of displacement, the orientation of the maximum concentration of microfractures is 35° from the precut surface. Hence, it is parallel to σ_1 across the boundaries of the specimen (Fig. 12B). For specimens with more displacement, the angles are greater (Fig. 12C). Because most microfractures form as extension fractures, they form parallel to the maximum principal stress, which is 35° from the precut surface. Therefore, microfractures at angles greater than 35° to the precut surface form within grains as extension fractures. They subsequently rotate with the grain as displacement of the precut surface progresses beyond 0.3 cm (Fig. 13). The sense of rotation agrees with the known sense of shear. Thus, normals to microfractures within natural cataclastic sandstone and gouge concentrate in a girdle because grains and fragments rotate about an apparent axis of rotation during pervasive cataclasis.

Cumulative Frequency Curves

Cataclastic sandstone and fault gouge have characteristic cumulative frequency curves resulting from the relative difference in intensity of cataclastic deformation of the two. The cataclastic sandstone shows a fine-grained portion that is more poorly sorted than its coarser fraction, thus the curve is skewed to the larger grain sizes. In some instances, fault gouge has a bimodal distribution of grain sizes, and in others gouges have unimodal distributions. A skewed curve for the cataclastic sandstone represents the comminution of just a small portion of the original grains. A bimodal curve for the gouge represents a cataclastic grain-size reduction of a major portion of the original material. In this case, the remaining original grains yield one mode and the small fragments the other. A bimodal gouge should not be confused with a bimodal sandstone found in deflationary deserts (Folk, 1968a). A unimodal curve represents a gouge with about all of the original grains reduced.

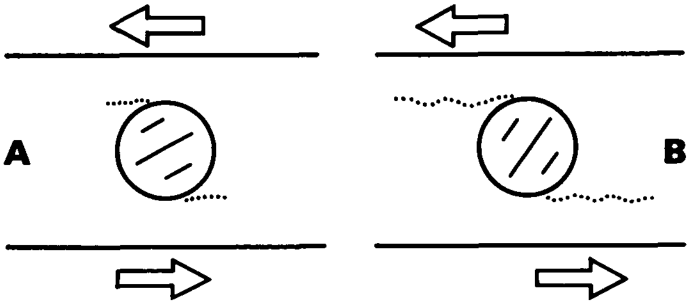


Figure 13. Illustration of rotation of ideal quartz grain within aggregate flowing cataclastically. Dots represent coating film of oxide being peeled off ideal grain. Arrows indicate sense of shear for boundary surfaces of precut sandstone.

As the gouge is generated during displacement along the precut surfaces, the grain-size distributions correspond to those of natural cataclastic sandstone (compare Fig. 3, curves II and III; Fig. 10, curve 0.64 cm). The curves are similar even though natural gouge is generated by tearing fragments from the host rock, whereas the experimental gouge is generated by shearing sand placed between flat surfaces that do not contribute material to the gouge.

Generation of gouge is accompanied by a decrease in median grain size and usually a deterioration in sorting, as illustrated for the Aztec Sandstone of the Muddy Mountain thrust fault (Fig. 3). A deterioration in sorting is indicated by a decrease in slope of the cumulative frequency curve. However, host rock and gouge may have about the same sorting as the gouge of the Bonita fault (Fig. 4).

Comparisons between original grain-size distribution and that of gouge reveal the relative differences in gouge development or — what is equivalent — the differences in the intensity of the cataclastic deformation. The relative intensity of cataclasis is best represented by the change in median grain size. A large change in sorting may occur with just a small change in median grain size during incipient cataclasis and the generation of a cataclastic sandstone. In contrast, intense cataclasis may reduce a sandstone to a gouge and thus reduce the median grain size without affecting the sorting.

Deformational Environments

The ability to determine environmental parameters may help to decipher the tectonic history of an area. Careful experimental work demonstrates the effect of displacement and confining pressure on the texture and fabric of quartz gouge. If this data can be extrapolated to natural faults, parameters such as confining pressure at the time of faulting might be inferred. But because the texture and fabric of gouge may vary with both confining pressures and displacement, one parameter must be known before the other may be inferred from the texture and fabric.

The orientation of the stress field during faulting may be determined with the microfracture fabric of cataclastic sandstone. Microfractures form as extension fractures parallel to σ_1 and at about 30° to fault surfaces. Once formed, the microfractures tend to rotate about an axis normal to the plane containing σ_1 and the movement vector of the fault. The sense of rotation agrees with the known sense of shear. This is an independent check on both the orientation of the stress field and the sense of shear of the fault. This method is more likely to work for cataclastic sandstone because the rolling of fractured grains is often too extensive to give a strong fabric maximum.

SUMMARY AND CONCLUSIONS

Natural quartz gouge develops at low temperatures and pressures in the upper crust primarily as a result of cataclasis. The volume of gouge increases to some unknown amount of displacement and then remains essentially constant. Development of natural gouge involves a decrease in grain size and sometimes a deterioration of sorting.

Cataclastic sandstone associated with gouge has a strong microfracture fabric; the microfractures form as extension fractures parallel to σ_1. The microfracture fabric thus may be used to determine the orientation of the stress field during faulting.

Experimentally generated gouge resembles its natural counterparts in (a) grain-size distribution after 0.44-cm displacement; (b) texture — some large, rounded original grains tend to survive and become completely incorporated by the fine-grained cataclastic matrix; and (c) internal fabric — microfractures are oriented in the plane defined by σ_1 and the direction within sliding plane perpendicular to the sliding direction.

The grain size and sorting of experimental gouge decrease with increasing confining pressure and increasing displacement.

During cataclastic deformation, individual grains rotate within the gouge, and the sense of rotation agrees with the known sense of shear.

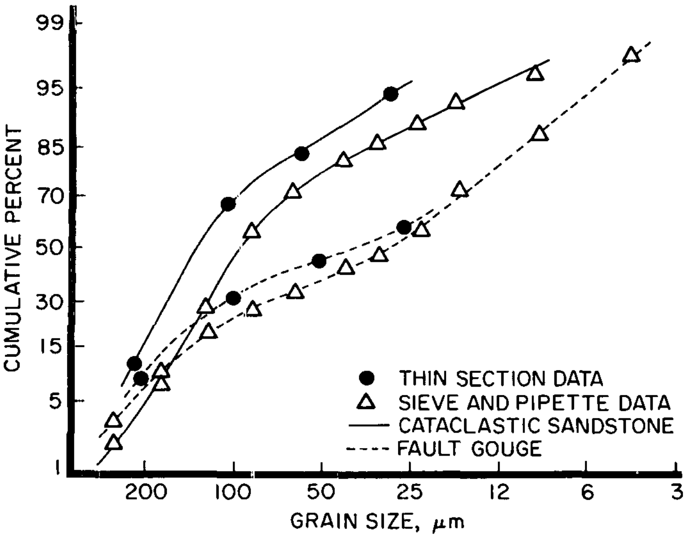
ACKNOWLEDGMENTS

This work was primarily supported by the U.S. Geological Survey and Advanced Research Projects Agency Order no. 1684, Contract no. 14–08–0001–12723. Work done at Lamont-Doherty Geological Observatory, Palisades, New York, was supported by the National Science Foundation, contract GA–36357X. This paper is based on a dissertation submitted in partial fulfillment of the requirements for a Ph.D. in geology at Texas A&M University. The use of facilities at the Center for Tectonophysics, Texas A&M University, is greatly appreciated. M. Friedman, J. Handin, J. M. Logan, D. W. Stearns, and A. Gangi gave valuable advice during this project. Richard Engelder provided efficient assistance in the field. The manuscript was reviewed by M. Friedman and C. Scholz.

APPENDIX 1. PROCEDURES FOR DETERMINATION OF FAULT-ZONE PARTICLE-SIZE DISTRIBUTIONS

The evolution of fault gouge from a parent sandstone can be characterized with the aid of cumulative frequency curves. Each curve is constructed by plotting the cumulative percentage of grains (by volume) against grain size. It is convenient to plot these data on graph paper for which the abscissa is the log of grain size and the ordinate is cumulative percentage represented in probability scale (Griffiths, 1967). Here a normal distribution is a straight line at some angle to the abscissa. The slope of the curves is a measure of particle sorting; sorting deteriorates with decreasing slope. Sorting coefficients are based on a measure of the spread of the middle 20 to 80 percent of the grain-size distribution. Because of the large volume of particles too small to be measured in thin section, the distributions of the finer sized fragments are not known, and the cumulative frequency curves are incomplete. Therefore, only the slopes of the curves are used to show the relative degree of sorting. Grain-size data for each specimen were obtained from thin sections by measuring the apparent longest dimension of each grain or fragment with an eyepiece micrometer. Each curve is based on 300 measurements.

To test the reliability of the thin-section particle-size data, cumulative frequency curves for cataclastic sandstone and fault gouge from the Muddy Mountain thrust fault were determined by means of standard sieve and pipette analysis after Folk (1968b). Thin-section data for only five size groupings (that is, four cumulative frequency data points) accurately represent the shape of the curve obtained by sieve and pipette analysis, for which the data are separated into 13 size groupings (Appendix Fig. 1). Sieve and pipette analysis consistently show a median grain size that is smaller than that from thin-section data. The difference between median grain size of cataclastic sandstone and fault gouge as measured by the two methods is about 0.3 phi-units. These differences agree with previous studies, which show that the median grain size from thin-section analysis is generally about 0.2 to 0.3 phi-units larger than that from sieve analysis (Friedman, 1958). Because the thin-section data prove to be reliable in defining the grain-size distribution and are easier to obtain than sieve and pipette data, all discussions of grain-size distributions are based on thin-section data. Finally, cumulative frequency curves varied by less than 2 percent between thin sections of similar hand specimens.



Appendix Figure 1. Comparison of sieve and pipette data with thin-section data for cumulative frequency curves of cataclastically deformed Aztec Sandstone within Muddy Mountain thrust fault zone.

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MANUSCRIPT RECEIVED BY THE SOCIETY NOVEMBER 26, 1973
REVISED MANUSCRIPT RECEIVED APRIL 1, 1974