Fault-related rocks: Suggestions for terminology

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ABSTRACT

Many traditional terms for fault-related rocks have undergone recent dynamic metamorphism under high-pressure discussions by various groups of specialists. A generally acceptable simplified framework encompassing these and associated structural terms is now needed for many geologic, engineering, and legal purposes. Such a framework is proposed here, focusing on a rate-of-strain versus rate-of-recovery diagram and relating this framework to the products of brittle and ductile deformation along faults.

INTRODUCTION

Many geologists, specialists and nonspecialists alike, are uneasy about the present status of terms for fault-related rocks. Rapid advances in understanding processes operating in both brittle and ductile fault zones have left terminology of this field in uncertain condition (Tullis et al., 1982). Although the work of Bell and Etheridge (1973) is considered by many as a turning point in understanding mylonites as products of ductile flow and crystal-plastic grain-size reduction rather than products of traditional mechanisms of clastic milling and breakage (Lapworth, 1885), some terms and definitions inappropriate to modern concepts have survived as relics from older literature. Some terminologies such as that of Higgins (1971) predate the recent emphasis on distinctions between brittle microcracking and ductile grain-size diminution processes. Still others seem a bit too complicated for general acceptance—e.g., Zeck's (1974) "cataclastites, hemiclastites, holoclastites, blastoditto and myloblastites."

Even "mylonite" has its problems (Hatcher, 1978); participants in a recent Penrose Conference on mylonites could list the general characteristics of these rocks but were unable to find a precise and generally acceptable definition (Tullis et al., 1982). The difficulties are more than simple academic debates, as these terms are in constant use for fault evaluations, seismic risk analyses, and courtroom interpretation of ordinary geologic nomenclature. Part of the impetus for this paper is the experience of several of us sitting on witness stands while lawyers tried to bend our sometimes imprecise geologic words into statements favorable or unfavorable to their clients or adversaries.

We wrestled with these problems at length in attempting to develop a practical terminology for fault-related rocks as part of a Nuclear Regulatory Commission study of Appalachian fault characteristics (Odom et al., 1980). Part of the problem, we concluded, was the need for an updated, widely available, simplified, conceptual framework into which the most common terms and mechanisms could fit. Our proposed system (Fig. 1) bears many similarities to the systems of Higgins (1971), Sibson (1977), Hatcher (1978), and especially to that of White (1982). It differs in many details either with respect to underlying mechanisms, definitions, or choices of which terms to preserve or abandon. The paper is designed primarily for geologists who have not been closely involved with the recent arguments regarding fault rocks but must nevertheless cope with the jungle of fault-related terms.

STRAIN VERSUS RECOVERY

The texture of strained rocks is largely a function of the interplay between strain and recovery. Strain is manifest as brittle fracturing causing grain-size reduction or as ductile processes reshaping surviving grains and storing strain energy as twins or other crystallographic dislocations. (Undulatory extinction in quartz is among the most familiar of these unrecovered crystallographic strain effects.) Most recovery processes, on the other hand, involve release of strain energy accumulated in the crystal lattices. This can be done by syntectonic recrystallization, commonly with a reduction in grain size, or by late to posttectonic annealing, commonly resulting in approximately equidimensional grains with intersection angles near 120°. Thus, much of the recovery represents strain relief either by complete recrystallization of the grains or by migration of the dislocations to grain boundaries or into less strained subgrains having small crystallographic misorientation with respect to the mother crystal.

Competition between rate of strain and rate of recovery/recrystallization is a major determinant of the texture of fault-related rocks, the rates being functions of composition, grain size, temperature, fluids, and the stress field. At one extreme, most earth materials undergoing rapid strain at relatively low temperature, with modest to no recovery, yield a cataclastic rock (Fig. 1). At the other extreme, where recovery/recrystallization dominates, the result is an ordinary metamorphic rock, even though total strain magnitude may be quite large and involve a wide range of penetrative structures. Between these two extremes is a spectrum of brittle to ductile fault behaviors and associated rock types. Sibson's (1977) discussion is an excellent summary of these associations in a major fault zone.

CATACLASITES

Brittle faulting at high rates of strain (high as compared to those at which crystal-plastic flow can proceed) typically results in microfracturing or macrofracturing across and within grains to produce breccia, microbreccia, and gouge. These rocks, termed "cataclasites" (Fig. 1), are characterized by lack of foliation and little or no evidence of frictionally generated thermal changes. (Synchronously or subsequently, thermal waters may impregnate these materials into a nearly amorphous mass, sometimes termed "flinty crush rock." Because this phrase has been used in other ways, we prefer the term "silicified fault breccia.") Depending on the extent of fracturing, cataclasites could be further divided into protocataclasites, etc., as suggested by White (1982). We prefer the generally comparable sequence of simpler terms: "breccia," "microbreccia," and "gouge" (or "rock flour" if poorly consolidated).

The distinction should be emphasized here between the above restrictive definitions of cataclastic rocks and Higgins's (1971) much broader definition, which includes mylonitic rocks under the same category.

With rapid fault motion, microbrecciation may be accompanied by local frictional heating and melting. Where local gashes or fissures open at times of fault motion, large but short-lived pressure differentials can cause pervasive fluidization and injection of broken and/or melted material. Quenching of the injected material produces *pseudotachylite,* a highly strained but nonfoliated microbreccia formed from the clast-laden melt and lithified with minor amounts of glass (Wenk, 1978; Maddock, 1983).

With low recovery rates, low temperature, and low to moderate confining pressure in most lithologies, the fault operates in a *stick-slip* mode (Fig. 1). In this mode, periods of quiescence occur as shear stresses build up to break asperities on the fault surface during episodes of sudden motion. Alternatively, aseismic or *stable sliding* is more likely to occur in thick gouge zones where the asperities need not be broken or at higher confining pressures where they steadily plow minor grooves on the fault surface (Engelder, 1974). However, even within thick gouge, shearing can be localized in thin zones exhibiting stick-slip motion (Engelder et al., 1975). The general regions of stick-slip (seismic) versus stable sliding (aseismic) behavior are suggested by the stippled pattern in Figure 1.

Fibrous minerals can grow within the fault zone to connect formerly adjacent points, provided deformation rates are slow and appropriate fluids are present. We propose the term "slickenfibers" for these oriented fibrous growths associated with fault surfaces. Polished fault surfaces are termed "slickensides", and the frictionally produced lines upon the surface are termed "slickenlines" (Fleuty, 1975). For seismic risk analysis the distinction among these classes of linear features should be main-

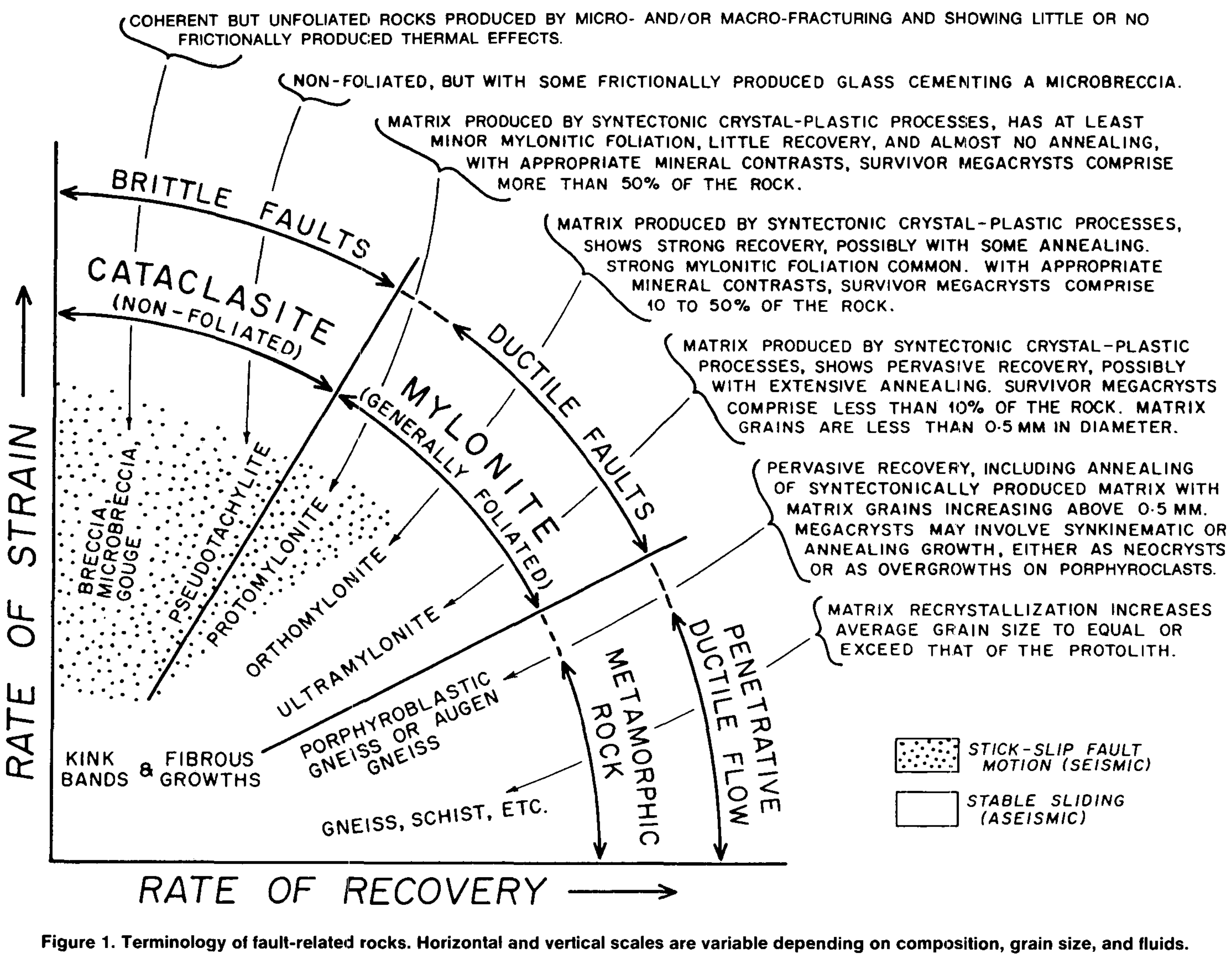

Figure 1. Terminology of fault-related rocks. Horizontal and vertical scales are variable depending on composition, grain size, and fluids.

tained because slickenfibers suggest aseismic creep displacement during their development. (However, healed cracks in some fibers may indicate interruptions by seismic events during their growth (Durney and Ramsay, 1973).

MYLONITES

Mylonites compose the region shown in Figure 1 that is marked by relatively high strain rate combined with appreciable recovery rate. The most common characteristic of the suite is the presence of mylonitic foliation, sometimes called fluxion structure, subparallel to planes of maximum shear strain. Despite the Greek root of the word (mylon = mill), mylonites have relatively little to do with clastic milling and breakage. For the most part, they represent diminution of grain size by syntectonic recrystallization associated with ductile strain or crystal-plastic processes (Bell and Etheridge, 1973; Hatcher, 1978). Larger crystals or mineral grains contained within the foliation are termed "megacrysts." Those formed by growth are termed "porphyroblasts"; those produced as survivors of incomplete megacryst destruction by either breakage or crystal-plastic processes are termed "porphyroclasts."

In the proposed system, *mylonite* is a general term for *coherent rocks with at least microscopic foliation, with or without porphyroclasts, characterized by intense syntectonic crystal-plastic grain-size reduction of the country rock to an average diameter less than 50 microns (0.5 mm) and invariably showing at least minor syntectonic recovery/recrystallization.* Absence of the word "fault" in this definition means that most but not necessarily all mylonites are associated with faults or fault zones as defined in the next section.

The most common members of the mylonitic suite are characterized by megacrysts representing survivors from destruction of preexisting less ductile mineral grains. If these survivors show little sign of significant recrystallization, constitute more than 50% of the rock, and are dispersed within a fine-grained matrix in which original grains or texture of the protolith have been destroyed by syntectonic recrystallization, the rock is a *protomylonite.* If the megacrysts in such a rock are distinctly lenticular, the term "lenticular protomylonite" may be used.

To distinguish intermediate members of this suite from the more general term "mylonite," we propose the term "orthomylonite": a coherent rock with foliated, moderately recovered matrix in which syntectonic recrystallization has reduced grain size of the country rock to less than 0.5-mm diameter and left 10% to 50% of that material as surviving megacrysts. In many quartz-rich rocks of this type, megacrysts may be flattened or stretched to axial ratios of 10:1 or even 100:1. For these rocks, the modifier "ribbon quartz" is commonly applied. For rocks in which ductile processes have destroyed essentially all the texture of the protolith (survivor megacrysts compose less than 10% of the rock) and extensive recrystallization of the matrix has produced grains less than 0.1 mm, the term "ultramylonite" is applied.

The above definitions focus on the matrix but include porphyroclast content as aids in preliminary field identification. Unfortunately, many monomineralic protoliths such as quartzites and marbles are unlikely to yield numerous megacrysts. These are difficult to fit into the above nomenclature using a porphyroclast criterion. For megascopic identification of these, the modifier "mylonitic" should be used (e.g., mylonitic quartzite and mylonitic marble). If subsequent microscopic examination indicates only minor subgrain formation and essentially no recrystallization, the term may be refined to protomylonitic marble, etc.; with more extensive recovery and recrystallization, the rock would be an orthomylonitic marble; with extreme recrystallization and grain-size reduction, an ultramylonitic marble would result.

Under high rates of recovery, syntectonic crystal growth processes play an increasingly important role in the formation of rock texture. The matrix may begin to show increasingly coarser grain size as a result of extensive syntectonic or posttectonic grain growth; porphyroblasts or augen (German = eyes) may begin to form by rapid growth of new mineral grains (*neocrysts*) or by overgrowths of new mineral material onto survivor megacrysts. When the matrix grain size of such a megacrystic rock exceeds 0.5–1 mm, it can be called a *porphyroblastic gneiss* or *augen gneiss,* depending on the nature of its megacrysts. It may or may not form in a fault zone as defined in the next section. In some terminologies this same rock has been called a blastomylonite, a term we prefer to avoid because of confusion in its past multiple uses (White, 1982) and because we wish to restrict mylonitic terms to rocks dominated by textural destruction and grain-size reduction. Where the recovery processes become so effective that average grain size exceeds 0.5–1 mm and approaches that of the protolith, ordinary metamorphic rock terminology should be used.

FAULTS, SHEAR ZONES, AND EUPHEMISMS

In the common phrase "fault-related rocks," the term "fault" can have many definitions and applications. In the present era of environmental impact statements and seismic risk assessments, an amazing number of euphemisms have been devised to avoid use of the word "fault," with all its legal and public-relations implications. Examples include: shear zones, displaced zones, zones of offset, shattered zones, discontinuities, and disturbed zones. Other complications include mechanical healing of some faults to make them stronger than the country rock and thus alter the seismic risk.

Some would restrict "fault" to zones exhibiting both loss of cohesion and tangential displacement. In cases where there has been no loss of cohesion across displacement zones, the terms "ductile fault zones" or "ductile deformation zones" (Mitra, 1978) have been applied. For many laboratory experiments and some classes of perfectly exposed field examples, such distinction between a "ductile shear zone" and a "fault" is relatively straightforward. For the exposure quality of most field examples such distinction is impractical. Further, even with perfect exposure, there must ultimately be some limiting case where the width of the ductile zone is so small in relation to its displacement that determination of whether cohesion has or has not been lost across the zone is difficult or impossible. Beyond this limit, the structure is a "ductile fault," even though many purists would argue that such a term is a non sequitur.

We suggest that the term "fault" be retained for *that entire class of phenomena characterized by relatively tabular or planar discontinuities in which the zone as a whole or any macroscopic part of it contains displacement parallel to the zone greater than 0.5 to 1 cm and displacement at least five to ten times greater than the width of that part regardless of whether the zone is marked by loss of cohesion or extreme ductile deformation.* This minimum displacement criterion is suggested here to eliminate arguments about ratios for very tight joints or other features having essentially no finite width. The fuzziness of 0.5 to 1 cm or ratios of 5:10 is intentional to preclude courtroom arguments as to whether a particular disturbed zone has a ratio of 9.7 or 10.3 and thus legally is or is not a fault. Also, under this definition, highly deformed limbs of some severely attenuated folds would be termed faults, a reasonable distinction considering that some highly asymmetric folds ultimately must have displacements transitional into faults.

Further subdivisions important for seismic risk analysis may be based on style of yield and strength contrasts between fault zone and country rock. *Ductile faults* involve permanent strain without loss of cohesion normal to the fault. *Brittle faults* are characterized by loss of cohesion normal to the fault at the time of last motion and may be subdivided into three categories: *unhealed brittle faults,* which have remained essentially unchanged since their last motion; *filled brittle faults,* which have been modified by new mineralization partially or totally filling and cementing open spaces, but having a shear or tensile strength below that of the country rock; and *healed brittle faults,* which have been modified by new mineralization and/or recrystallization such that shear and tensile strengths of the fault zone are essentially equal to or greater than those of enclosing rocks.

Within ductile fault zones, mylonite production may occur in zones centimetres to kilometres in thickness, but within them younger brittle features may be concentrated in thin bands representing only a small percentage of the total thickness of the main zone. These late-stage, brittle components, though easily overlooked because of poor recovery in drill core and poor surface exposure, are among the most critical features for seismic risk analysis. Too often, investigators at sensitive locations have expended great effort in defining and dating ductile and mylonitic aspects of a major fault zone while largely ignoring these small but critical unhealed brittle faults that indicate the younger and most dangerous brittle behavior of the overall zone.

STRAIN AND RECOVERY HISTORY

The history of deformation and metamorphism of a rock mass commonly extends over a considerable period of time during which several stages of strain may occur under differing rates and conditions. The result can be a complex array of superimposed strain and recovery features or textures varying from ductile to brittle.

The evolutionary history of a rock in the vicinity of a major fault zone might follow the path illustrated in Figure 2. The main rock mass might pass through a series of deformations involving generally low strain rates in going to high metamorphic grade and back to surface conditions. Superimposed on this general pattern could be a number of brief pulses of high strain rates, as indicated by the spikes in Figure 2. Frictional heating at higher strain rates might cause temporary, slightly increased recovery rates, as suggested by curvature of the spikes to the right. Early-formed breccia and gouge [(A) in Fig. 2] or mylonite (B) would be homogenized and in part camouflaged by later metamorphism and ductile flowage. Mylonitic and cataclastic rocks produced after the metamorphic peak would be much more likely to survive in recognizable form. Some of the early-formed mylonites (D) would be likely to have a variety of younger deformational features superimposed on them, such as foliation, kink bands, and passive and/or flexural folds, or they might be slickensided or brecciated by late fault motions (E). Thus, a typical mylonitic specimen should be considered the end result of a long history of these types of deformations and metamorphisms under a variety of pressure, temperature, and strain conditions.

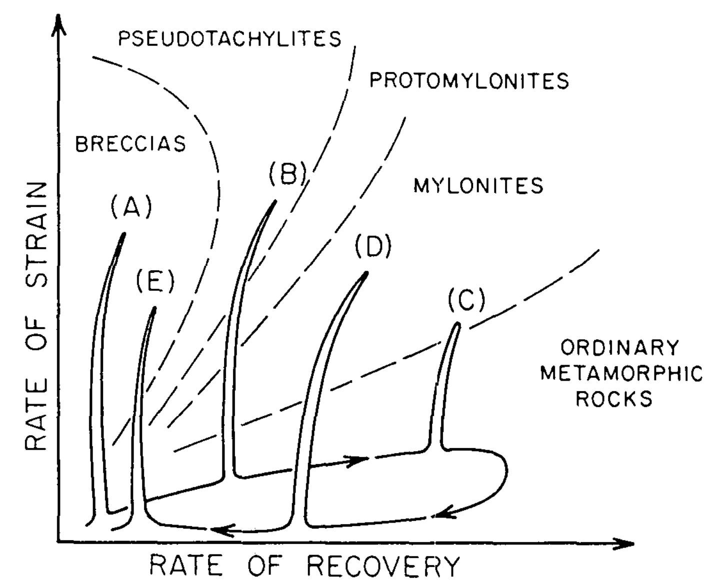

Figure 2. Hypothetical history of typical fault-related rock passing through coordinates of Figure 1.

SUMMARY

The attempt here has been to establish a practical framework for terminology of fault-related rocks and the zones in which they occur, a framework within which both the field geologist and the rock-deformation specialist can operate. The distinction of foliated versus nonfoliated texture for separating mylonitic and cataclastic rocks follows White (1982) as a relatively simple field criterion. Additional refinements using porphyroclast to matrix ratios follow Higgins (1971) as guides to field identification. Ultimately, the terminology relies on field determinations being verified by microscopic identification of strain and recovery mechanisms in the matrix, details of which are beyond the scope of this short paper.

Some specialists undoubtedly will be displeased with the simplifications of some of these proposals. Nevertheless, faults and fault-generated materials are being described constantly by a hodgepodge of terminologies for many geologic purposes, including critical engineering analyses of seismic risk. Our discipline urgently needs some updated, practical framework for these descriptions. This is one possible version for consideration by the profession.

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