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Fracture and flow in natural rock deformation

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Abstract: Field observation shows that brittle fracturing and ductile flow are often intimately related under a wide range of metamorphic conditions. By their very nature, brittle fractures tend to be discrete and ductile flow more distributed, so that strong localization is often more readily attributed to brittle fracture or to subsequent ductile reactivation of a brittle precursor. Brittle fractures commonly show little regard for existing compositional boundaries and can crosscut them at a low angle, whereas ductile localization is typically bound to bands of different composition and/or rheology. Very localized regional fault zones can extend for hundreds of kilometres with widths on the order of hundreds of metres or less. They commonly crosscut many different compositional units at low angles, which suggests a potential brittle precursor to the mylonite zone now observed. In general, ductile viscous flow initially localized on discrete compositional or rheological precursors may actually tend to broaden rather than localize with time. The interplay between brittle fracture and localized viscous flow in shear zones, and the associated tectonic pressure effects relative to the adjacent matrix, are critical for understanding fluid flow in heterogeneously deforming rocks and thus for the interpretation of veins, fluid-rock interaction, migmatites and melt accumulation.

Keywords: brittle fracture, ductile flow, localization, fluid-rock interaction, tectonic pressure.

Fracture and flow are usually seen as alternative or competing mechanisms of rock deformation, with brittle fracture dominating in the upper crust and ductile crystal plastic flow at depth. However, direct field observation shows that in nature the two mechanisms are often intimately related in the development of common deformation structures such as folds, boudins, and shear zones. On the smaller scale, intra- and inter-granular microfracturing may also be crucial for the introduction of water during mesoscopically "ductile" flow, leading to reaction-enhanced softening and hydrolytic weakening effects (e.g. Fitz Gerald *et al.*, 1991). In general, coeval and cyclical fracture and flow are often crucial for deformation at all crustal levels (and possibly even within the upper mantle) and not just within a limited "brittle-ductile transition" zone at mid-crustal depths.

Localization vs. broadening of deformation zones

Practically all deformation structures of interest to structural geologists involve heterogeneous strain and localization of deformation. However, a basic question remains whether strain tends to localize or spread with time. Often it is assumed *a priori* that strain tends to increasingly localize, promoted by non-linear rheology (e.g. power-law viscous behaviour) and strain softening due to (1) recrystallization and grain size reduction, (2) development of a crystallographic preferred orientation (CPO), (3) reaction-induced softening (e.g. phyllonization), and (4) shear heating. However, all these mechanisms lack a strong and continuing positive feedback that could effectively drive localization. Recrystallization and grain size reduction tend to change the deformation mechanism toward grain-size sensitive creep with a consequent reduction in the power-law stress exponent, which counteracts the tendency to localize. The development of a CPO can initially lead to strain softening but soon approaches a steady state microstructure with little additional softening. The same applies to reaction-softening. Once the reaction is well advanced there will be a decrease in the rate of further strain softening (e.g. when basically all the feldspar is already transformed to mica in a phyllonite). In all these cases, the process can only continue by involving more of the adjacent country rock in the transformation – that is by actually broadening the zone. Shear heating could be a very efficient means of decreasing the effective viscosity and thereby localizing deformation. The feedback effect is, however, negative because lowering the viscosity correspondingly decreases the rate of further heat production. Thermal runaway associated with shear heating is also very dependent on the scale (becoming increasingly difficult as the length scale decreases) and on the boundary conditions, with constant load promoting runaway and constant velocity (or strain rate) boundary conditions tending to hinder its development (Brun and Cobbold, 1980; Fleitout and Froidevaux, 1980).

However, the strongest localization occurs during discrete fracture due to the positive feedback between decreased mean stress ("pressure") in the fracture zone and the pressure-dependent yield criterion for brittle fracture. Such fractures can have extreme length to width ratios, with joints of sub-mm width extending for hundreds of metres.

It follows that fractures and faults are generally much more localized than ductile shear zones and that strongly localized natural banded structures could be more readily explained if they actually initiated as brittle fractures – a topic that will be considered further below.

Influence of compositional boundaries on fracture and flow

The elastic properties, angle of internal friction and cohesion of a wide variety of rocks are rather similar,

Figure 1. Aplite dyke in granodiorite, Neves area, Eastern Alps (for general location, see Pennacchioni and Mancktelow, 2007). Note the localization of ductile shearing on the rim of the dyke and the discrete fracture crosscutting the dyke boundary at a low angle. One euro coin for scale, width of dyke ca. 15 cm.

with the result that frictional slip and fracture in rock are largely independent of rock type. In natural exposures, it is commonly observed that fractures can crosscut compositional boundaries without regard to the interface, in some cases even at quite low angles (Fig. 1). In contrast, the rheological parameters for flow of different rocks can be very different and depend on a wide range of factors such as composition, grain size, water content, impurities, etc. For ductile flow, the behaviour can be considered in terms of an effective viscosity (which may be a function of strain rate for non-linear behaviour) linking deviatoric stress to strain rate. Since the shear stress parallel to a material interface is the same on either side of the interface it follows that the ratio in effective viscosity of adjacent materials must be directly reflected in the corresponding shear strain rates parallel to the interface. In practice, this means that in nature ductile strain is often localized on compositional boundaries and, in contrast to brittle fractures, does not tend to transect boundaries (and certainly not at a low angle). For example, in figure 2 shear zones have localized on the boundaries of an aplite dyke, which is clearly more "competent" (i.e. it has a higher effective viscosity) than the surrounding granodiorite. Localization of shear on the boundaries is only observed when the layer is stronger than the matrix. Less competent basic dykes (lamprophyres) from the same area show a higher and quite homogeneous shear strain within the dyke itself and a discrete transition across the boundary to low strain in the adjacent granodiorite, without any flanking ductile shear zone (Pennacchioni and Mancktelow, 2007).

Figure 2. Localization of shearing on the rim of an aplite dyke in granodiorite, Neves area, Eastern Alps. One euro coin for scale.

Brittle precursors to ductile shear zones

Ductile shear zones can localize on pre-existing rheological boundaries related to original compositional differences but they can also localize on precursor fractures. This is well established from direct field observation in relatively homogeneous unlayered rocks, such as major plutonic intrusions (Simpson, 1985; Segall and Simpson, 1986; Guermani and Pennacchioni, 1998; Pennacchioni, 2005). Such plutons commonly develop joints during cooling and extensional or shear fractures during any subsequent deformation. In some cases, it is possible to still document the transition from precursor fracture to duc-

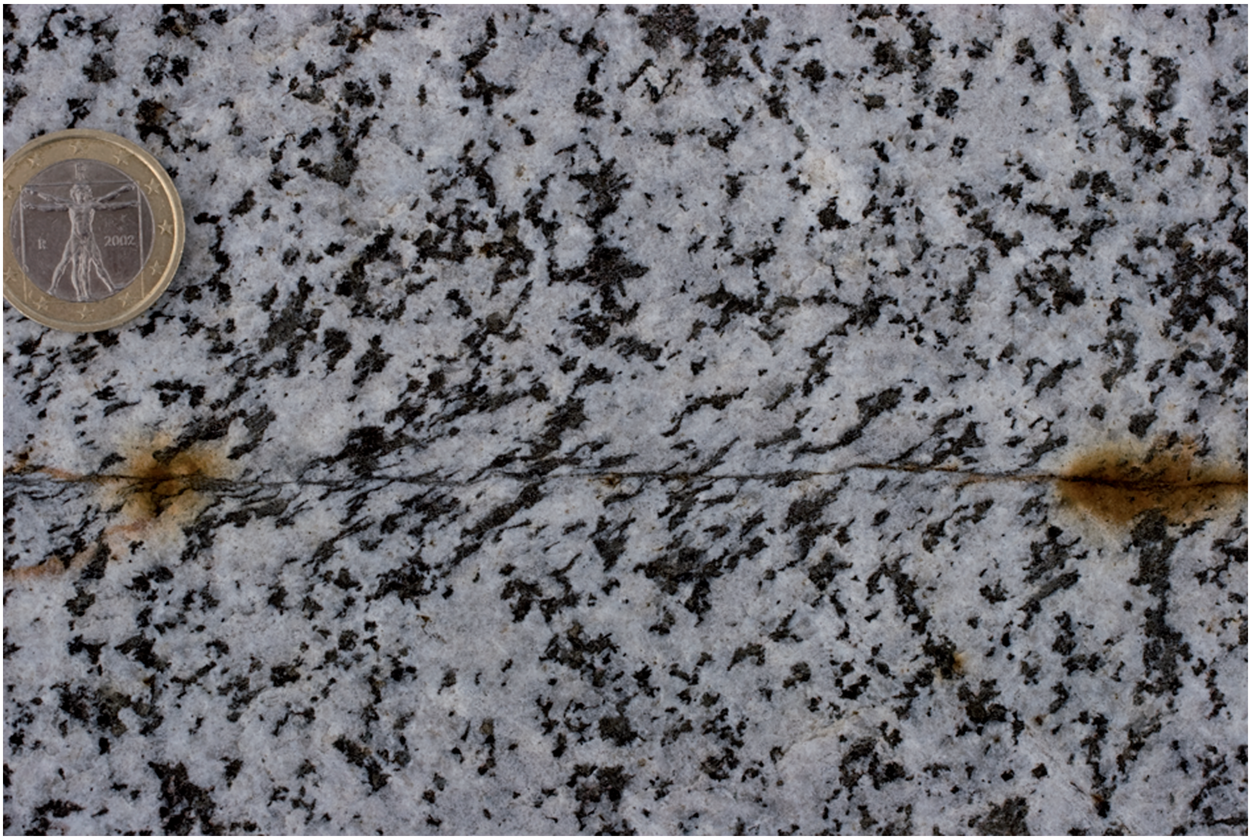

Figure 3. Incipient ductile shear zone localization on a precursor, biotite-rich fracture, now preserved as a central septum, which sometimes can still be recognized even in more fully developed shear zones. Neves area, Eastern Alps. One euro coin for scale.

tile shear zone (Mancktelow and Pennacchioni, 2005). In others, the pattern of ductile shear zones maintains the characteristic geometry of the precursor fractures (Mancktelow and Pennacchioni, 2005) or a central septum reflecting the initial fracture may be preserved (e.g. as is clear in the incipient shear zone of figure 3). Recently, it has also been demonstrated that precursor fractures are also critical for shear zone development in schistose rocks from the classic location of Cap de Creus, NE Spain (Fusseis *et al.*, 2006).

Ductile shear zones do not readily propagate into intact homogeneous rock but remain bound to rheological boundaries. Fracturing may therefore be an important mechanism for progressively involving more of the rock mass in the deformation, which must occur as the bulk strain increases. This would involve cycles of fracturing (perhaps initially even jointing related to cooling for plutonic intrusions), ductile reactivation and development of a shear zone network, renewed fracturing due to strain accommodation problems and associated stress concentrations, and subsequent localized ductile shearing on the new fractures. This cycle could repeat itself through time and space during progressive deformation and might be difficult to recognize once the bulk strain has reached higher values and most of the rock is pervasively deformed.

The regional pattern of major shear zones, such as the Periadriatic Fault in the Alps (e.g. Schmid *et al.*, 1989), is also strongly suggestive of a brittle precursor. These major fault zones were often referred to as “Lines” in the literature because, on the map scale, they do indeed plot as lines with a very narrow width relative to their length, corresponding to extreme localization. Such faults also cross-cut lithological boundaries, often at low angles, which, as noted above, is much more typical of a brittle fault than of a progressively localizing ductile shear zone. These discrete lines are now loci for narrow mylonite zones, showing a rapid but generally gradational transition into the adjacent units to either side. The latest structures developed at large total displacement and shear strain are again commonly brittle and extremely localized, with a narrow zone of cataclasite or fault gouge typically only a few metres to tens of metres wide overprinting the mylonites. A similar situation is observed in many major normal faults, such as the Simplon Fault Zone in the Alps (e.g. Mancktelow, 1992), where exhumation and cooling of the footwall leads to a transition to dominantly brittle behaviour and increasing localization on a quite discrete "detachment fault" (referred to in the literature as the "Simplon Line"). This is again a direct field example that strong localization is much more characteristic of brittle fracture than of ductile flow. Indeed, the widespread preservation of mylonites in the footwall of such major normal faults is only possible because the subsequent overprint by brittle fracturing is so strongly localized on a single narrow zone.

Tectonic pressure and brittle/ductile behaviour

Both faults and shear zones are banded structures that are long relative to their width, and their development is generally associated with a difference in mean stress between the band and the surrounding matrix (Mancktelow, 1993, 2006, 2008). However, the effect is opposite in the two cases. Brittle failure in a Mohr-Coulomb material is associated with a decrease in pressure in the fault zone whereas almost all ductile shear zones will be transpressive or "stretching faults" (Means, 1989) and the weakened zone within the shear band will therefore develop a higher pressure than the adjacent matrix. This has important implications for pressure-dependent melting and melt accumulation in migmatites associated with shear zones, as well as for migration and fluid-rock interaction in shear zones. As discussed in Mancktelow (2006), the observation that fluids typically migrate into shear zones rather than being expelled suggests that many "ductile shear zones" in fact involve a component of brittle fracture. This brittle component promotes fluid flow into the zone both by enhancing the permeability and by reducing the pressure in the zone.

Fracture under high-grade metamorphic conditions

In the typical simple model of lithospheric deformation, brittle fracture is limited to the upper crust although, for low geothermal gradients, the upper part of the lithospheric mantle could also be brittle (e.g. Ranalli and Murphy, 1987). However, in nature local brittle fracture clearly occurs even under upper amphi-

Figure 4. Biotite (and garnet)-rich cataclastic fracture zone, Neves area, Eastern Alps. The metamorphic assemblage in these healed fractures is consistent with the peak upper amphibolite facies metamorphic conditions reached in this area. Locally such fractures crosscut amphibolite-facies ductile shear zones (e.g. Fig. 1), indicating that at least some such fractures developed under upper amphibolite facies conditions. One euro coin for scale.

bolite to granulite facies conditions typical of the middle to lower crust (e.g. Fig. 4). Such high-grade brittle fracture is not uncommonly observed in strong dry rocks that have been dehydrated by metamorphism and melt extraction (e.g. Yardley and Valley, 1997) and can result in seismic faulting and pseudotachylyte formation, which in turn may act as precursors for subsequent, very strongly localized, high-grade ductile shear zones (Pennacchioni and Cesare, 1997; Mancktelow and Pennacchioni, 2004). In fact, Austrheim and coworkers (e.g. Austrheim and Boundy, 1994; Austrheim and Engvik, 1997) have clearly demonstrated that seismic faulting and associated pseudotachylyte development can even occur under (ultra-)high pressure eclogite facies metamorphic conditions. These fractures subsequently allow infiltration of water, resulting in fluid-rock interaction and the localization of ductile shear zones on the precursor fracture network.

Conclusions

There is now a considerable body of field data establishing that ductile shearing may localize on brittle precursors under metamorphic conditions up to upper amphibolite and even UHP eclogite facies, with these observations covering scales ranging from individual grains to the lengths of mountain belts. The interaction between brittle and ductile deformation also determines the pressure distribution relative to the surrounding matrix in these localized strain zones and thus the direction of fluid or (in migmatites) melt migration. Deformation may involve multiple cycles of brittle fracture, localized ductile shear and more distributed flow in time and space and progressively straining more and more of the rock mass. Such a development history may only be obvious in the incipient low strain stages, as an increasingly pervasive overprint tends to obscure these relationships in strongly deformed zones.

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